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Giri Rajasekhar Gunnu

Safety and efficiency enhancement of anchor handling operations

with particular emphasis on the stability of anchor handling vessels

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Thesis for the degree of Philosophiae Doctor

Trondheim, July 2017

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Dedicated to my dear parents

Thank you for your belief in me and for all the support and encouragement throughout my career.

Summary

The overall objective of this thesis is the development of a framework for enhancing the safety and efficiency of anchor handling vessels (AHVs) during anchor handling operations (AHOs). In other words, the proposed framework contributes to an optimized solution for AHVs with the objective of balancing risk and cost. An optimal strategy considering cost and safety is achieved by moving away from standard weather restriction limits to vessel-specific limits ("by focussing on safety"). With this strategy in mind, a methodology is proposed for defining vessel-specific operational limits with the goal of not compromising safety.

On 12 April 2007, the Bourbon Dolphin accident occurred in the North Sea; eight of the ship's crew lost their lives. In general, there are stakeholders involved in these operations, for example, designers, shipping companies, operators, statutory bodies, governmental bodies, and insurance companies. This accident alarmed the public and drew the attention of government regulators and other stakeholders. These stakeholders have a role in minimizing risk and improving safety. To achieve these goals, they have their own procedures, guidelines, and standards. However, these existing procedures and international standards are not well established for mitigating risk and maintaining a safety margin for AHVs during AHOs. For this purpose, the offshore (or oil and gas) industry must improve the existing procedures or establish new procedures and methods.

Due to their characteristics, these AHOs come under the category of complex, weather-restricted marine operations, which imposes additional challenges for the vessels and the personnel involved in these operations. Therefore, the practice in the industry is that AHOs are performed up to a maximum significant wave height of 3.5 m and a mean wind velocity of 40 knots. Furthermore, AHOs contribute 10 to 20% of the total drilling well cost in offshore oil and gas exploration. The operational cost can be reduced by increasing the available weather window or operability (or reducing downtime); this reduction can be achieved by increasing operational limiting parameters related to weather. Therefore, enhancement of the safety (or minimization of the risk) and cost efficiency of AHVs during AHOs is considered a research topic. This research addresses AHV safety issues directly during AHOs and indirectly in terms of cost.

The world is not perfect. Hence, it is not possible to design vessels that are 100% safe and cost effective to handle operational loads during AHOs. Therefore, to conduct safe AHOs, a combination of better vessel selection, operational limitations, operational planning and crew training is used. Before defining operational limits, it is essential to identify the influence parameters for vessel capsizing, that is, environmental, hardware, software and human factors. These parameters can be broadly classified into two categories. The first category is related to vessel behaviour: vessel stability and vessel drift-off in a horizontal plane. The second relates to human performance – skill, knowledge, and Situational Awareness (SA) – and depends on the personnel involved in these operations, for example, an AHV's master and deck officers, tow master, offshore installation manager (OIM), marine representative, rig winch operator and deck crew, surveyor, and other vessel deck officers. With respect to the safety and performance of AHVs, the key personnel are the AHV's master and winch operator. The vessel master has three roles: being aware of vessel behaviour, identifying an appropriate control strategy and executing that strategy. Even a decision to stop or proceed with the operation is a responsibility of the master or of whoever is in charge of the bridge. Therefore, the personnel involved in operations must be aware of the influence of the magnitude of mooring loads and other parameters of vessel behaviour.

The key sequence of events related to the Bourbon Dolphin accident are as follows: vessel drift-off (with respect to the desired mooring line track), a large angle of attack, a large overturning moment, a large initial heeling angle (or static heeling angle) and, eventually, the vessel capsizing. First, the excessive drift-off from the planned anchor track is an initiating event related to this accident. Therefore, the progress of vessel drift and angle of attack are simulated and analysed for potentially dangerous situations. The analysis results show that insufficient positioning capability is one of the reasons behind the initiating event. For this reason, in this study, the thrust-utilization plot concept was proposed. Here, the effect of the mooring line load was considered in addition to the general practice with environmental loads.

As mentioned previously, the large static heeling angle was the event immediately preceding capsizing. It is essential to assess vessel stability thoroughly in the design and analysis phase of AHOs to prevent similar accidents. Thus, the existing stability criteria are reviewed, and it is noticed that these criteria do not cover AHV stability when the vessel is subject to mooring load during the AHO. Additionally, there is no criterion to be found for monitoring stability during the operation phase. Therefore, two stability criteria are established, namely, the 1) critical static heeling angle criterion and 2) critical rolling angle criterion. The first criterion is useful in the design phase for assessing vessel allowable static heeling angle (which is a function of the thrust force, mooring load, current and wind) for a well-defined operating sea state. Moreover, this criterion is helpful for operators when assessing vessel safety status and identifying the risk mitigation (or control) strategies for preventing capsizing during the execution phase of the operation. The second criterion represents the critical dynamic rolling angle in waves for an estimated total heeling moment induced by the thrusters, mooring line, current and wind. This criterion is useful for assessing vessel stability in the analysis and planning phase of the operation.

Although the operational limits are defined in the analysis and planning phase, it is not possible to prevent vessel capsizing unless there is awareness of the vessel's behaviour. At present, the existing on-board monitoring systems are not useful for assessing the vessel's stability status when it is subjected to mooring load during AHOs. Therefore, in this study, an artificial neural network (ANN)-based on-board monitoring system is proposed for assessing vessel static heeling angle by considering the effect of operational parameters.

Even when the vessel's stability margin (in terms of vessel static heeling angle) can be predicted (with a condition monitoring system), it is difficult to identify the best control strategy when the vessel is approaching capsizing. Moreover, if the operation must be performed in new areas (such as deep waters) or higher waves than are normally anticipated, such operations can enforce additional constraints on the vessel master during decision-making. To overcome these constraints, an optimization-based decision support system (DSS) is proposed for identifying the best possible set of control strategies. Although many control strategies are available, some control measures are preferable to others based on the operational situation. For this reason, a hierarchical approach is considered for finding the optimal control strategy for a given operation.

The following benefits are achieved by this study:

- Improving the safety of the vessel and its crew during AHOs;
- Understanding vessel handling capability under normal and failure conditions (propeller or thrusters);
- Increasing the vessel's operating weather window;
- Improving the utilization of vessels;
- Reducing overall costs related to rig moves and drilling operation;

- Providing a clear and straightforward criterion for selecting vessels and establishing operational limits via the thrust-utilization plot concept.

Note that the framework presented in this thesis can be extended to other types of marine operations such as fish trawling, pipe laying, and crane operation.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) as partial fulfilment of the requirements for the degree of Doctor of Philosophy at the Department of Marine Technology, NTNU.

This doctoral work has been performed at the Department of Marine Technology, NTNU, in a partnership with SINTEF Fisheries and Aquaculture (now SINTEF Ocean) and the Centre of Ships and Ocean Structures (CeSOS). The Ph.D. has been funded by the Norwegian Research Council. In particular, the thesis is part of the strategic institute programme “Safe Operation of Subsea Systems (SOSS)” at SINTEF Fisheries and Aquaculture (now SINTEF Ocean). The Ph.D. work has been performed from August 2008 to November 2016 in close collaboration with my main supervisor, Professor Torgeir Moan. The co-supervisor was Dr. Haibo Chen, Managing Director Asia at Lloyd’s Register Consulting.

Only a limited number of publications have emerged in anchor handling operation. Furthermore, it is a relatively new and challenging area for scientific research. Therefore, to work in this area requires both theoretical insights and practical knowledge. Moreover, my initial Ph.D. fellowship ended on January 31, 2013. Therefore, I took a fulltime position as a Senior Naval Architect in Global Maritime, Stavanger from February 2013 to September 2015 and continued my research work part-time. The employment in Global Maritime involved work on marine operations, which is relevant to my research work.

Before starting my Ph.D. studies, I worked in a Classification Society as a Ship Surveyor. There, my focus was on minimizing risk and improving safety. Knowledge acquired through experience gave me a focus on the balance between safety and cost in marine operations. Knowledge acquired through studies and experience has been used for the development of new concepts and methods in this study. I hope that the findings in my study can be useful for the key stakeholders and personnel involved in AHOs such as designers, shipping companies, operators, statutory bodies, governmental bodies, and insurance companies. Furthermore, I am an optimist and hope that the research findings will lead to cost effective, safe and reliable anchor handling operations in general. Although the study is focussed on AHOs, the basic approach addressed in this study can be used for other marine operations.

Trondheim, ---------------------------

July 2017 *Giri Rajasekhar Gunnu*

Acknowledgement

The research was performed at the Centre of Ships and Ocean Structures (CeSOS) and at the Department of Marin Technology, was led by Professor Torgeir Moan, and was performed in the period from 2008 to 2017 partly full times and partly part time. He critically appraised my research work, papers and thesis, which brought me countless headaches but, nonetheless, was vital to the completion of the research work and to establishing myself as an independent researcher. I would like to thank him for giving me the opportunity to learn from his experience. His guidance and support during the work are gratefully acknowledged. Special thanks to Dr. Haibo Chen for his helpful comments, ideas and suggestions. In studies that resulted in two articles, I collaborated with Xiaopeng Wu, a colleague at CeSOS. This collaboration has led to fruitful discussions; I would also like to thank him very much for his work.

This thesis was made possible by financial support from SINTEF Fisheries and Aquaculture (now SINTEF Ocean) through CeSOS. I would particularly like to thank Dr. Vegar Johansen for his support and encouragement. I wish to extend my thanks to all those individuals and organizations who provided ample information and shared their experiences related to the safety aspects of AHOs. Furthermore, I wish to express my gratitude to Farstad Shipping ASA for granting me permission to be an observer on board the AHV Far Sapphire (AHV) during AHOs. Special thanks are due Svein Leon Aure and Muren Åge from Farstad Shipping ASA for their support in granting permission for field observations of AHOs. Additionally, I wish to express my gratitude to Øyvind Andersen for providing simulator training at the Ålesund simulator centre.

I also thank Ole Andreas Hermundstad, Dariusz Fathi, Edvard Ringen, Knut Mo, and Renato Skejic in Marintek (now SINTEF Ocean) for helping to familiarize me with the SIMO and ShipX software. I am gratefully indebted to Gisle Fiksdal at Lodic AS, Aswin Kumar Bandaru at DNV, Øystein Johnsen and Kjell Olav Holden for providing an understanding of the state-of-the-art used in this thesis. During my tenure at Global Maritime, the opportunity to interact with Jakob Ravnås, Ole Gunnar Helgøy and Thorgeir Anundsen helped me to gain further knowledge on AHVs and AHOs. Thanks to them and other colleagues from Global Maritime.

I wish to thank my fellow Ph.D. students, postdocs and researchers for their friendship and help during my tenure at CeSOS and IMT. Special thanks to Madjid Karimirad, Nilanjan Saha, Gao Zhen, Mohamed Shainee, Made Jaya Muliawan, Ekaterina Kim, Babak Ommani, Maxime Thys, Reza Firoozkoohi, Vincentius Rumawas, Asle Natskår, and Karl Gunnar Aarsæther for their fruitful discussions on scientific and other topics during office hours, lunch hours and coffee breaks.

My friends have morally supported me through the long struggles of Ph.D. studies. I want to express my gratitude to all of them. Specially, I am greatly indebted to Dasharatha Achani, Ugandhar Kema and Kishore Kosuri for their proofreading, which has profoundly improved the composition of the papers and the thesis.

I would also like to thank the professors and the staff at the Department of Marine Technology for their help whenever I asked for it. Special thanks are due the administrative staff: Sigrid Bakken Wold, Marianne Kjølås, Karelle Gilbert-Soni, Linda Grønstad, Annika Bremvåg, Mostafa Jalali and Bjørn Tore Bach. They have contributed to making the process of this work enjoyable both socially and scientifically.

Finally, I express my gratitude to my family, particularly my parents, my brother and my wife, Srujana, and son Ruthvik Srivathsav. I dedicate this work to my mother Gunnu Suseelamma and my father Gunnu Papa Rao. My mother has been a motivator for me from my childhood onwards; she is my first teacher, and my father has provided continuous support through my career. Without their support, I would not have reached this stage.

Trondheim, July 2017
Giri Rajasekhar Gunnu

List of Appended Papers and Visit Report

The thesis consists of an introductory part, seven appended papers (four journals and three conference papers) and a visit report. These documents are reported in Appendix A.

Anchor handling vessel stability during anchor handling operations

Paper 1: **Gunnu, G.R.S.**, Moan, T., Chen, H., 2010. Risk influencing factors related to capsizing of anchor handling vessels in view of the Bourbon Dolphin accident, In: Proceedings of Systems engineering in ship and offshore design, Royal Institution of Naval Architects, Bath, UK.

Paper 2: **Gunnu, G.R.**, Moan, T., 2012. Stability assessment of anchor handling vessel during operation considering wind loads and wave-induced roll motions, In: Proceedings of 22nd ISOPE, The International Society of Offshore and Polar Engineers, Rhodes, Greece.

Paper 3: **Gunnu, G.R.**, Moan, T., 2017. Stability assessment of anchor handling vessels during operations, Journal of Marine Science and Technology, June, 2017.

Paper 4: **Gunnu, G.R.**, Moan, T., 2017. An assessment of AHV stability during anchor handling operations using a method of artificial neural network, Ocean Engineering, 140, pp. 292-308.

Paper 5: **Gunnu, G.R.**, Moan, T., 2017. Decision Support System for ensuring the stability of anchor handling vessels during operations, (manuscript phase).

Anchor handling vessel drift-off during anchor handling operations

Paper 6: **Gunnu, G.R.S.**, Wu, X., Moan, T., 2012. Anchor Handling Vessel Behavior in Horizontal Plane in a Uniform Current Field During Operation, Proceedings of the 2nd Marine Operations Specialty Symposium. Marine Operations Specialty Symposium-(MOSS2012), Furama Riverfront, Singapore, pp. 307-324.

Paper 7: Wu, X., **Gunnu, G.R.S.**, Moan, T., 2015. Positioning capability of anchor handling vessels in deep water during anchor deployment, Journal of Marine Science and Technology, January, 2015.

Observation of anchor handling operation

Report: **Gunnu, G.R.S.,** 2011. Visit report of rig move Songa Delta from Far Sapphire vessel, Norwegian University of Science and Technology, Trondheim, Norway, p. 48.

Declaration of Authorship

All the seven papers that serve as the core content of this thesis are co-authored. Except for paper 7, I was the first author and responsible for initiating ideas, establishing the numerical models, performing the analysis and calculations, providing the results and writing the papers. In paper 7, I was the second author, contributed to the initial ideas, and helped with corrections and constructive comments when writing the paper. Furthermore, with respect to this last paper, I provided helpful discussions and proofreading.

Professor Torgeir Moan is the co-author for all seven papers. He contributed support, corrections and constructive comments to increase the scientific quality of the publications.

Xiaopeng Wu was the first author of paper 7 for establishing the numerical models, performing the analysis and calculations, providing the results and writing the paper. He was also the co-author of paper 6 for establishing the numerical models, performing the analysis and calculations, and providing the results and discussions.

Dr. Haibo Chen was the co-author of paper 1. He has contributed useful discussions and proofreading of the manuscript.

Abbreviations

AHO	Anchor Handling Operation
AHTS	Anchor Handling Tug/Supply
AHV	Anchor Handling Vessel
ALARP	As low as reasonably practicable
API	American Petroleum Institute
BHP	Break Horse Power
CeSOS	Centre of Ships and Offshore Structures
DNV	Det Norske Veritas
DP	Dynamic Positioning
DSS	Decision Support System
ETA	Event Tree Analysis
FM	Failure Modes
FAR	Fatality Accident Rate
FMEA	Failure Mode Effects Analysis
FPSO	Floating Production, Storage and offloading (unit)
FTA	Fault Tree Analysis
HAZID	Hazard Identification
HAZOP	hazard and Operability Analysis
HSE	Health & Safety Executive
IMCA	International Marine Contractors Association
IMO	International Maritime Organization
ISM	International Safety Management
ISO	International Organization for Standardization
MODU	Mobile Offshore Drilling Units
MOU	Mobile Offshore Unit
NMD	Norwegian Maritime Directorate
NPD	Norwegian Petroleum Directorate
NTNU	Norwegian University of Science and Technology
NWEA	North West European Area
OIM	Offshore Installation Manager
OSC	Offshore Simulator Centre
OSV	Offshore Support Vessel
PCC	Permanent Chain Chaser
PCP	Permanent Chaser Pendant
PSA	Probabilistic Safety Assessment
QRA	Qualitative Risk Assessment
QRA	Quantitative Risk Assessment
RB	Rule-Based
ROV	Remotely Operated Vehicle
SA	Situational Awareness
SB	Skill-Based
SIMO	Simulation of Marine Operations – Computer code name
SJA	Safe Job Analysis
SLIM	Success Likelihood Index Methodology

SMS	Safety Management System
SOLAS	Safety of Life at Sea
SOSS	Safe Operation of Subsea Systems
SPM	Single-point Mooring
SWL	Safe Working Load
THERP	Technique for Human Error Rate Prediction
UHF	Ultra High Frequency
UK	United Kingdom
VHF	Very High Frequency

* For the abbreviations that appear only once, the definitions are given in the main text when appear.

Contents

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Chapter 1

Introduction

This chapter outlines the background, motivation, objectives, scope, research context and question, and limitations of this study. The first part of this chapter presents background and motivation: the need for the development of operation-oriented stability criteria and positioning capabilities; Situational Awareness (SA) related to vessel stability; and identification of the right action for avoiding the occurrence of vessel capsizing. The second part of this chapter outlines the scope and limitations. At the end of this chapter, my contributions and thesis structure are presented.

1.1. Background and motivation

The objective of the research is to establish a suitable model to mitigate the risk associated with offshore and marine operations such as anchor handling, pipe laying, and fish trawling. The work also considers natural hazards and operational issues. Therefore, it is essential to understand the risk factors associated with these types of operations, particularly when vessels operate in adverse weather conditions.

The motivation for research in anchor handling operation (AHO) was the Bourbon Dolphin vessel capsizing on 12 April 2007 in the North Sea while deploying anchor line No. 2 of the "Transocean Rather". This accident was caused by many factors, as documented in the accident report (Lyng *et al*., 2008) and (Gunnu *et al*., 2010). The lack of a suitable operational safety limit, lack of a safety evaluation, lack of SA, and lack of appropriate decision-making are the main causes behind this accident. Environmental, hardware, software and human factors influenced the accident. Accidents in the marine and offshore sectors do occur, and statistics show that they appear to occur due to either individual factors or interaction among individual, technical, and organizational factors (or features). Generally, the events initiating accidents are attributed to the operator, and latent root cause errors are attributed to the organization. Research conducted by various organizations shows that more than 75% of ship accidents worldwide occurred due to human and organizational factors. Indeed, to address these factors, the IMO adopted the International Safety Management (ISM) Code in 1993. This Code provides a framework for companies to establish integrated Safety Management Systems (SMS) to reduce accidents caused by human error and organizational errors.

In fact, the selection of better AHVs, operational planning and effective ship handling might have helped to prevent the abovementioned accident. The selection of better vessels might have ensured a sufficient vessel stability margin that, in turn, might have helped to prevent the capsizing event. However, planning is always important because regardless of how efficiently the designers design the vessels, operation plans must allow for accident events. In the absence of proper planning, an operation's cost can increase and the operation can be riskier than is necessary. Despite the planning, it is not always possible to ensure safe operation because of the stochastic nature of events that can lead to accident events. Examples include equipment breakdown and uncertainty in weather forecasts. Therefore, to conduct a safe operation, the vessel master must act according to the operational situation. To this end, the vessel master needs systems that can aid in terms of translating the vessel situation (stability) in an easily understandable way (situational awareness) and assist in identifying an appropriate control strategy. Nonetheless, it appears that the industry has not focussed on developing such systems. Moreover, qualified, skilful bridge crew are essential for executing efficient vessel handling. These skills can be improved with the help of training.

To prevent capsizing, the industry has thus far employed the following practice:

- Vessel stability is assessed in the design and analysis phase for an estimated operational load;
- Critical operational scenarios and control strategies are described in the operation manual in the planning phase (rig move procedure).

Moreover, there are mandatory training requirements for crew working on board and condition monitoring systems for assessing the vessel position with respect to the rig, anchor location and other AHVs. Nonetheless, the capsizing of the Bourbon Dolphin occurred because a gap exists between the actual vessel potential and practice in the industry with respect to the capability to assess stability margin and position. Therefore, efforts should be conducted to reduce this gap to prevent capsizing of AHVs in future AHOs.

Accordingly, the focus in this thesis is primarily on enhancing the safety of AHOs without a further increase in operational costs. First, the "influencing factors" present in the Bourbon Dolphin accident (2008) are discussed. Second, the existing stability criteria and their limitations are addressed, and new criteria are established for assessing vessel stability in the planning and the execution phase of the operation. In this thesis, the developed stability criteria are the allowable static heeling angle and allowable rollback angle. Moreover, the parameters influencing vessel stability are discussed. Third, a method is presented for predicting vessel stability during operation. Fourth, a decision support system is proposed for assisting the vessel's master in better decision-making during execution of anchor deployment or recovery operations. Furthermore, this study includes an approach for assessing vessel drift-off and positioning capability during operation.

1.2. Notable accidents in AHOs

Accidents during AHOs can be categorized as occupational accidents and vessel accidents. Occupational accidents can occur when handling heavy equipment or high-tension mooring lines (chain or wire) during AHOs. The fatal accident rate (FAR) value related to occupational accidents (working accidents) during AHOs is 37.4 (Haugen *et al.*, 2004). When calculating the FAR, each person on board the vessel is assumed to be exposed for 12 hours per day. This accident rate has been reduced through better anchor handling systems, personnel protection equipment (PPE), and safety procedures.

Concerning vessel accidents, three possible accident scenarios can occur: vessel capsizing (capsizing of an AHV), collision (collision between AHVs during tandem operations, collision between a vessel and a rig when receiving a pennant from the rig, and, in extreme cases, loss of the rig), and fire. Although the frequency of occurrence of vessel accidents is low, accidents such as the Bourbon Dolphin and Stevpris accidents (see Figure 1.1) have alarmed the industry due to their severity and human losses. Other accidents include the Maersk Terrier in 1994, Far Minara in 1996, Maersk Seeker in 2000 and Viking Queen in 2001. Therefore, vessel accidents, particularly vessel capsizes, are considered in this thesis.

(a) Bourbon Dolphin (Lyng et al., 2008) (b) Stevns Power (Nielsen, 2004)

Figure 1.1: Capsized AHVs

1.3. Research context

Drilling rigs are generally moored with 8 to 12 anchor lines and anchors. These anchors are deployed with a special offshore vessel called an AHV. These operations are considered expensive and highly risky. The expenses are largely due to higher vessel day rates and waiting periods for operational weather windows. For instance, AHOs typically contributes 10 to 20% of the total well cost in offshore exploratory drilling. The Bourbon Dolphin and Stevpris accidents demonstrated the need to improve the safety of AHOs. Therefore, it is essential to study the risk factors associated with these types of operations, particularly when vessels operate in adverse weather, and to provide a risk mitigation strategy for improving safety.

1.4. Challenges in AHOs

The efficiency of the AHV during AHOs depends on the balance between safety and cost. The apparent conflict between these two factors pushes the involved personnel, vessels, and systems to their maximum limits. Figure 1.2 illustrates the conflict between risk-willingness and risk-aversion in terms of benefits/rewards and loss/accident. Obviously, the challenges with AHOs are 1) to minimize vessel drift-off with respect to the desired track and 2) to maintain the vessel stability margin. Effectively achieving these goals requires an optimum life cycle approach in terms of design/analysis, planning, and execution of the operation.

Conversely, due to the lack of oil and gas resources in shallow waters, the industry is pursuing petroleum exploration in deeper water, which implies more challenges during AHOs, such as

- Increasing the demand on personnel, vessels and systems to their ultimate safety limits (such as capsizing);
- Handling vessel under lower safety margins due to, for example, deep water, heavier loads, larger forces, tougher environments, and demanding weather conditions;
- Addressing risk associated with complex control systems, models of organization, and operational tasks;
- Perceiving the consequence of complex and stressful situations;
- Identifying optimal decision and execution strategies.

The above list is no means by exhaustive.

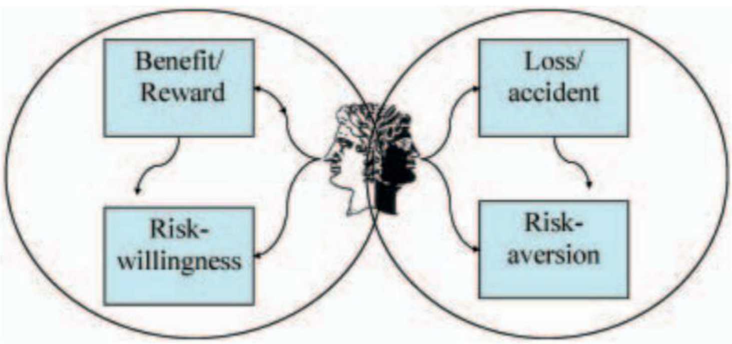

Figure 1.2: Janus face and ambiguity of risk (Lindøe and Olsen, 2009)

Indeed, it is essential to study the effect of risk factors associated with these types of operations on vessel stability and performance, which are dependent on factors such as vessel design parameters, operational requirements, environmental conditions, and involved personnel skills, both onshore and offshore. When addressing risk mitigation strategies, AHOs present unique challenges in terms of design and analysis, planning and execution that are outlined in the following subsections.

1.4.1. Design

In designing an AHV, the main objective is to design vessels that can safely perform AHOs such as anchor deployment or recovery, pre-laying, and towing at the lowest possible cost. AHOs can often require much waiting and idle time. A few hours off-service can cause large economic losses for involved stakeholders in the operations. The typical downtime of the vessels in their lifetime is approximately 50%, as illustrated in Figure 1.3. The reasons for downtime include excessive vessel motions, lower ship manoeuvring capabilities, lower ship handling capabilities, lower stability margin (or lower reserve stability), poor crew comfort, and statutory requirement constraints. It is quite challenging to design a vessel that can achieve less downtime (or better operability) without compromising safety.

Typically, vessel stability during operation depends on traditional design parameters, such as vessel shape, mass distribution and the general arrangement of the vessel, and on special parameters such as the number and position of tow pins with respect to the vessel centreline and midship, size of the stern roller and transom shape. In vessel design, stability limits should be defined by considering design and operational parameters such as the magnitude of the mooring load, vessel heading (vessel bearing) with respect to the mooring line, angle between the mooring line and vertical axis, mooring line position with respect to the tow pins, transverse thrust force, wind velocity and direction, current velocity and direction, and vessel drift velocity. This information is helpful for the operator when selecting the vessel based on operational demands. Moreover, this information is helpful for the master to avoid catastrophic failure such as capsizing or a large static heeling angle (initial heeling angle).

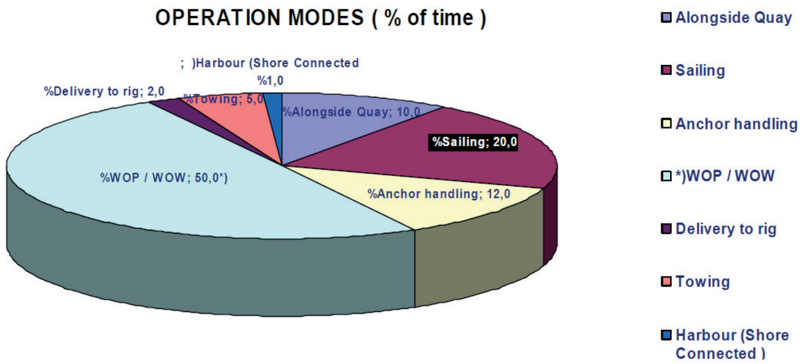

Figure 1.3: Example of operation profile with 50% waiting time on position (WOP) or weather (WOW) (Sollid, 2009)

Significant efforts are required to study AHV stability to avoid accidents such as the Bourbon Dolphin (2008) and Stevns Power (2004) accidents in future operations. Although appropriate stability criteria are available for various types of transportation vessels and semisubmersibles, limited research has been done on the stability of AHVs in the operation phase. This thesis aims to provide a new stability criterion for AHVs during operation. Moreover, critical parameters are identified that could provide vessel-handling guidance to the master (or watch office) to help effectively minimize the detrimental effects of operational load. Thus, a parametric study related to the operational parameters affecting vessel stability is performed.

1.4.2. Analysis and planning

In the planning phase of AHOs, the possible alternative operational scenarios are established based on factors such as the selected (or available) vessels, defined weather conditions, estimated operational loads, and duration of the operation. These scenarios are assessed by considering the effect on the safety of the system (vessel, rig, and equipment), involved (offshore) personnel, environment, and cost. For selected, planned operational scenarios, a suitable risk mitigation strategy is documented in the operational manual. A copy of this manual is distributed to concerned personnel. However, the choice of scenario depends on the stability and positioning capability limits. For this purpose, analyses are conducted to identify operational requirements and constraints and safety requirements for possible hazardous scenarios. The analysis results are used either to define available vessel-specific limitations or to select a suitable vessel by considering the balance between functional and safety requirements. The best approach to follow up these requirements is to establish operational limits and include them in the operational procedures. However, it is challenging for the personnel involved in the analysis phase to assess vessel stability for an estimated operational load, which requires realistic stability criteria. Furthermore, it is challenging to maintain vessel position and direction. Therefore, it is essential to develop a stability criterion and a positioning capability criterion that can address these challenges by considering the major operational parameters.

1.4.3. Execution

Optimal design, planning and execution of the operation are required for performing a more safe and efficient operation. Most AHOs are unique, varying considerably in terms of their physical attributes and work content. Due to this uniqueness characteristic, each operation requires a varying amount of resources and a different weather window. The variability in the environmental parameters makes it extremely difficult to completely assess at an early stage (design and planning stage) the challenges that will be imposed on the operation. Therefore, it is difficult to plan the operation effectively, and management of the operation in the execution stage becomes important.

During the execution stage (from the starting to last stages of the operation), the AHV's master continuously checks the available information on board, such as environmental parameters (wind parameters from wind sensors and wave information from the rig/other resource), the magnitude of the mooring load at the winch monitor, the vessel position and heading, and vessel drift-off. Moreover, the master must monitor vessel heading and position with respect to the rig and target location (navigation software is used for this purpose). Good vessel-handling skills of the master are important for safe operations in view of vessel stability. Environmental conditions and mooring loads can significantly reduce stability margins, thus possibly resulting in capsizing. In this situation, the master can abandon the operation if he judges that it is unsafe to continue the operation. However, the master should have a clear idea before abandoning or delaying the operation due to its negative result on the cost of the project. Any decisions related to such a judgement are conveyed to the involved personnel. Nonetheless, such decision systems related to vessel stability are subjected to loads, such as environmental and mooring loads, and are scarce in present industrial practices. This situation can be observed through the Bourbon Dolphin accident wherein most of the decisions related to vessel stability were handled in an ad hoc and disjoint way. Therefore, it is necessary for the industry to improve safety and thus improve decision-making for these operations.

1.5. Research questions and objectives

The objective of the study is to establish a suitable methodology for enhancing the safety of AHOs, with emphasis on the stability of AHVs. To address the challenges mentioned in Section 1.4, robust positioning capability criteria and stability criteria, a suitable operational limit state, situational awareness, evaluation of the stability margin and a decision support system are required. In this study, these aspects are addressed with a focus on a balance between vessel safety and cost. Moreover, the challenges outlined in the previous section drive a change of focus from "technically-centred" to more "human-centred" aspects, i.e., human factors play a pivotal role in vessel safety. Therefore, this study considers hazards, environmental conditions (wind, wave, and current parameters) and operational issues such as hardware (vessels and their equipment), software and human decisions. The research questions studied in this thesis are as follows:

RQ1: What were the causes behind the Bourbon Dolphin accident?

RQ2: How quickly did the angle of attack (the angle between the mooring line and vessel centreline) develop?

RQ3: Did the vessel have sufficient positioning capability during the AHO?

RQ4: Are there any stability criteria that can be used in the design and analysis phase for assessing vessel stability in AHOs? If not, how can vessel stability be improved?

RQ5: How can operational limit state criteria be developed?

RQ6: How can situational awareness of the vessel stability during operations be improved?

RQ7: How can capsizing when the vessel moves towards a dangerous zone be mitigated?

Based on the questions above, the following main objective can be formulated:

"To identify and develop technical and other necessary measures for enhancing the safety and efficiency (performance) of AHVs during AHOs."

Along with the main objective, several intermediate research goals can be formulated. These intermediate goals will help guide the thesis work over its duration to finish this thesis successfully. Because the following goals have been achieved, it can be stated that the main objective has also been met:

- To investigate the Bourbon Dolphin accident scenario and identify the best accident prevention strategies;
- To identify the needs of key stakeholders;
- To identify risk factors associated with AHVs during AHOs;
- To develop methodologies for assessing vessel safety in critical, extreme situations and operational conditions;
- To develop an approach to prevent loss of position and direction, and the progress of a larger angle of attack during the design and analysis and planning phases;
- To develop a methodology for preventing an occurrences of large static heeling angle (initial heeling angle) of a vessel during the design, analysis and planning, and execution phases;

- To develop criteria for assessing AHV stability in the design and analysis and operation planning phases;
- To analyse the effect of mooring load along with other operational parameters on the vessel stability and positioning capability;
- To gain basic knowledge and understanding of operating parameters' influence on vessel stability;
- To identify vessel-specific limitations and operational conditions that can limit vessel performance in the horizontal plane (maintaining vessel position and direction);
- To define a limit state for assessing vessel safety during AHOs;
- To develop a methodology for assessing the vessel stability margin in terms of the vessel static heeling angle easily and accurately during the execution phase of the operation;
- To develop a methodology for identifying context-based best control strategies for preventing AHV accidents in future operations;
- To enhance competence and knowledge related to parameters on vessel stability and positioning capability;
- To develop a methodology for identifying the best actions and decisions for safe operation when the vessel is in critical and extreme situations;
- To develop rules, regulations, guidelines and standards for a vessel and its equipment, requirements, and training procedures for on-board personnel and to establish thresholds for vessel safety linked to operational and environmental demands.

1.6. Aim and scope

The thesis addresses AHOs during anchor deployment and recovery. The discussion of the subject primarily includes different safety measures relevant to vessel stability and positioning capability. The stability and positioning capability of AHVs largely depends on vessel design, construction at the shipyard, maintenance, regulatory and statutory bodies' requirements, the operator and the complexity of the operation. This sort of study is complete only when all the different influence factors for the stability and positioning capability are considered. However, this phenomenon is highly complex due to the involvement of many parameters and their interdependency and inherent uncertainty. Therefore, the present study considers important operational-oriented parameters with respect to the vessel stability and positioning capability during AHOs. Changes in vessel characteristics, e.g., due to corrosion and wear of equipment over the vessel's life period and due to the influence of maintenance, are not considered. The factors influencing stability and positioning capability are considered based on the available information. It might be possible to miss certain factors that might increase in importance. The following aspects were covered in this study:

- Literature survey on AHVs and AHOs;
- Literature survey on risk analysis;
- Identification of critical scenarios and hazards of AHOs;
- Vessel drift-off assessment during AHOs;
- Literature survey on existing stability requirements;

- Stability criteria for assessing AHV stability during AHOs;
- Operational limit state for assessing vessel stability margin during AHOs;
- Methodology for situational awareness;
- Methodology for a decision support system.

1.7. Summary of contributions in this thesis

Figure 1.4 outlines key study domains and their relevance to the thesis, key contributions such as conference and journal papers and the contributors behind them.

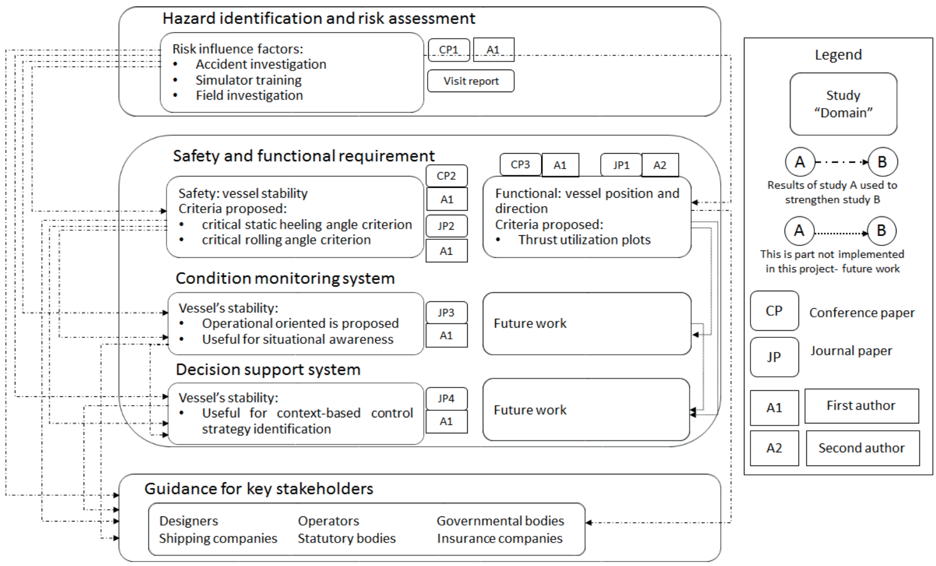

Figure 1.4: Overview of the research study

CP1 Gunnu, G.R.S., Moan, T., Chen, H., 2010. Risk influencing factors related to capsizing of anchor handling vessels in view of the Bourbon Dolphin accident, In: Proceedings of Systems engineering in ship and offshore design, Royal Institution of Naval Architects, Bath, UK.

Relevance to the thesis: The paper addresses the research question RQ1. This paper presents our initial findings in studies on hazard identification and risk assessment of AHOs and the details of factors influencing capsizing of anchor handling vessels. A generic model is developed based on the study of the Bourbon Dolphin accident. The key influencing parameters are identified: a large static heeling angle (initial heeling angle), vessel drift-off and a lack of situational awareness.
My contribution: This paper is the result of studying the Bourbon Dolphin accident. The Ph.D. candidate performed the accident study and established a generic framework for risk-influencing factors related to AHO. The Ph.D. candidate is the lead author of the paper.

CP2 Gunnu, G.R., Moan, T., 2012. Stability assessment of anchor handling vessel during operation considering wind loads and wave induced roll motions, In: Proceedings of 22nd ISOPE, The International Society of Offshore and Polar Engineers, Rhodes, Greece.

Relevance to the thesis: This paper answers research question RQ4. The key influencing factors in the Bourbon Dolphin accident are identified in CP1; the first factor is the vessel static heeling angle (initial heeling angle) and/or vessel stability. This paper focusses partly on this safety requirement ("vessel stability"). A slightly modified IMO weather criterion is established in the paper. The proposed criterion is useful for vessel stability assessment in the operational phase.

My contribution: The criterion proposed in the paper is an extension of the existing IMO "Severe Weather and Rolling Criterion (weather criterion)". The Ph.D. candidate established this criterion, and he is the leading author of the paper.

CP3 Gunnu, G.R.S., Moan, T., Wu, X., 2012. Anchor Handling Vessel Behavior in Horizontal Plane in a Uniform Current Field During Operation, Proceedings of the 2nd Marine Operations Specialty Symposium. Marine Operations Specialty Symposium-(MOSS2012), Furama Riverfront, Singapore, pp. 307-324.

Relevance to the thesis: This paper answers research question RQ2. The key influencing factors in the Bourbon Dolphin accident are identified in CP1; the second key factor is vessel drift. This paper focusses partly on the function requirement ("vessel drift"). Vessel stability depends on the angle of attack and transverse thrust force. Both parameters depend on the vessel behaviour in the horizontal plane. A methodology for assessing vessel motion in the horizontal plane is established.

My contribution: The Ph.D. candidate described and established scenarios for assessing vessel motion in the horizontal plane and contributed to writing papers. Xiaopeng Wu performed simulation and contributed to paper writing. The Ph.D. candidate is the lead author of the paper.

JP1 Wu, X., Gunnu, G.R.S., Moan, T., 2015. Positioning capability of anchor handling vessels in deep water during anchor deployment, Journal of Marine Science and Technology, January, 2015.

Relevance to the thesis: This paper answers research question RQ3. The key influencing factors in the Bourbon Dolphin accident are identified in CP1; vessel drift-off is an initiating event in the Bourbon Dolphin accident. Vessel drift-off and the angle of attack can be controlled by applying suitable thrust forces in the transverse direction. Hence, it is essential to estimate the required thrust capacity to handle vessels during AHOs.

My contribution: Xiaopeng Wu is the first author of this paper. His contribution was performing the simulation and writing the paper. The Ph.D. candidate is the second author of the paper. The Ph.D. candidate contributed to establishing scenarios for assessing vessel positioning capabilities.

JP2 Gunnu, G.R., Moan, T., 2015. Stability assessment of anchor handling vessels during operations, Journal of Marine Science and Technology, June, 2017.

Relevance to the thesis: This paper answers research question RQ5. The key influencing factors in the Bourbon Dolphin accident are identified in CP1; the first factor is the vessel static heeling angle and/or vessel stability. This paper focusses partly on the safety requirement ("vessel stability"). Limit state criteria are established for assessing vessel stability during the analysis and planning phase and execution phase.

My contribution: With the help of the proposed modified weather criteria in CP2, the limit state criterion was established by considering the influence of parameters related to stability. The Ph.D. candidate established this criterion, and he is the lead author of the paper.

JP3 Gunnu, G.R., Moan, T., 2015. An assessment of AHV stability during anchor handling operations using a method of artificial neural network, Ocean Engineering, 40, pp. 292-308.

Relevance to the thesis: This paper answers research question RQ6. The key influencing factors in the Bourbon Dolphin accident are identified in CP1; a lack of situational awareness is one of the reasons behind the Bourbon Dolphin accident. The master should be aware of vessel stability and vessel drift. It is possible to monitor vessel drift-off by means of available on-board systems. However, it is difficult to be aware of vessel stability. Hence, it is essential to establish a methodology for integrated monitoring system.

My contribution: The Ph.D. candidate developed an integrated monitoring system. The modified weather criteria and limit state criteria proposed in CP2 and JP2 were used. The Ph.D. candidate is the lead author of the paper.

JP4 Gunnu, G.R., Moan, T., 2015. Decision Support System for ensuring the stability of anchor handling vessels during operations, manuscript phase.

Relevance to the thesis: This paper answers research question RQ7. This paper presents our final findings in a study on context-based DSS. The methodology is developed by considering influencing parameters as studied in CP1, stability criteria defined in CP2 and JP2, a stability assessment procedure developed during the operation phase defined in JP3 and control parameters ("heading and/or transverse thrust").

My contribution: The Ph.D. candidate developed this DSS by considering the limit state criteria proposed in JP2 and optimization and is the lead author of the paper.

1.8. Thesis outline

The Ph.D. thesis starts by describing the research basis and its questions and approach, the state-of-the-art, the methodology, and finally conclusions and recommendations for future work. The research work performed in the Ph.D. study is documented in the articles listed in Appendix A. The dissertation aims at clarifying the ideas behind the selected scope of work, the methods applied and the mutual connectivity of the individual articles in the context of a research study. Finally, the thesis also outlines the main results from selected relevant research articles. Specifically, two articles were written in cooperation with my research colleague at CeSOS, Xiaopeng Wu, and another article was written in cooperation with Dr. Haibo Chen. The article with Xiaopeng Wu focusses on assessment of AHV behaviour in the horizontal plane and positioning capability in deep water AHOs. The article with Haibo Chen consists of a Bourbon Dolphin accident study. The following outline describes the main topics of each chapter.

Chapter 1: This chapter provides the background and motivation, challenges in AHOs, objective and scope, and outline of the thesis.

Chapter 2: This chapter starts with introducing the state-of-the-art related to AHVs, practices in anchor deployment and recovery, and the role of personnel involved in the operation. Then, it describes the Bourbon Dolphin accident. Finally, it presents typical operational aspects and demands of AHOs.

Chapter 3: The first part of this chapter provides an overview of risk assessment and human and organizational factors. The second part of this chapter focusses on hazards in AHOs and risk assessment of AHVs in AHOs. The third part of this chapter focusses on identification of the key root causes related to the Bourbon Dolphin accident. Furthermore, this part addresses the key influence parameters related to the vessel capsizing, which are documented in Article CP1 (see Appendix A). Finally, key findings and recommendations in this chapter are summarized.

Chapter 4: This chapter presents a methodology for assessing AHV behaviour in the horizontal plane and vessel positioning capability for a defined thruster configuration. Furthermore, this chapter focusses on establishing criteria for assessing vessel positioning capabilities. The methodology is described in detail in Articles CP3 and JP4 (see Appendix A). Then, this chapter focusses on establishing stability criteria for the planning and operation phases, situational awareness (condition monitoring system), and context-based DSS. In the first part, a detailed explanation is provided on existing and newly proposed AHV stability criteria. Further details of this methodology are included in Articles CP2 and JP1 (see Appendix A). The second part discusses methodology for assessing situational awareness related to vessel stability during operation. The escalation of an accident situation, operational aspects and demands, and safety assessment in planning and operational phases are described in this chapter. The methodology for vessel situational awareness is summarized in detail in Article JP2 (see Appendix A). The last part presents a methodology for assessing a context-oriented decision-making system. The background on DSSs and AHVs' need for them are described in the chapter. The proposed context-based decision-making system is presented in detail in Article JP3 (see Appendix A).

Chapter 5: This chapter includes a summary of the research work, contributions and the main concluding remarks. It outlines goals and objectives achieved in this research work, and the key findings presented in the articles are summarized. Furthermore, the chapter summarizes the recommendations for future work in the relevant domain.

Chapter 2

General practice in AHOs

This chapter consists of five parts. The first addresses an overview of the state-of-the-art related to AHOs. Furthermore, it elaborates commercial and design aspects and rules and regulations. The second part describes common practices in anchor deployment and recovery. The third part describes key personnel roles during AHOs. The fourth part describes the Bourbon Dolphin accident and conclusions from the investigation committee. The final part defines typical anchor handling aspects and demands.

2.1. Overview

Oil and gas exploration is extensively performed by using mobile drilling rigs. Hence, AHOs are a fundamental part of the offshore oil and gas industry and increasingly of other domains such as aquaculture and wind energy. Only limited literature is found for AHOs. Therefore, it is a relatively new and challenging area for scientific research. Before discussing details about AHOs, it is important to understand when these AHOs are used, which is described in this section.

2.1.1. Mooring system

Floating offshore structures are usually held in position by means of mooring systems, which are designed by considering aspects such as the functionality (exploration, production and accommodation) of the structure and water depth. These mooring systems are used in various fields of ocean engineering, e.g., a Single-Point Mooring (SPM) system for storage buoys or spread-mooring systems for semisubmersibles. For example, large floating drilling platforms are positioned by introducing up to 20 mooring lines with different geometrical and material properties. In general, mooring lines consist of combinations of chains, wires and synthetic rope. In addition, submerged buoyancy tanks can be used along the mooring lines. Thus far, the deepest moored depth is 1853 m for the production platform near the coastline of Brazil established in the year 2000. Although the deep-water mooring procedure appears as straightforward as mooring in shallow water, personnel are supposed to be familiar with higher loads, longer wire lengths and distances, and occasionally new equipment. For example, Foulhoux (1999) described typical steps in deep-water anchor installation. As mentioned previously, for shallow and deep-water oil and gas exploration/production rigs, the common mooring line configuration is chains and wire ropes or their combination. In the 21st century, exploration/production is moving towards ultra-deep waters. Chains and wire rope or their combination are not suitable for ultra-deep waters due to weight constraints. To overcome such constraints, synthetic ropes have been developed for use as mooring lines.

The mooring system is designed to position the rig or floatel (here after called rig) for estimated wind, wave and current loads. The loads induced in the mooring system are divided into quasi-static and total dynamic loads. The quasi-static load is the load due to the swell, wind, current and frequency of the mooring system (Vryhof Anchors, 1999). For quasi-static loads, the system tends to move at a low frequency, generally with a period of 140 to 200 seconds. In addition to quasi-static loads, there are individual wave forces that cause a high frequency (wave frequency) motion. This high frequency motion causes dynamic shock loads with a motion period of 10 to 14 seconds. These loads come from the rolling of the vessel and the movements of the anchor lines through the water. Indeed, the quasi-static load plus the individual wave loads are components of the total dynamic load. Typically, the quasi-static loads are equal to 50% to 90% of the total dynamic load (Vryhof Anchors, 1999). The general practice is to perform a bottom survey for each new site at which a rig is to be positioned. The required information typically includes the seabed soil type, water-depth contour lines, and obstructions (such as pipelines and corals) and debris on the seabed. The bottom survey is the responsibility of the operator and is often performed in conjunction with a geotechnical survey of the area. The information from the seabed survey is used for selecting the anchor type and anchor size. The mooring pattern is occasionally modified to avoid seabed obstructions or debris. The modifications are related to changes in the mooring line length and/or direction.

2.1.2. Anchor handling operation

AHOs involve a series of operations during rig de-positioning (anchor recovery from the seabed), rig move (towing the rig to a new location) and rig positioning (deployment of anchors into the seabed). As previously mentioned, these operations are performed with the help of specially designed AHVs or tugs. The range of AHOs and the sequence of steps associated with each type of operation are described in books (Gibson, 1999; Hancox, 1994; Maudsley, 1995; Ritchie, 2007) and manuals (Vryhof Anchors, 1999). The activities performed in anchor handling and rig move operations are summarized below:

- Anchor handling;
- Transfer / receiving PCP;
- Chasing out / stripping back;
- J hooking / grappling;
- Crane / lifting operations;
- Winch operations;
- Breaking out;
- Recovery / decking the anchor;
- Recovery and deployment of mooring system;
- Fitting of specialized moorings;
- Bolster/ un-bolster anchor;
- Setting anchor.

2.1.3. Anchor installation using AHVs

The common method for anchor installation is based on using an AHV. The AHV deploys the anchor and the mooring line to the seabed. It uses the bollard pull to embed the anchor into the seabed as shown in Figure 2.1. The anchor is embedded until it gains the required holding capacity corresponding to the required installation load. The maximum installation load depends on the available bollard pull capacity. If the required installation pull exceeds the vessel's bollard pull capacity, an option is to use two AHVs to pull in tandem, as shown in Figure 2.2.

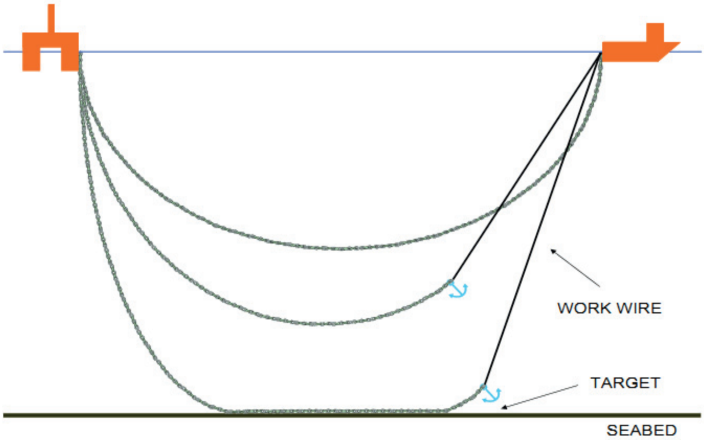

Figure 2.1: An AHV uses its work wire to deploy the anchor and position it at the anchor target on the seabed (Wennersberg, 2009)

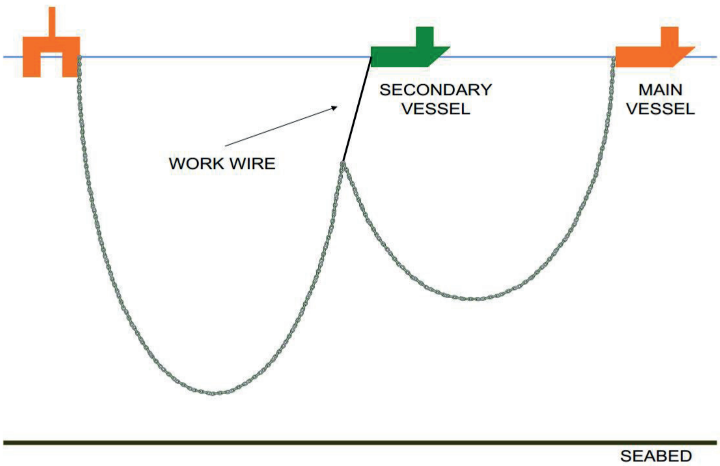

Figure 2.2: Tandem operation (Wennersberg, 2009)

2.1.4. Anchor handling vessel

The offshore oil and gas industry requires large anchors and vessels capable of setting these anchors. The anchors are laid in a mooring pattern. Originally, normal tugs were used for these operations, but due to the need for larger handling capacities, demand has developed for specialized vessels. Thus far, the Anchor Handling Tug (AHT) (shown in Figure 2.3), Anchor Handling Tug/Supply (AHTS), and Anchor Handling Vessel (AHV) have been built for this purpose. An AHTS is a combination supply and anchor handling vessel. These vessels are designed with high horsepower to tow drilling units and perform

AHOs, and they can carry supplies to platforms. These vessels are used for various functions as listed below:

- Towing of offshore platforms, drilling vessels, lighters, barges, and production modules/ vessels;
- Anchor handling and installation of rigs;
- Running of the rig's on-board anchors;
- Mobile installations at sea;
- Mooring placement and assistance;
- Assistance in offshore construction and installation;
- Standby rescue operations;
- Supply services for platforms (transporting both wet and dry cargo in addition to deck cargo).

Figure 2.3: AHV Far Sapphire ("Far Sapphire - IMO 9372169," n.d.)

Moreover, these vessels are equipped with firefighting, rescue and oil recovery equipment. A typical AHV deck layout is shown in Figure 2.4. In general, deck equipment on an AHT consists of items such as tow-wire, spare tow-wire, stretchers, pennants, shackles, hinge links, a grapnel, a J-chaser or a J-lock chaser, chains, pelican hooks, pins or a Shark jaw, a towing gog, a chain stopper, a Karm fork, a Triplex stopper and a roller (see Appendix B). Hui *et al*. (2010) described the basic equipment needed to complete an AHO.

2.1.5. Commercial status of AHVs

Hui *et al*. (2010) performed a market study on the demand for AHTS vessels and the crew situation. The conclusion of their work was that AHTSs would continue to decrease in coming years due to low oil prices. However, the demand for high-end AHTS vessels has recently increased. The vessels' term day rates are approximately NOK 100,000 for AHTS vessels having a capacity of less than 18,000 BHP (Vad and Engås, 2010). North Sea spot and term day rates are shown in Figure 2.5 and Figure 2.6. The rates are higher for stronger and larger vessels. Comparisons between day rates and global average annual oil prices are shown in Figure 2.7. The charter prices of AHTS vessels in 2011 were in the range of 5000 to 32,000 pounds per day for a capacity equal to or greater than 16,500

BHP. Similarly, prices are 4000 to 25,000 pounds per day for a vessel with a capacity range from 10,000 to 16,499 BHP. Figure 2.8 illustrates that oil field discoveries move towards deeper waters.

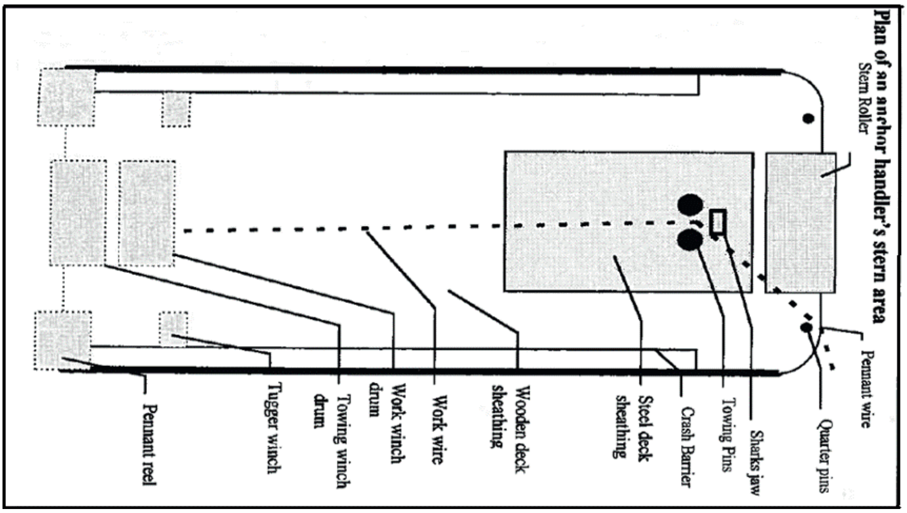

Figure 2.4: Deck layout of an AHV (Gibson, 1999)

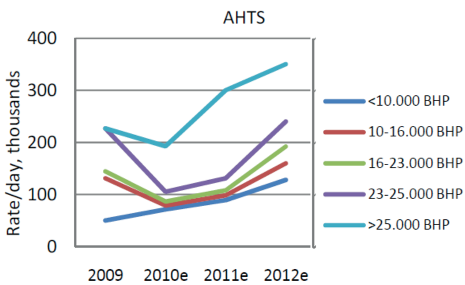

Figure 2.5: North Sea spot day rates for an AHTS (Vad and Engås, 2010)

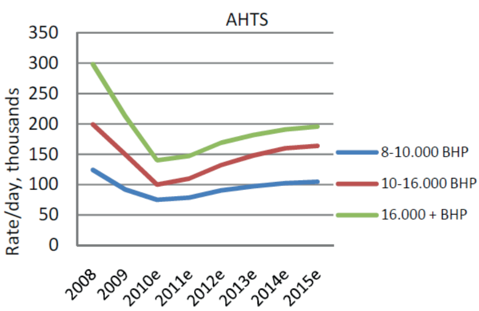

Figure 2.6: North Sea term day rates for an AHTS (Vad and Engås, 2010)

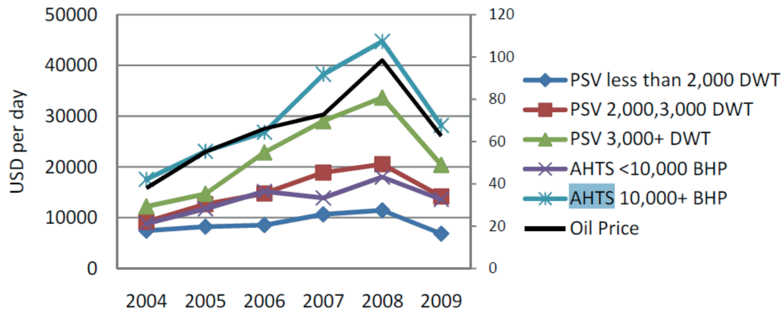

Figure 2.7: Global annual average oil price and day rates by segment (Vad and Engås, 2010)

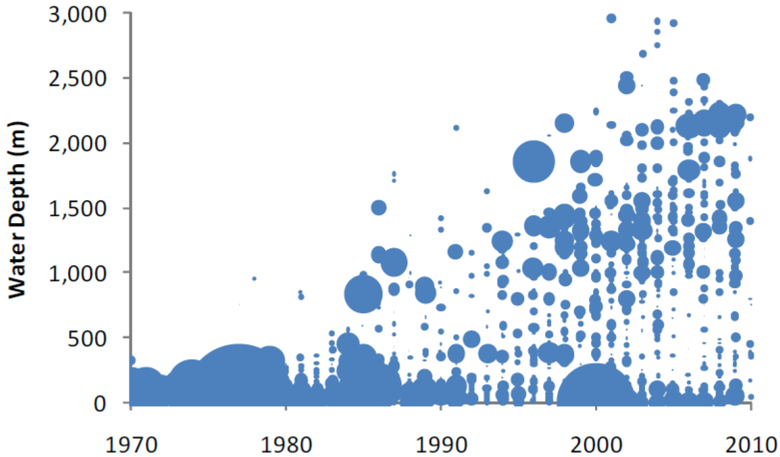

Figure 2.8: Oil field discoveries by size and water depth (Sano et al., 2012)

2.1.6. Design improvements in AHVs

Demands on ship performance have increased over time. The technological development of the ships has been rapid to meet increased demands such as larger deck space, higher engine-brake horsepower, and higher bollard pull. These vessels have been designed to have a large deck space and cranes available to deploy a range of equipment required for oil field exploration. The vessels are typically characterized by their engine size in terms of brake horsepower, their resulting bollard pull or their towing/anchor handling capacity. The vessel's stern is designed as a concave shape, which allows an anchor and its chain to run freely over the stern roller. A specialized anchor-handling winch is designed for AHOs. The vessel principle depend on previously mentioned equipment specifications and operational demands. Thus, there is a wide variation in vessel characteristics and specifications in the available fleet. The range of variation in vessel transom design, tow pin configuration, manoeuvring devices and anchor handling equipment is especially large. For example, the length of the vessel is typically from 50 m to 110 m, and the beam varies from 15 m to 25 m; the bollard pull is in the range of 65 to 423 tons; and the pulling capacity of the winch is in the range of 140 to 650 tons. The engine power of a new vessel is in the range of 35,000 BHP. The average age of anchor handling tug supply vessels as of 2011.04.01 is 19.4 years. The age of 40 to 50% of vessels in the existing fleet is approximately 25 years. The total existing global AHTS fleet is approximately 1400 as of June 2010 (Vad and Engås, 2010). Based on industry insight and supply chain models, (Rose, 2011) examined the future characteristics of OSVs. Mendes *et al*. (2009) described a mathematical model for scheduling AHVs in fleet management. Their work states that the duration of AHOs varies because of the uncertainty of weather conditions. Moreover, they stated that the spot rates of these vessels are quite high compared with long-term rates. Shyshou *et al*. (2010) described a simulation model for the fleet sizing problem.

In the 1990s, the maximum extent of offshore activities was in the range of a water depth from 200 m to 500 m. Due to limited oil resources in shallow-water regions, offshore activities extended to harsh environments and water depths of up to 3000 m, implying additional operational challenges for the personnel involved. Hence, the demand for larger and more sophisticated vessels is increasing to perform safe and efficient operations; the designers have focussed on larger winch and engine capacities. Vessel design is moving towards a deep draft, a very large size and high horsepower to meet the service demands of the new generation of deep-water rigs and production platforms. The demand largely includes the requirement to tow sophisticated new drilling rigs and to handle their anchors, chains and mooring lines.

Systems have been devised for reducing or eliminating the FAR (see Section 1.2) related to occupational accidents (Figure 2.9). As described by Tanner (2008), all duties related to anchor handling or hauling an object (such as, for instance, a buoy) can now be performed remotely without any seaman on deck. According to his work, this feature would most likely spread rapidly in the anchor-handling world because seamen are unwilling to expose themselves in such risky operations. Antonsen (2009) and Håvold and Nesset (2009) studied the relationship between culture and the safety of offshore supply vessels in the Norwegian petroleum industry.

2.1.7. Rules and regulations

These vessels operate in Norway in accordance with rules and regulations from the Norwegian Maritime Directorate and the Norwegian Petroleum Directorate. Furthermore, these vessels are operated according to procedures of oil companies and ship owners (see Figure 2.10). Sarthy and Ham (2005) have described modern offshore support vessels from a classification perspective in terms of specialized functions and capabilities. Statutory requirements applicable to these vessels have also been discussed. Jong and Kadir (2010) presented an overview of the rules and regulations for offshore support vessels.

2.1.8. Rig move plan

A rig move operation is potentially hazardous and highly risky because the loads exerted by the winches and chains occasionally exceed the vessel limitations. Safe working procedures (NWEA, 2009) and instructions are to be established for these operations. At the same time, personnel affected by these operations are to be informed about these working procedures and instructions. The rig move plan considers possible loads during the AHO.

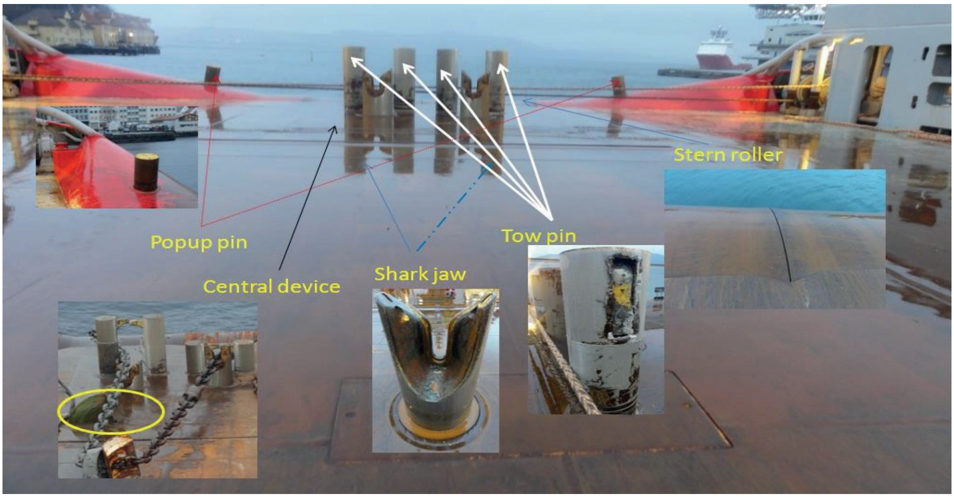

Figure 2.9: Deck layout and equipment associated with an AHO (Gunnu, 2011)

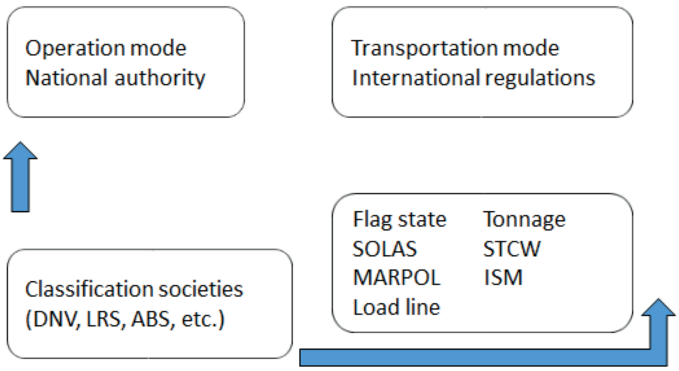

Figure 2.10: Rules and regulations applicable for AHVs

Personnel involved in these operations must be aware of vessel operational limitations including the power and freeboard. During the rig move, the safety of the vessel, crew and environment is of paramount importance. Therefore, stakeholders and personnel involved in these operations must act to prevent hazards and hazardous scenarios. The operator is responsible for ensuring adequate planning (including contingencies) and risk assessment of the entire AHO before commencing the operation (MSF, 2011). It is critical to identify and set trigger and hold points, which determine the operation's start/stop/hold or risk assessment (GOMO, 2013). Wherever tandem operations are to be performed, prior to the operation, the risk must be assessed and updated in the operational procedure. Furthermore, the operational procedures must define lead and supporting vessels. The hazards and their triggering and holding points must be described in the rig move plan (MSF, 2011). The operation must be stopped as soon as triggering points occur. The hazards and associated effects during an AHO should be identified. In addition, the risk associated with hazards should also be identified.

2.2. Common practices in anchor deployment and recovery

The rig can be positioned by either by mooring or a dynamic positioning system. A major drawback of the anchor mooring system compared with the dynamic positioning system is related to its logistics, which demand more time for the rig/unit relocation. Two types of mooring systems are widely used: the catenary mooring system and the taut mooring system. If the available footprint is smaller, then the taut mooring system is a better option than the catenary mooring system. The taut mooring system has an advantage in deep water applications. However, this thesis primarily focussed on anchor deployment and recovery in a catenary mooring system.

2.2.1. Catenary mooring system

Most semisubmersible drilling rigs are fitted with a conventional chain or a combined chain and wire catenary mooring system. The mooring system can employ high-holding power anchors using 3" or 3 1/4" diameter anchor chain and mooring wire of at least 3" diameter. This type of system is typically "self-contained" on board the drilling rig. The limiting parameters of conventional catenary mooring systems are their length, weight, and capacity to hold the rig within its minimum desired area of the watch circle in greater water depths.

During the normal AHOs described in Section 2.1.3, the installation or recovery of the mooring lines is accomplished with either one or two AHVs. Each AHV will work on opposite mooring lines of the rig simultaneously, whereas the tug is used for station-keeping assistance. The size and horsepower of the AHVs are the key parameters of the regular mooring operations. For laying anchors, generally, AHVs use either a ring chaser or a pendant buoy system, as described in subsequent sections. The use of the rig’s mooring system is normally the most economical means of rig positioning compared with the dynamic positioning system if the rig’s positioning location is within the optimum capabilities of the rig. In general, rigs require the assistance of an AHV to install or recover their anchors in a mooring spread. Currently, various methods are commonly used for anchor deployment and recovery. Two of these methods are discussed in detail in subsequent subsections.

2.2.2. Conventional anchor deployment

In today’s industry practice, two types of anchor deployments exist: conventional and pre-set. Other than “pre-lay anchor deployments”, the anchor deployments that have been regularly used in the industry are treated as “conventional” anchor deployments. The present section discusses conventional anchor deployments, whereas “pre-set” anchor deployment is discussed in Section 2.2.3. Furthermore, in conventional anchor deployment, the most widely used deployment methods are the pendant buoy system and the permanent chaser system, which are described in subsequent sections.

Pendant buoy system

Figure 2.11 shows a schematic view of the pendant buoy system. In the anchor handling book, Hancox (1994) elaborates the methodology of anchor deployment and recovery with this system. Typically, the principle components in the system are the pendant, buoy and crowns. Anchor pendant buoys are usually attached to the anchor crowns using pendant wire rope. During the rig's de-positioning, move and positioning, the AHV picks up the buoy and pulls the pendants to recover and run the anchors. Because the pendant buoy system usually requires a long length of the pendant wire ropes, as seen in Figure 2.11, using it in deep water applications is not economical and efficient. Moreover, the AHVs must recover the pendant wire from the rig system, store it on their decks during the rig move and return the wire back to the rig mooring system at the rig's new location. Therefore, the wire rope handling is both time consuming and hazardous. Furthermore, these buoys float on the sea surface and are hazardous to passing vessels. Therefore, these buoys are prohibited in the North Sea (Zumwalt, 1986). At the same time, because the system uses long pendant wire lengths in handling operations, its use is not more economical and efficient for deep-water applications due to the longer recovery time.

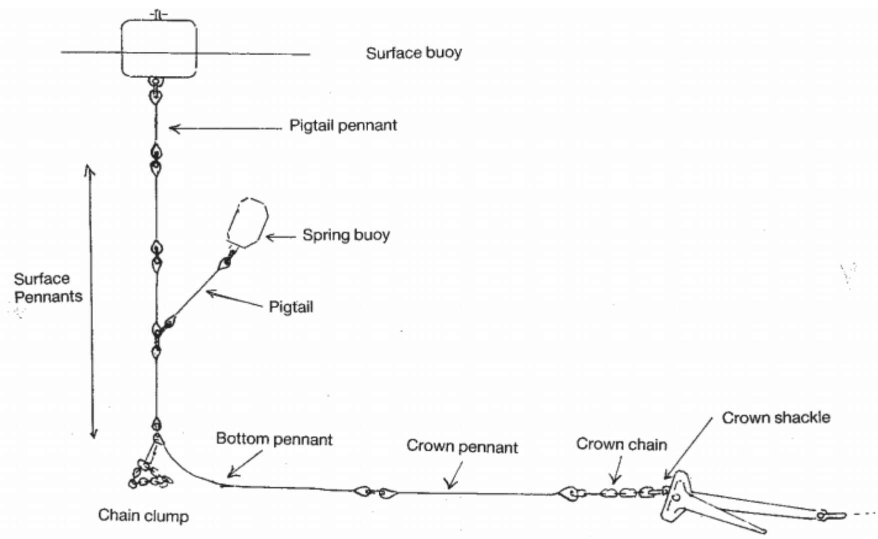

Figure 2.11: Pendant buoy system (Hancox, 1994)

Permanent chain chaser system

Figure 2.12 demonstrates the arrangement of a permanent chain chaser (PCC) system. In the North Sea, a permanent chain chasing system is typically used regarding anchor deployment and recovery. When the rig is station keeping, the permanent chain chaser (PCC) is hung to the rig's column. During the rig move, the anchor is retrieved to the rig's bolster, and the PCC is stored above the anchor to facilitate subsequent anchor deployment. To deploy the anchor at the next location, the AHV picks up the PCC from the rig and deploys the anchor to the prescribed position. The mooring line remains attached to the rig during this process. For the anchor deployment, the vessel lowers the anchor to the seabed with the working wire attached to the chaser, and the rig tensions the mooring line to the anchor to achieve the prescribed holding capacity. The vessel then pulls the chaser back along the installed mooring line until the chaser reaches the rig and hands it over to the rig. The process repeats until all mooring lines are installed and tensioned to the desired load.

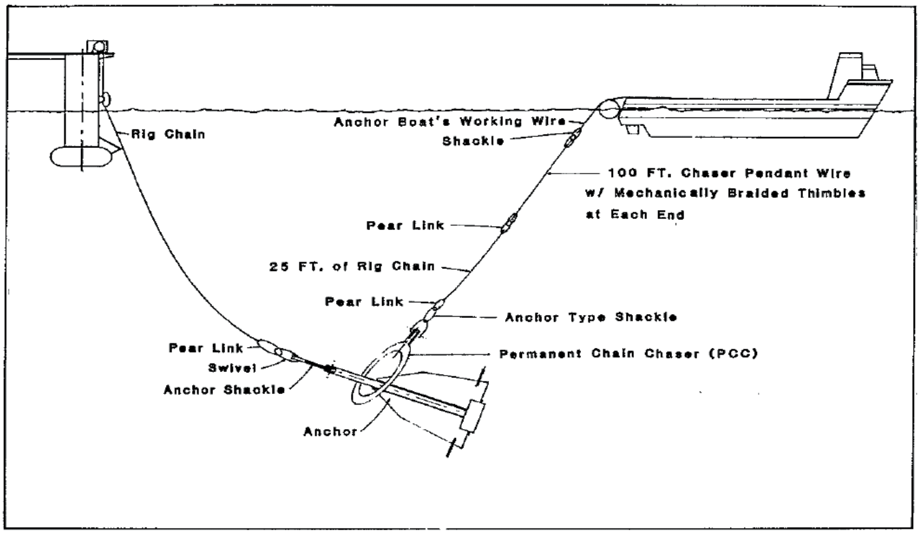

Figure 2.12: Typical permanent chain chaser system (Zumwalt, 1986)

The mooring lines are to be recovered when the rig must be relocated. For recovery, the above-mentioned procedure is more or less followed in reverse order. The operational steps for recovering mooring lines are outlined below:

- The AHV recovers the PCC from the rig while paying out its work wire and pulling the chaser towards the anchor;
- The anchor is unsettled and then recovered. Coordination between work wire pay-out and a bollard pull of the vessel is required for unsettling the anchor;
- The rig retrieves the mooring line while the AHV recovers the work wire and anchor;
- The PCC is passed to the rig; it is secured on the rig's column once the anchor is bolstered.

When all mooring lines are recovered, the rig is free to move. The PCC system is a time-saving system compared with the pendant mooring system. However, the time it takes to set or recover the mooring lines depends on the water depth, weather conditions, selection of AHVs, and planning efficiency. The PCC system takes approximately 12 hours for the rig mooring line recovery or deployment, operating in a 500 m water depth, if there is no interruption due to adverse weather, equipment failure or anchor holding capacity. Typically, the same operation takes approximately 24 hours with a pendant-wire buoy system. The PCC size is selected according to the maximum load it is subjected to during AHO. Usually, the maximum load does not occur when deploying or recovering the anchor, but it can occur when it is unsettling from the seafloor. The PCC system is not satisfactory when wire rope is used as a mooring line instead of chain. The reason is that the PCC system can damage the wire rope, particularly at its termination, when wire is used as a mooring line.

2.2.3. Pre-lay anchoring system

The governing requirements for mooring operations on the Norwegian continental shelf have been in continuous development. A major trend in the requirement is the demand for higher safety margins. Such margins lead to a more conservative approach in mooring analyses and in turn lead to design for higher mooring loads. Thus, few existing installations have a winch capacity to handle these loads on their own. This drawback can be overcome by two options. The first option is to replace existing vessel winches with winches of higher capacities, whereas the second option is to pre-install anchors. The industry prefers the second option due to additional advantages. Typically, the pre-install anchoring operation is performed with the help of large AHVs. Eventually, rig station keeping can be done by connecting rig mooring lines to the pre-installed anchors.

Over the past 30 years, mooring equipment has become more sophisticated, and its performance has been improved, whereas the associated rig move and mooring methods have not improved appreciably. The established methods require cooperation between multiple AHVs when picking up a mooring system, towing the rig to the new location and deploying and testing the mooring system before the rig starts drilling. Pre-lay mooring systems for drilling rigs have existed for almost two decades. However, they have grown in favour over the past couple of years among oil companies. The pre-lay approach is becoming popular in deep waters. It has the potential to become standard practice across the world's oil and gas industry. The complete rig move cycle using the pre-lay system is unlikely to be shorter than using the rig's own wire and chain (conventional rig move) system. The standard procedure for pre-installing the bottom chain using AHVs is to run out the full length of the chain that is to be pre-installed before the rig arrives. The AHV then connects its working wire to the chain and pulls the anchor until the pulling load reaches the prescribed value predicted from the mooring analysis. The anchor is then proven to have a holding power at least equal to the prescribed load, which is a governing criterion.

Pre-lay anchoring procedure

The pre-lay mooring system is also called a pre-set (or pre-laying) mooring system. The disadvantage with this approach is that it requires two sets of anchors. One set is used for the unit that is already positioned, whereas the other set is used for the unit that is to be positioned at the next location. Using a pre-lay anchor system, rig station keeping can be performed in a weather window of approximately half of the window needed for a normal (conventional) mooring operation. The method used for pre-lay anchors is outlined in Figure 2.13. Heavy-duty offshore buoys are deployed to indicate the approximate position of the anchors. Rig connection to the pre-laid system is shown in Figure 2.14. The anchors are generally installed by applying a load equal to the maximum intact load (from the mooring analysis). For permanent mooring systems, the installation loads are to be held for a period specified by classification societies or other statutory bodies. Because all anchor lines must be tested before the platform starts to work, the pre-tensioning procedure should be performed for each line to ensure proper penetration of the anchor in the seabed, as shown in Figure 2.15. The test is usually performed successively for two diametrically opposite lines when the winch capacity is sufficient with respect to the required tension force. When the winch capacity is insufficient to produce the required line tension but all other components fulfil the safety requirements, the pre-tension might be performed by synchronizing the work of several winches on one side of the platform while the tested anchor on the opposite side is blocked by a static brake. During such a procedure, to avoid undesired displacement of the platform from the drilling position, simultaneous control of several winches is used (Tomiša and Krovinović, 1999). Once the pre-lay anchor is connected to the rig, the AHVs are released sequentially as early as possible.

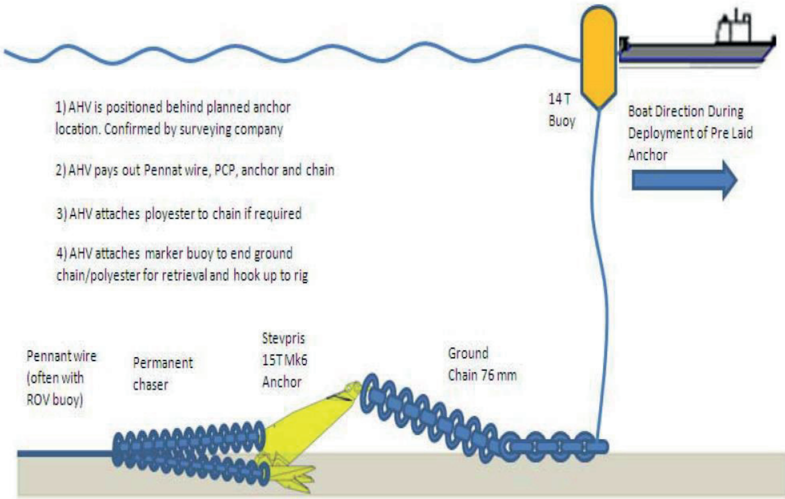

Figure 2.13: Method of pre-lay anchors (Saasen et al., 2010)

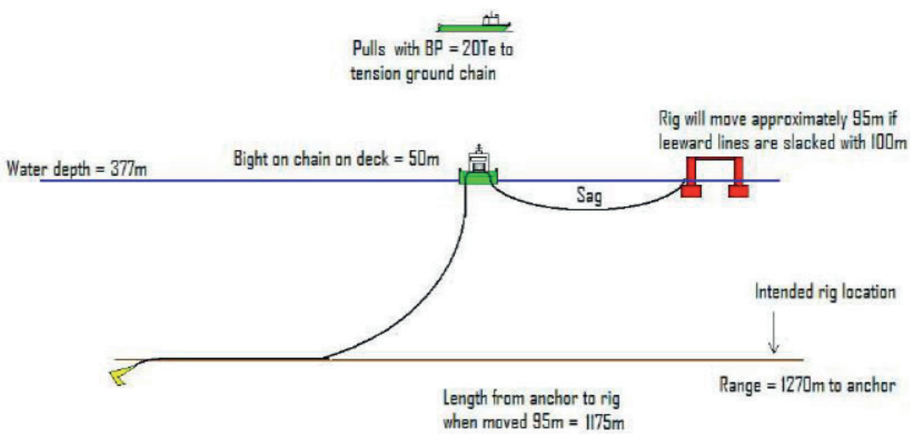

Figure 2.14: Connection of anchor chain to rig chain in pre-lay anchor system (Saasen et al., 2010)

Advantages with the pre-lay mooring system

Pre-lay mooring operations are beneficial for rig owners and operators. AHOs contribute 10 to 20% of the total well cost of offshore well explorations. By installing mooring lines at drilling sites prior to rig arrival, less rig time is used during connecting and disconnecting the system (compared with conventional rig moves). This approach reduces the necessary weather window for the rig move and thus the risk of "waiting for weather". Moreover, there is no rig time spent when resetting anchors. The decreased time for the rig move results in more operational time, which delivers significant cost benefit for the rig owners. In addition, a pre-lay approach negates the threat of anchor drag incidents.

Pre-lay means that a significant part of the mooring work is conducted weeks in advance and at the optimal time with respect to the weather conditions and vessel availability or prices. It takes several weeks to pre-lay the anchors and lines and to then pick them up after the rig is moved to the next location. It is possible for the rig to work during these periods. Hence, operators have greater control and flexibility over the operation. Moreover, they have the flexibility to plan operations by considering available vessels and crew. There is an additional cost associated with pre-lay, with extra money for an extra mooring system needed. However, the concept makes each rig move a single operation and reduces the risk of rig day-rate costs. Oil companies have thus far not considered pre-lay the best option due to the additional cost of the mooring systems and uncertainty about the potential operational benefits. The experiences of InterMoor (2012) have shown that there are five areas in which operators can gain benefits: reduced rig time during mooring operations; reduced exposure to risk; greater control of costs; a higher standard of mooring integrity; and increased capacity for deeper water.

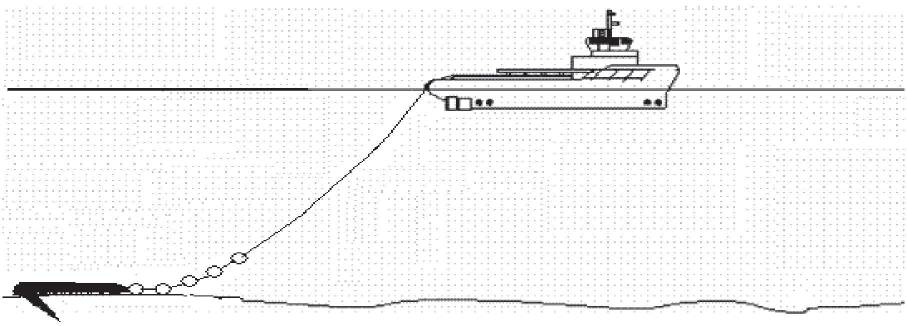

Figure 2.15: Pre-lay – a single AHV establishing the test tension

The key issues with rig moves are the day rate for the anchor-handling vessels and the high cost of the entire rig spread. Whether day rates are for long-term hire or charging a standby rate, the meter is running all the time. Oil companies do not want to waste time and money waiting for good weather or riding out storms. Therefore, wherever the weather and sea states change rapidly, single vessel pre-lay is an effective means of minimizing the risk of having high waiting-on-weather costs, resulting in a reduction in operational cost. Indeed, for minimizing operational costs, pre-lay can be a better option. Removing the rig and other vessels from the operation greatly simplifies the procedure. The vessel involved has complete control of when to work and when to stop working, so the time pressures associated with traditional rig moves are eliminated from the equation. Several oil companies operating on the Norwegian Continental Shelf have chosen to pre-lay moorings, and the trend is continuing. The rig is hired for drilling. The time spent on mooring, rig move and de-mooring is dead time (that does not contribute economically) in view of the real operation. The advantage with the pre-lay methodology is to reduce the dead time substantially.

Another significant benefit of pre-lay operations is improved mooring integrity. The integrity and condition of a rig's mooring equipment must be checked every five years. Pre-lay equipment, in contrast, is checked before every operation and is chosen for its appropriateness at the given location. Special types of anchors can be used for the seabed where a rig lacking these anchors is operating. Pre-lay also helps companies to keep track of their mooring assets and certifications.

In fields in which there is already a large quantity of equipment on the seabed, pre-lay is often a preferred option because it reduces the risk of damaging equipment such as wellheads and umbilicals. This consideration is vital for drilling in mature fields. In pre-lay operations, anchors can be placed very precisely by using state-of-the-art surveying equipment (with the help of an ROV). Another important feature of pre-lay moorings is that they extend the water depth capability of a rig beyond what its on-board mooring system allows.

By releasing AHVs sequentially, the operators can reduce the cost of the entire rig move operation (Saasen *et al*., 2010). Saasen *et al*. (2010) indicated that for pre-lay anchors, the required weather window is 29 hours, which is significantly less than that required for conventional operations. Moreover, the traditional AHO would have experienced two days waiting on weather and spent extra time on anchor handling due to deterioration in weather window conditions.

The following advantages can be achieved by a pre-lay mooring system:

- Safety: Lower risk for accidents during installation due to more time to install the mooring equipment in controlled forms before the rig arrives. There is an increased focus on mooring safety and quality due to other factors associated with drilling in deeper water depths. It improves safety for personnel and the installation;
- Low risk for damaging subsea equipment: Lower risk for damaging existing infrastructure on the seabed;
- Saves time and cost: Normally, the 2-3 days required to install mooring equipment in good weather conditions decreases significantly if the equipment is installed prior to rig arrival, which can contribute substantial cost savings with current rig rates;
- Effective use of AHVs;
- Reduction of the number of vessels required to move the rig;
- Uncertainty with respect to the holding power of the anchor is eliminated;
- More-accurate positioning of anchors;
- The process meets the requirements from the authorities.

In conclusion, pre-laid moorings reduce rig move time and risks, save money, provide a safe and controlled operation, and increase the mooring integrity (due to laying anchors with proper holding capacity) and the water depth capacity of a rig.

2.3. AHV crew qualification requirements

2.3.1. Masters

The vessel master is responsible for the navigation of the AHV during AHOs under the direction of the person in charge of the mobile offshore unit (MOU). The master requires relevant expertise and experience with the vessel class or design he/she is aboard. In addition, the vessel stability is his/her responsibility; however, it should be checked with the MOU in charge prior to commencing operations. Typically, during AHOs, the vessel master has the following responsibilities:

- Navigation and control of the AHV (passage planning, conning and external communication);
- Manoeuvring (including mooring and anchoring);
- Control of vessel seaworthiness (ballast, stability and watertight integrity);
- Management of the AHO;
- Winch handling;
- Communicating with deck crew, rig and other AHVs.

The requirement in the North Sea for a master not having previous anchor handling experience is that he/she should perform at least 5 rig moves accompanied by an experienced (anchor handling) master, or a suitable combination of rig moves and simulator training, before he/she is assigned an anchor handling assignment. A chief officer with significant anchor handling experience is also acceptable. A master with previous anchor handling experience as vessel master but for whom this experience is more than 5 years past should have an overlap period of at least 14 days with an experienced AHV master. In addition, during this period, at least one AHO must be performed (OLF/NSA, 2003). Compliance with these requirements should be documented by the ship owner.

2.3.2. Tow master

AHOs will be executed under the direction of the person in charge of the MOU. The requirement in the North Sea for the tow master is that he/she should actively participate in the execution of at least five rig move operations in a similar MOU type or a suitable combination of rig moves and simulator training (satisfaction of this requirement should be documented.). In addition, he/she should have extensive knowledge of relevant rules and regulations and extensive knowledge of the rig move plan.

2.3.3. Chief officer

If the chief officer is supervising anchor handling work on deck, he/she must have anchor-handling experience and be competent in anchor handling procedures and guidelines and anchor handling equipment setup and function and be familiar with associated hazards and risks. The officers working on the bridge during AHOs have tasks that can affect the safety of those working on deck. Thus, the officer should be familiar with anchor handling deck work operations and the associated hazards and risks. The requirement in the North Sea for the chief officer is that he/she should have previous AHO experience with at least 5 rig moves or a suitable combination of rig moves and simulator training. Compliance with these requirements should be documented by the ship owner.

2.3.4. Winch operators

The winch operator must be competent in winch operation and safety systems and in their functions and limitations. Vessel and/or MOU owners ensure the necessary training of winch operators. A certificate must be issued.

2.3.5. Vessel deck crew

Personnel assigned independent work on deck during AHOs should be familiar with guidelines and procedures; furthermore, they should be familiar with the safety aspects. They should also be familiar with the use of ultra-high frequency (UHF) and/or very high frequency (VHF) radio. Able-bodied seamen with no previous anchor handling experience must be trained in guidelines, procedures and safe equipment use before being assigned to do independent anchor handling operational work on deck. Compliance with these requirements should be documented by the ship owner.

2.4. Bourbon Dolphin accident

The vessel and operational background related to the Bourbon Dolphin accident, key conclusions from the investigation report, NMD recommendations, OSC study findings and further research questions for ensuring AHV safety in AHOs are summarized in Appendix C. This research addresses solutions (or methods) for the following aspects mentioned in the investigation report (see Appendix C) to enhance AHV safety during AHOs:

- Stability rule conditions for anchor handling are to be prepared.
- The stability book is to be improved (effectively following current regulatory requirements).
- The use of simulator training is to be encouraged.
- Vessel-specific anchor handling procedures are to be prepared by the companies.
- Rig move procedures should include details of the realistic forces involved, and the understanding of vessel crews should be ensured.
- Rig move procedures should detail weather limitations to prevent disagreements about the initiation or suspension of operations.
- Rig move procedures should be operation specific and easy to understand.

2.5. Typical operational aspects and demands in AHOs

Critical phases of AHOs or operational scenarios are as follows:

- Combined lifting, towing and positioning;
- Operating in current, swell, waves and winds (which generate large dynamic forces in addition to the already existing large static forces);

- Vessel subject to larger sideway forces;
- When collecting or delivering anchor, poor ship handling possibly leading to collision with the rig or a semisubmersible;
- Extracting anchor from an already deployed position;
- Vessel drift due to deteriorating weather and increasing current;
- Grappling activity (collision with another vessel);
- Engine overheating when vessel operating with full towing power;
- Entanglement with pipelines positioned on the seabed;
- Jumping chain during deployment (which can damage the vessel structure);
- AHV mooring line entangling with existing mooring lines (or a previously deployed mooring line when performing operations close to it);
- Stretching wire or chain (which can break);
- Lowering or picking up buoys.

The following limitations can be faced during AHOs:

- Competence on stability and manoeuvring;
- Operational procedures with clear go/no go criteria;
- Propulsion system;
- Communication system with other vessels and rig;
- Communication system within the vessel's own crew;
- Emergency releasing system;
- Navigation system;
- Vessel stability;
- Vessel steering and manoeuvring;
- Ability to hold up against weather;
- Available thrust;
- Twisting anchor chain;
- Incorrect anchor deployment;
- Efficiency of vessel propulsion and control.

2.5.1. Bollard pull requirement

In current practice, the minimum requirement of the Bollard Pull (BP) is defined by the insurance companies by considering the wind area and operable weather conditions. With this requirement, in theory, the unit should be at least manoeuvrable for the maximum weather criteria defined in the operating procedures.

2.5.2. Dynamic position

In current practice, even when the vessel is equipped with a dynamic positioning system, use of that system is not permitted when the wire is connected (or disconnected) to the rig because, even today, no existing computer logic can process the large external dynamic forces induced by the wire on the vessel. The problem with writing such an algorithm for computer controlled manoeuvring is that it occurs as a result of human action. These actions are random in nature, with no predictability compared with the weather or current, for example (Clark, 2005).

2.5.3. Weather

Prior to the AHO, the weather conditions must be evaluated continuously until the forecasted weather conditions are within the acceptable limits. Operations will not commence without the consent of the platform manager and AHVs' masters. When defining allowable weather limits, the following constraints related to the vessel play a vital role:

- Stability characteristics;
- Drift-motion characteristics;
- Available power;
- Speed limit.

Typically, the allowable weather conditions during AHOs depend on the size of the available AHVs. However, for performing AHOs, the present practice in the industry is a maximum significant wave height of 4 m. Furthermore, the required weather window should be sufficient for completing the operation in a safe manner.

2.5.4. Vessel loading condition

The vessel loading condition can be influenced by an error prone interface design, the organizational culture and the division of responsibility between different departments of the ship. Moreover, the effects of human factors, such as fatigue or seasickness, further affect the loading condition.

2.5.5. Stability aspect

In general, AHVs are designed with a high initial metacentre height (GM) to ensure sufficient stability in all operational conditions. Consequently, vessel motions such as pitching and rolling are greater in heavy seas. Thus, it is uncomfortable for the crew working on board. Therefore, ballast tanks are used to reduce these motions. However, on the negative side, these tanks contribute to the free surface effect, reducing the initial GM. Consequently, vessel stability decreases (Holmroos, 2014).

2.5.6. Large magnitude of the mooring load

A higher magnitude of the transverse moment due to the mooring load during AHOs might occur for the following reasons:

- Deviation of the vessel's bearing with respect to the mooring load direction;
- Mooring line position with respect to the vessel's tow pin;
- Operational performance;
- Vessel handling skills;
- Quality of supervision and action.

2.5.7. Connection aspects

The complex connection between an AHV and a rig can be broken down in a sequence: Rig-Rig Chain – Kenter-Adaptor-anchor – Kenter-Swivel – Kenter-Chain tail – Kenter-Chain tail – Kenter-PCP wire – Kenter-Chain tail – Kenter-Chain tail – Kenter-pennant wire – Kenter-Chain tail. Manually connecting these components can cause wire-related accidents, which are major concerns in AHOs. Whenever possible, the anchor chain is captured in between the tow pins, and chains are stopped at the korman fork when making further connections. In any case, there should be constant communication between the deck and the bridge. Under no circumstances must the anchor be pulled onto the deck in a sideways position, nor shall the AHV brake the anchor with the chain secured in a Shark jaw. Chain stoppers should be used to prevent a load being placed on the windlass when breaking loose the anchor. For this purpose, the AHV should be positioned as closely as possible in line with the chain direction.

2.5.8. Manoeuvrability or vessel handling

The manoeuvring characteristics of an AHV are an important aspect of safe and efficient AHOs. Associated functional and safety requirements for operating AHVs in various situations demand high manoeuvrability characteristics. Successful manoeuvring is interpreted as the ability of the vessel to go anywhere, varying from the straight-ahead path without any rudder action to tight turning with significant rudder action. In general, low-speed vessels with high block coefficient such as AHVs are known to have poor manoeuvring characteristics due to their full hull form (with a small length-to-beam ratio). Moreover, during AHOs, the mooring load induced by the heavy wire / chain acts on the vessel; indeed, vessel manoeuvrability decreases further.

2.5.9. Installation constraints

Preferably, AHOs above subsea installations and pipelines should not be performed because these operations can damage the abovementioned subsea assets. Moreover, mobile units should handle anchors and other heavy items in a safe position to avoid falling items hitting and damaging subsea installations or pipelines. When crossing pipelines, anchors and other heavy items must be secured on deck to mitigate the risk due to dropped objects.

2.5.10. Decision constraints

The efficiency and result of the operation depend entirely on the quality of decisions and actions taken from planning phase to the final phase of the operation. For illustration purposes, a typical decision tree underlying safe and economic operation is shown in Figure 2.16. Before commencing the operation, key personnel plan the operation by considering the associated risk. With this risk in mind, the decision is made in vessel selection and limiting parameters, which have a significant effect on achieving functional and safety goals. During the start of the operation, the master and other parties should monitor the weather conditions and vessel condition to decide either to start the operation or to wait until the weather conditions are appropriate for starting. For this purpose, the AHV master continuously monitors the available information on board such as environmental parameters (wind parameters from wind sensors and wave information from the rig / other resource), the magnitude of the mooring load at the winch monitor, and the vessel position and heading. In addition, navigational software is used for monitoring the vessel position and heading with respect to the rig and target location. At present, the practice in the industry is that the master judges the vessel behaviour. This judgement is highly dependent on his experience and knowledge. Thus, a correct decision and corrective action by the master can lead to optimal operation and vice versa; a wrong action and decision might delay the operation or lead to accident situations. In general, one anchor deployment or recovery takes approximately 4 to 8 hours. In addition, the rig de-positioning and positioning activities take approximately 24 to 48 hours. At the same time, the environment and the mooring load change continuously. Thus, many actions and decisions are taken during the operation. At any point of the operation, if the master forms an opinion that it is unsafe to continue the operation further, he can abandon the operation. Subsequently, the operation will be resumed if the situation is deemed safe to continue. The quality of decisions during the operation depends on SA, vessel capabilities and constraints. A framework for a better DSS is proposed in Chapter 4. A DSS is helpful in assisting the vessel master in two ways: 1) situational awareness associated with the vessel stability margin and positioning capability and 2) the choice of a better control strategy for continuing safe and efficient AHOs.

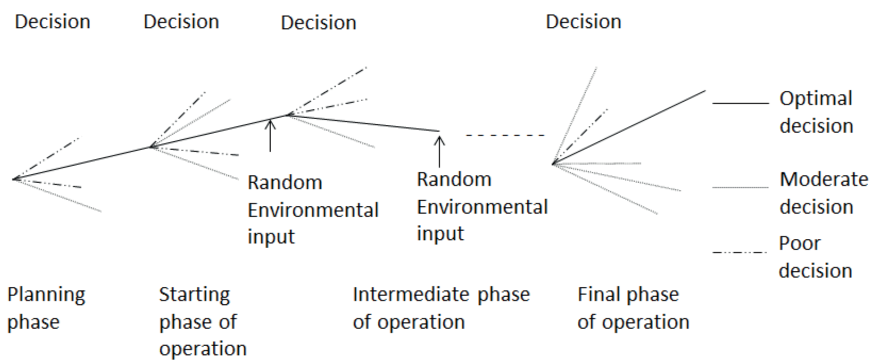

Figure 2.16: Decision tree for safer and economic operation

Chapter 3

Identification of risk-influencing factors in AHOs

This chapter consists of six parts. The first part addresses the definition of safety and accident. The second part presents the definition of risk, hazards and threats. Furthermore, it elaborates on risk assessment techniques. The third part presents a generic overview of the human and organizational factors. The fourth part describes the most critical equipment failures, critical phases and hazards in AHOs. The fifth part addresses the risk assessment of AHVs in AHOs. The final part consists of a summary of this chapter.

3.1. General

Hazard identification, risk assessment and control measures require a sequence of information gathering and application of a decision-making process. Moreover, these terms assist in discovering what might cause a major accident (hazard identification), how likely a major accident is to occur and the potential consequences (risk assessment), and what options there are for preventing and mitigating a major accident (control measures).

3.1.1. Definition of an accident

An accident is commonly a result of a chain of several undesirable events that is defined (MSA, 1993) as "a status of the vessel, at the stage where it becomes a reportable incident that has the potential to progress to loss of life, major environmental damage and loss of the vessel". By their nature, major accidents are rare events that are beyond the experience of most personnel involved in operations. These accident events tend to be events of low frequency and high consequence. However, circumstances or conditions could lead to a major accident. Thus, it is necessary to identify and manage them proactively. The seriousness of the accident is dependent on a compound set of technical failures, operating errors, fundamental planning and design errors, and management and organizational errors. The sequence of events involved in the development of accident situations is shown in Figure 3.1.

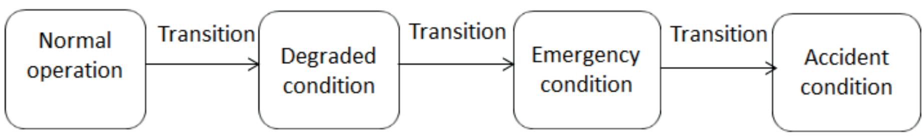

Figure 3.1: Schematic illustration of the development of an accident situation

Historical data in (WOAD, 1996) provide accident rates for mobile (drilling) and fixed (production) platforms according to the initiating technical and physical events of the accident. Similarly, the Japan Marine Accident Inquiry Agency (Uchida, 2004) classified merchant ship accidents into 16 categories: 1) collision, 2) collision (single), 3) grounding, 4) foundering, 5) flooding, 6) capsizing, 7) missing, 8) multiple accident, 9) fire, 10) explosion, 11) machinery failure, 12) equipment damage, 13) facility damage, 14) death and injuries, 15) safety hindrance and 16) navigation hindrance. In the above list, capsizing is in the major accident category. Capsizing is a catastrophic phenomenon that can cause death to the personnel on board. Therefore, capsizing is considered an accident scenario in this research work.

3.1.2. Definition of safety

The Oxford dictionary defines "safety" as "freedom from (absence of) danger or risks". In other words, safety can be expressed as the absence of undesirable accidents that can lead to catastrophic consequences such as fatalities or injuries, environmental damage and property loss. A standard quote on safety is, "Learn from the mistakes of others, because we will not live long enough to make them all ourselves". Learning is important to operational personnel. In contrast, engineers are used to learning from others by using their methods. In other words, safety can be defined as the inverse of risk. The definition is not only inverse in a formal sense but also inverse in a qualitative sense. In general, safety-focussed organizations are productive and profitable. The top of the organization hierarchy has a pivotal role in maintaining a safety culture.

What is safety in a true sense? To obtain a clear view, the above question must be further split into the three following sub-questions:

- What is safety all about?
- Why is operational safety necessary?
- What do we need to improve operational safety?

3.1.3. Accident models

Hazard analysis methods and other safety engineering techniques are always developed based on an accident causality model. Linear accident models, such as Heinrich's Domino Theory (1931) and Reason's Swiss Cheese Model (Reason, 1997), are commonly used. Moreover, control-based accident models, such as Hollnagel's Functional Resonance Accident Model (FRAM) (Hollnagel, 2004) and Leveson's System-theoretic Accident Model and Processes (STAMP) (Leveson, 2004), are more relevant to the safety of complex sociotechnical systems.

The accident pyramid (see Figure 3.2), also referred to as the safety triangle, and was derived from a 1931 study by H.W. Heinrich. Heinrich's Domino Theory accident model was supported by research he conducted when employed as an engineer for an insurance company. This theory describes an accident as a chain of discrete events that occur in a temporal order. His major research study comprises a subjective assessment of the causes in 75,000 accident insurance cases. He concluded that 88% of accidents resulted from 'unsafe acts' and 10% from 'unsafe conditions', totalling 98% judged preventable, with the remaining 2% judged unpreventable (force majeure). This theory is widely accepted in the industry. The pyramid shown in Figure 3.3 illustrates accident causation; unsafe acts lead to minor injuries and over time to major injuries. Moreover, Heinrich suggested five dominoes in a sequence:

- Social environment and ancestry (e.g., alcoholism and stubbornness);
- Fault of the person (e.g., bad temper, recklessness and carelessness);
- Unsafe act (mechanical and technical) or unsafe condition (performing a task without the appropriate personal protective equipment);
- Accident;
- Injury (outcome of some but not all accidents).

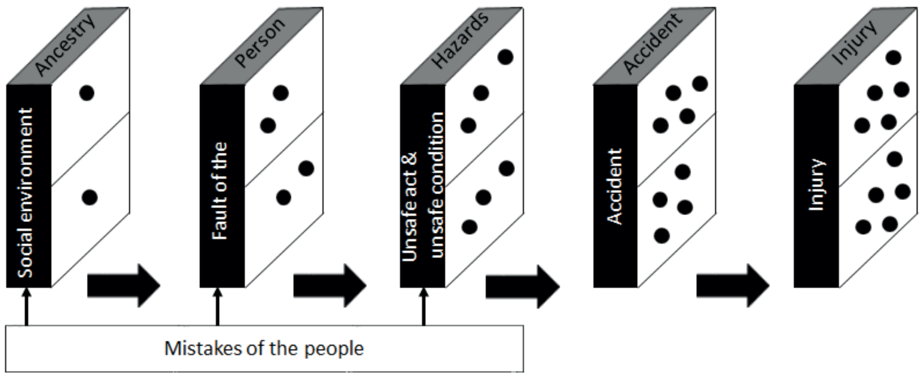

Figure 3.2: Heinrich's Domino Theory (Heinrich, 1931)

Heinrich also highlighted that the first three (i, ii and iii) combining factors lead to accidents and consequently injuries. Moreover, Heinrich (1931) reported from his research the following ratio for three different types of incidents: major injury/minor injury/near-miss incidents = 1:29:300 (see Figure 3.3). In the past, industries performed human error analysis to blame the person who commits an error. In general, lessons were learnt on analysis after the accident. Occasionally, near misses provide sufficient understanding of the human errors in a system.

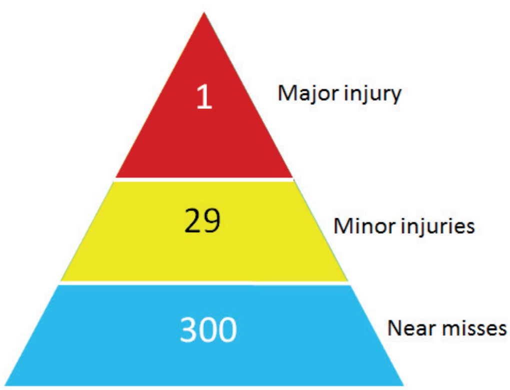

Figure 3.3: Heinrich's 300-29-1 model (Heinrich, 1931)

The theory behind system accidents is explained by Reason's Swiss Cheese Model (Reason, 1997). In accordance with this theory, holes in layers of safety barriers (layer of defences or safeguards) can be created by active and latent failures. The human contributions behind the above failures are classified into four levels. Each level corresponds to one of the four layers of Reason's model, as shown in Figure 3.4. These layers are listed below:

- Unsafe acts;
- Preconditions for unsafe acts;
- Unsafe supervision;
- Organizational influence.

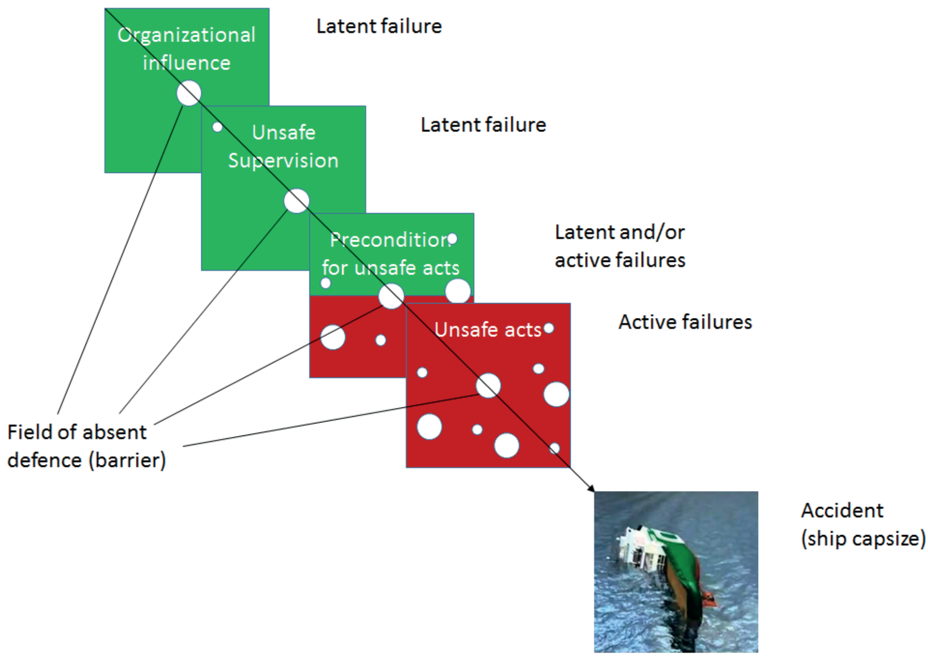

Figure 3.4: The Swiss Cheese Model of accident causation (Reason, 1997)

Unsafe acts and mechanical hazards constitute the central factors in the accident sequence. By eliminating either factor, any one of the first three factors from Heinrich's Domino Theory or a combination of them makes the action of the preceding factors ineffective, an approach focussed on in this study.

3.2. Risk assessment and mitigation in general

Since the late 1970s, quantitative risk assessments (QRAs) have been performed in the oil and gas industry in Norway. Norway was for a long time the only country to systematically implement QRAs; in 1981, the Norwegian Petroleum Directorate (NPD) announced guidelines for evaluating the safety of platform concepts (Moan and Holand, 1981). However, in 1984, quantitative criteria were introduced for the first time in NPD regulations (NPD, 1984). Since the 1990s, marine and offshore industries around the world have been developing and applying a variety of risk-modelling and decision-making techniques. For example, in the UK, following the public inquiry into the 'Piper Alpha' accident, Lord Cullen recommended in the report to implement QRAs in the UK legislation. Accordingly, in 1992, the Safety Case Regulations (HSE, 1992) became law in the UK, and it has since then been mandatory to perform risk assessments in the UK offshore industry to address safety issues (Vinnem, 2014).

Initially, risk assessment was used for verification purposes in designs. Later, due to accidents such as the 'Herald of Free Enterprise', 'Derbyshire' and 'Piper Alpha' accidents, risk assessment was used for verification purposes in both design and operations. Thereafter, the tendency has been that risk assessment is used not only for verification purposes in the design and operational processes of marine and offshore engineering systems but also for making decisions from the early stages. Usually, several QRA techniques are applied to operations and technical systems. These techniques can also be applied for analysing humans and their contribution to a risk. The key personnel involved in the design, planning and operations have some level of risk awareness. However, in practice, the focus on risk assessment of anchor handling operations is limited. In this situation, the key personnel involved in these operations are less aware of the risk level, which can be noticed in the Bourbon Dolphin accident.

3.2.1. Hazards

A hazard is a source of potential harm or a situation with the potential to cause loss. According to the definition in IMO (2002), a hazard is "a potential to threaten human life, health, property or the environment". Hazards are classified into two groups: controlled and uncontrolled. A HAZID analysis is likely to identify the full range of hazards that could cause a potential major accident for the full range of operational modes consisting of normal operations, emergency situations or abnormal conditions. To identify all hazards, the HAZID must consider past, present and future conditions, hazards and potential incidents. Past incidents provide an indication of what has gone wrong in the past and what could go wrong in the future. Techniques such as a hazards and operability study (HAZOP), equipment failure case definition, checklists, the what-if technique, brainstorming, task analysis, fault tree (FTA) and event tree analysis (ETA), failure mode effects analysis (FMEA), failure mode effects and criticality analysis (FMECA), and historical records (WOAD, 1996) of incidents can be used in HAZID. Effective hazard identification depends on the understanding of the operation and having the right people participating in the process in the right places. Kobylinski (2003) has classified hazards related to typical ship stability into the following three categories:

- Environmental hazards related to the action of wind and seaway;
- Hazards related to the heeling moment caused by shifting of the centre of gravity;
- Hazards related to the heeling moment created by external pulling forces.

Furthermore, the potential causes related to the second category are listed below:

- Free surfaces of liquids;
- Icing;

- Water absorption by deck cargo;
- Crowding of passengers on one side;
- Loose goods;
- Water in the deck well, water inrush, opening not closed;
- Suspended loads.

The potential causes related to the third category are listed below:
- Forces created in turning;
- Forces created by the towing hawser;
- Forces created by fishing gear;
- Forces created by the anchor cable;
- Forces created during replenishment at sea;
- Forces created when grounded.

The consequence of the hazards could include any one or a combination of the following:
- Sickness, injury or death of workers;
- Damage to property and investment;
- Degradation of physical and biological environment;
- Interruption of oil/gas production and disruption of business.

How can we control these hazards?
- Identify general design criteria that must be met?
- Identify specific devices and procedures?
- Identify specific design methods for reducing, controlling or eliminating hazards?

3.2.2. Definition of risk

The risk is mathematically expressed by a combination of likelihood and consequence, commonly as their product (Vinnem, 2014):

Risk = Likelihood x Consequence;

where Likelihood = is the probability of occurrence of an impact that affects the environment t, and Consequence = fatalities, injuries, economic loss and environmental impact if an event occurs. The likelihood and consequence values can be expressed in terms of quantitative values such as the statistical probability or the amount of money lost. The risk can be minimized by reducing the probability of damage, the consequence of damage or both. However, a level exists beyond which the risk consequence cannot be tolerated.

3.2.3. Risk assessment

Risk assessment is the determination of the quantitative or qualitative estimate of risk. A “Risk Assessment” is a careful examination of the process and its elements to ensure that the right decisions are made and adequate precautions are in place for preventing risks. Risk assessment is essential as a support for making decisions concerning risk control relating to the following:

- Human life;
- Environment (internal and /or external);
- Property.

Furthermore, risk assessment is a process that consists of three processes: risk identification, risk analysis, and risk evaluation. Risk identification is used to find, recognize, and describe the risks that could affect the achievement of objectives. Risk analysis (cause analysis with hazard frequency analysis and consequence analysis) is used to understand the nature, sources, and causes of the risks that have been identified to estimate the level of risk. It is also used to study the effects and consequences of risk and to examine the risk controls that currently exist. Risk evaluation is used to compare results from the risk analysis against the risk criteria to determine whether a specified level of risk is acceptable or tolerable. For analysing hazards, the API 14J (1993) guidelines recommend hazard analysis methods such as checklists, what-if analysis, HAZOP, FMEA, FTA, ETA, cause consequence analysis, and human error analysis. Moreover, other risk assessment procedures, such as PRA and safety review audits, are widely used in the marine and offshore industries (Dhillon, 2007). The sequence of steps in risk assessment is shown in Figure 3.5. To achieve a systematic and comprehensive risk assessment, experts in the relevant industries actively conduct brainstorming sessions in the steps shown in Figure 3.5.

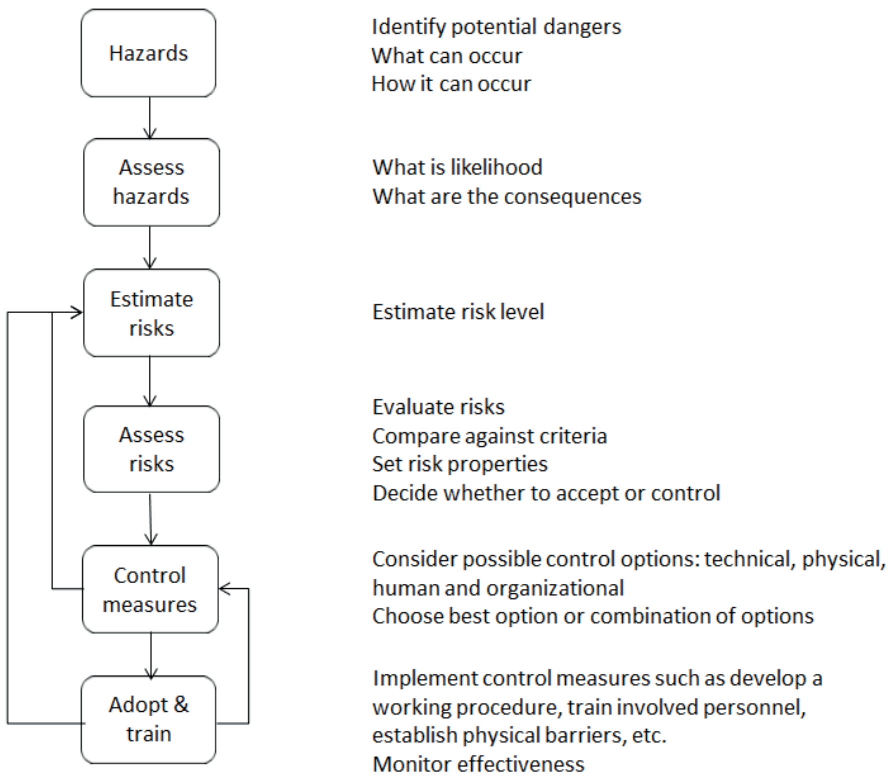

Figure 3.5: Flow chart of risk assessment

3.2.4. How to measure and evaluate risk

The offshore industry is primarily focussed on quantitative risk assessment (QRA) related to production platforms when drilling. Similarly, it focusses on offshore installation and towing operations. Quantitative risk assessment (QRA) provides a systematic method for identifying risk contributions, influencing factors and potential risk mitigation measures. Importantly, it also provides a means of quantifying the benefits of mitigation employed to account for a risk. However, with respect to implementation in AHOs, the quantitative risk assessment methods have limitations such as limited data or, in some cases, no data at all. The data related to human factors (due to the individual and/or organizational factors) are limited.

3.2.5. Influencing diagram

When there are little or no empirical data available, the influence diagram is useful for identifying influencing factors related to risk. Such diagrams are viewed as being able to link failures at an operational level with their direct causes when accounting for the effect of underlying organizational and regulatory influence. These diagrams are similar to Bayesian networks but distinguish between random variables, utility variables and decision variables with circles, diamonds, and boxes, respectively. In addition, these variables are connected in an influence diagram. This method enables reflecting both the hardware and human factors that influence accident scenarios (Moore *et al*., 1993; Moore and Bea, 1991). In general, these diagrams are used for representing key identified risks, alternatives, and outcomes to represent their interconnections and their relative ordering (Howard and Matheson, 1989; Madsen, and Kjærulff, 2008; Shachter, 1986).

3.2.6. Fault tree

This technique was introduced in 1962 at Bell Telephone laboratories by H.A. Watson for evaluating the Minuteman I Intercontinental Ballistic Missile (ICBM) Launch Control System. Fault tree analysis (FTA) is a graphical representation of immediate, intermediate and basic events that result in the accident event or top event, which is often called a critical event (Kristiansen, 2013; Rausand, and Høyland, 2004). The frequency of a top event can be calculated with the help of quantitative assessment. However, whenever the information about basic events is not available, the qualitative assessment of the top event can't be performed.

3.2.7. Safety barrier concept and classification

Chen (2003) explained that a risk analysis can be divided into an initiating stage and a recovery stage. It is unlikely to have systems with zero threats; thus, there is no possibility for 100% accident-free events. It is very difficult for a single person to understand the functionality and limitations of complex systems or operations. Occasionally, human beings are required to interact with other human beings to maintain the safety of the system. The risk can be lowered either by deploying suitable risk reduction methods or by increasing the number of protection layers (barriers) between the hazardous events and the consequences (see Figure 3.6). Sklet (2006) explained the types of barriers and their performance measures (see Figure 3.7).

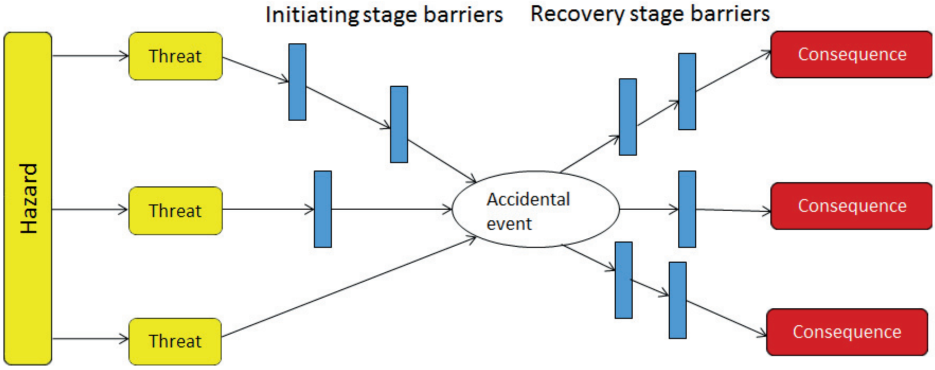

Figure 3.6: Illustration of barrier significance in risk reduction (Trbojevic, 2001)

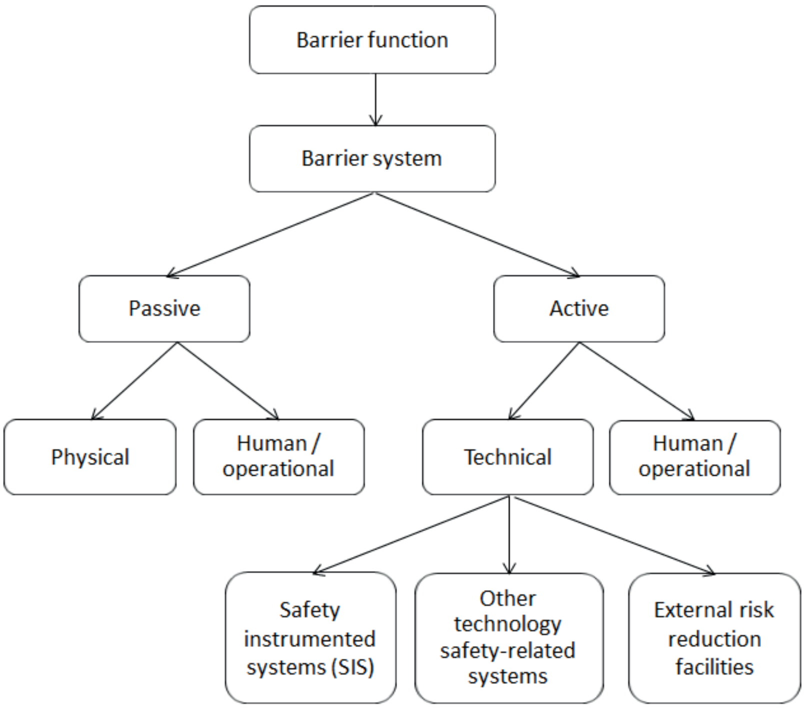

Figure 3.7: Classification of safety barriers (Sklet, 2006)

3.2.8. Risk acceptance criteria

According to the Health and Safety Executive (HSE, 2001), risk is divided into three categories (see Figure 3.8):

- Negligible, in which case no risk reduction measures are needed;

- Tolerable, in which case the risk should be "as low as reasonably practicable – ALARP" and the cost involved in reducing the risk should be less than the benefit gained;
- Intolerable, in which case risk mitigation must be performed irrespective of cost.

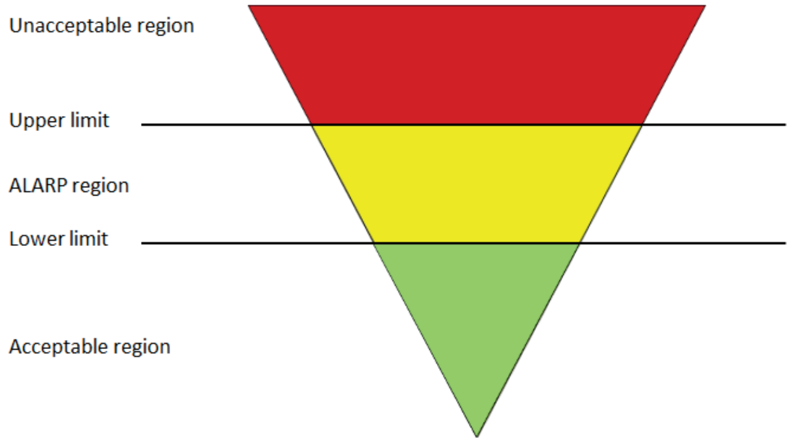

Figure 3.8: HSE framework for the tolerability of risk (HSE, 2001)

3.2.9. The ALARP principle

ALARP means 'As Low as Reasonably Practicable', which is a principle used in making decisions about risk occurrences. This principle was initially applied in the nuclear industry (HSE, 1988) and was later adapted to offshore installations (HSE, 1988). In the Norwegian oil and gas industry, traditionally predefined risk acceptance criteria were used. These criteria are made based on both internal/external regulations and company objectives. However, when the ALARP principle is used, one does not stop when the estimated risk level is within the limits of acceptable risk; rather, one must keep searching for other risk reducing measures and implement them as long as it is reasonably practicable. Therefore, cost efficiency and the ALARP principle are strongly related. The concept of cost efficiency is to evaluate the benefit of implementing further risk reducing measures. If the expected cost of implementing a new risk reducing measure is lower than the expected benefit, this risk-reducing measure will be implemented and adopted in Norway.

3.2.10. Risk matrix

One of the best ways to visualize the risk level is perhaps through a risk matrix. The probability of occurrence has been categorized in terms of likelihood (1 to 5) and the consequence (A to E), the categorization is shown in the risk matrix in Figure 3.9. This figure shows the qualitative risk assessment which is proposed by the API committee for refinery equipment. The yellow part (medium) of the risk matrix represents the ALARP region, where further risk reducing measures must be implemented if it is presumed to be cost effective. The red area represents a risk level unacceptable while the green area represents a risk level as an acceptable.

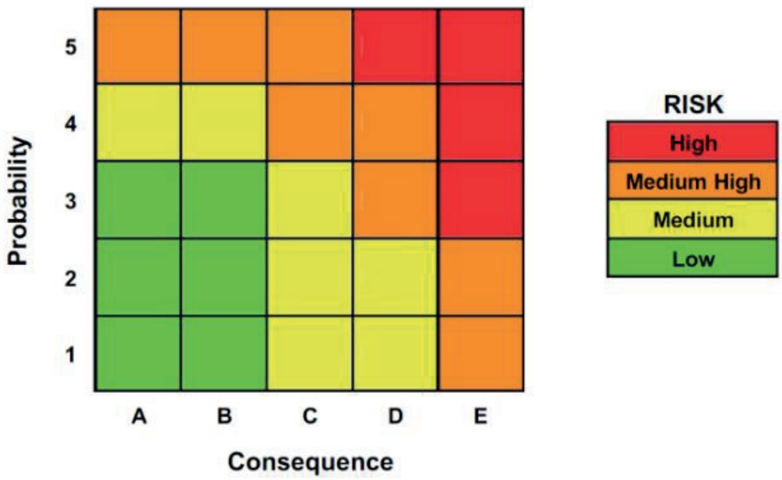

Figure 3.9: Risk matrix proposed by API for the categorization of risk

3.2.11. Risk control hierarchy

It is not possible to prevent all risks in AHOs, but it is possible to reduce the probability of a consequence by implementing suitable risk reduction measures. Therefore, all reasonably practical steps are to be taken to eliminate or reduce each identified risk. Risk reducing measures should be prioritized according to a control hierarchy. A typical risk control hierarchy is as follows:

- Elimination: Implement measures to eliminate hazards;
- Substitution: Implement measures to reduce hazards;
- Engineering controls: Implement measures to prevent or reduce hazards using engineering controls built into the system design. Engineering controls can be passive or active. In the hierarchy of controls, passive controls are higher than active controls;
- Segregation / separation: Implement measures to separate the hazard from other hazards or people, assets and the environment;
- Reduction in time of exposure: Reduce the time during which exposure to the hazard can occur;
- Procedures: Use safe systems of work (i.e., procedures, instructions, control of work, and supervision) to control hazards by ensuring that the operation is performed safely by the personnel involved.

3.2.12. Relevant regulations and standards

Public and governmental bodies are concerned about safety in the offshore industry, particularly regarding potential harm to the citizens working there and to the environment. Moreover, accidents can affect the economy of the society. The risk associated with the application of relatively new technologies is of concern. Therefore, to improve safety or control risk, these bodies establish procedures and practices, define provisions of training (by means of on-board simulators) and awareness, and mandate installation provisions of warning devices. Obviously, the probability of natural phenomena, such as weather, waves, gusts, and lightning, are out of human control, but the consequences can be controlled. The principal elements that can be controlled are the safety features of the system and the safety procedures used in its operation and support, accounting for factors on the vessel and in the environment. Moreover, in the planning phase, it is important to ensure that the right decisions are made.

In the offshore industry in Norway and the UK, it is the responsibility of the operator to demonstrate compliance with safety target levels or show that the risk to persons is as low as reasonably practicable (HSE, 1992). In accordance with the ISM code (IMO, 2014) and national/international legislation, risk must be documented to ensure safe operation of the ships. Different regulations/standards are issued, e.g., by ISO 19900 (2013) and ISO 2398 (1998) and by NORSOK (2002; 2007; 1998; 1998), and the authority of the NPD and the Petroleum Safety Authority Norway (PSA) is related to maintenance programmes and further related to safety-critical systems.

3.3. An overview of human and organizational factors

Traditionally, human factors in the maritime domain can be studied through accident/incident analysis. However, there is a drawback with the traditional approach. Occasionally, it might not reveal the human errors that do not induce accidents/incidents beforehand but that could cause accidents/incidents in the future. Such errors are called latent factors (or latent hazards). Therefore, the focus of this subsection is to present the influence of human and organizational factors on the safety of AHOs. Investigation reports on the accidents and incidents are one way to identify the influence of human factors on the AHOs. In fact, human intervention is always possible in the life cycle of an operation (beginning from design, build, and operation) either directly or indirectly. The level of effect varies from operation to operation and even organization to organization.

With emphasis on AHOs, the likelihood of a potential error being committed by an individual might be one in a million, but such an error could lead to a major catastrophe. It is impossible to identify all the possible errors that individual human beings could make in a scenario. Identifying an error an individual make is very different from understanding why they make it. Unless we understand why people make errors, it is truly not possible to develop effective mitigation strategies. Typically, human errors occur due to factors such as lack of knowledge and experience, wilful recklessness, misjudgement, improper lookout, poor decision-making, poor competence, time pressure, workload/stress, execution errors, lack of information, failure of interpretation, failure of observation, failure of planning, inadequate or non-existent working procedures, poor level of supervision, incorrect action, inadequate action, action on wrong object, delayed action, ignored action, underestimation, action at the wrong time, too long action, too short action, action in a wrong direction, action in a wrong sequence, action in a wrong place, poor diagnosis, poor information processing, difficulty recalling information or making decisions, tiredness, negligence, ignorance, jealousy, arrogance, recklessness, wishful thinking, wrong assessment, wrong intension, laziness, sluggishness, boredom, lack of education, superciliousness, and commercial pressure. To find solutions for human errors, the focus in this study is on examining why people make errors rather than on the errors themselves.

3.3.1. Background

Accidents in the process and nuclear industry, such as Flixborough (1974), Seveso (1976), Three Mile Island (1979), Bhopal (1984), and Chernobyl (1986), have increased the influence of human errors and human reliability on system failures. Moreover, these accidents indicate that humans are not 100% reliable. Baker *et al.* (2002) have summarized the human error contribution to accidents in different industries as follows:

- Approximately 50% of tug and tow boat accidents;
- 90% of ship collisions (US National Transportation Safety Board);
- 85% of ship accidents (Navy Safety Centre);
- 75% of merchant ship accidents (Germany);
- 66% of marine oil spills (UK).

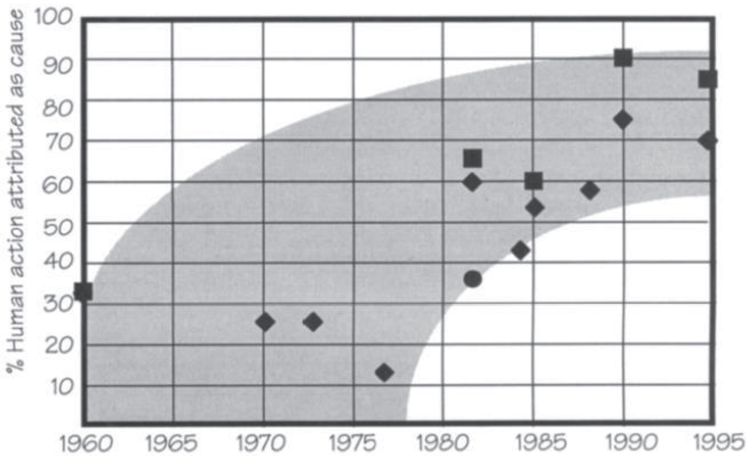

Figure 3.10: Number of accidents in which human actions were considered the main causes (Hollnagel, 1998)

Figure 3.10 summarizes the trend in the attribution of accident causes across a range of technical domains. The percentage is obtained from the following fraction:

$$\frac{C_M}{C_M + C_T + C_O + C_{MT} + C_{MO} + C_{TO} + C_{MTO}}$$

where C_M are the causes attributed to human factors, C_T are the causes attributed to technological factors, C_O are the causes attributed to organizational factors, and C_{MT} are causes attributed to a combination of human, technological and organizational factors. Over the period, technology has evolved to include redundant systems and fault tolerance to eliminate most accidents due to technical fault. Thus, the industry focus has shifted towards human performance. In general, over the period, the causes attributed to technological factors are reduced due to the technical components' high reliability. Moreover, the technical subsystems are designed wholly or partly with fault tolerance. Therefore, the denominator decreased. Indeed, the percentage of human factor (error) contribution is increasing, as seen in Figure 3.10.

There are wide variations in human errors that contribute to marine accidents. This variation is dependent on the source of data and the definitions applied to categorize human errors. Nevertheless, it is reasonable to state that human error plays a significant role in accidents. Bea *et al.* (1997) investigated human and organizational factor effects on the safety of offshore platforms. Their study showed that 80% to 85% of accidents occurred due to human errors. The contributions of human errors during various phases in high-consequence accidents are shown in Figure 3.11; 80% of human errors occurred during the operation phase. The effects of human errors on marine accidents have been investigated by various maritime organizations and researchers, e.g., McCafferty and Baker (2002); Baker *et al.* (2002); Baker *et al.* (2002); and Card *et al.* (2005), who reported that more than 75% of ship accidents worldwide are due to these errors. Based on a study of 364 stability causalities for merchant ships, Kobyliński (2008) concluded that in approximately 80% of the cases, the causes are human and organizational errors due to sequences of events that involve environmental and ship loading conditions and ship handling aspects. According to the Swedish Marine administration (Kobyliński, 2008), error-prone situations in maritime operations are classified into three categories, as follows:

- 71% of accidents result from errors of crew members and a lack of understanding;
- 10% result from a lack of knowledge and training;
- 19% result from other factors.

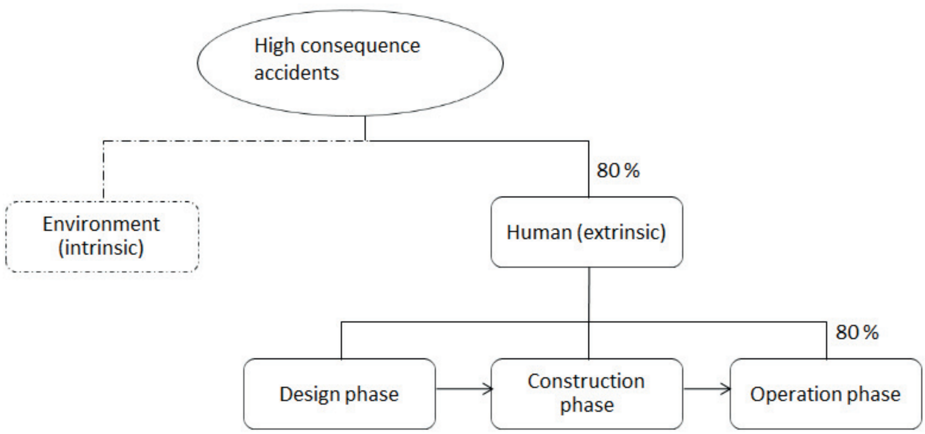

Figure 3.11: Causes of high-consequence accidents (Bea et al., 1997)

Until 1980, accident investigations primarily focussed on the individual level to blame the person who committed an error. In response, the core points of the research topics were cognitive, perceptual and physiological demands. Consequently, a new generation of automated systems was designed to help operators. Despite the introduction of this approach, system failures continued to occur. Accidents such as Challenger (1986), the Piper Alpha platform disaster (1988), the Alexander L. Kielland accommodation platform collapse (1980), Ocean Ranger capsize (1982), the Texas City refinery explosion (2005), the Deepwater Horizon drilling rig explosion (2010), the Fukushima nuclear power plant disaster (2011), the loss of Air France Flight 447 (2009) and the consequence of the Sea Empress disaster in Milford Haven in 1988 could not be prevented. An analysis of past accidents indicates that accidents are caused by interactions between technical, human, organizational, managerial, social and environmental factors. To address the root causes of accidents, the focus of analysts moved towards the managerial and organizational level rather than only on lower levels such as human performance (see Figure 3.12).

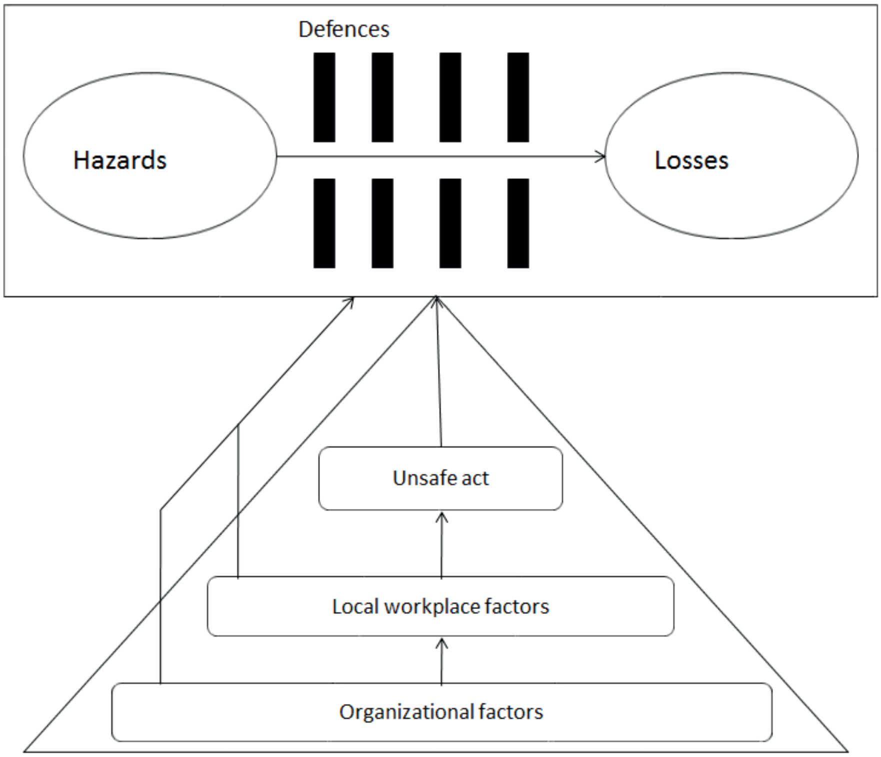

Figure 3.12: Stages in the development and investigation of an organizational accident (Reason, 1997)

3.3.2. Definition of human error

Human error and human factors are often used interchangeably, which creates confusion. Therefore, defining human factors and human error is necessary. The UK's Health and Safety Executive (HSE, 2009) definition of human factors is as follows:

Environmental and organizational and job factors, system design, task attributes and human characteristics that influence behaviour and affect health and safety.

Furthermore, human factors are defined as the interactions between personnel and the organization, systems and equipment with which they interface. The concept of human error, whether intentional or unintentional, is defined by (Lorenzo and Association, 1990) as follows:

Any human action or lack thereof that exceeds or fails to achieve some limit of acceptability, where limits of human performance are defined by the system.

3.3.3. Error-prone situations due to human limitations

The subject of human factors is concerned with understanding the capacities and limitations of personnel in their jobs. With this understanding, it is possible to eliminate or control the effects of human weaknesses and exploit human strengths. Human weaknesses can include limitations on information processing capabilities, whereas human strengths can include adaptability. Humans have, for example, limitations from memory, visual acuity, information processing, distractions, fatigue, decision-making biased by experience and knowledge, and rigid problem solving. These factors can adversely influence human actions and decisions, leading to the possible creation of hazards. The master or person in charge of vessel handling might implement wrong vessel-handling skills either by mistake or by inadvertently using an incorrect procedure. It is important to acknowledge the influence of human factors on hazards at all levels, from planning and writing procedures to operations. Apparently, effective safety strategies are required to reduce the occurrence and consequences of human errors.

3.3.4. Skill, rule and knowledge-based error taxonomy

Human error models and error taxonomies were developed to categorize human failure during major accidents. Different human error perspectives yield different levels of understanding of the problem and solution approaches. The perspective of human errors in the aviation field is categorized and explained by Wiegmann and Shappell (2003). Errors in the maritime field can be similarly categorized into six major categories: order-wise cognitive, ergonomic, behavioural, seasickness, psychological and organizational errors. Reason says that errors can be examined from three viewpoints: behavioural, contextual, and conceptual. Moreover, errors can be distinguished into skill-based, decision-based, perceptual and violation errors. From the literature, it is apparent that four human error classifications are widely used (see Appendix D). In this study, the skill, rule and knowledge-based error taxonomy from Reason (1990) is used (Appendix D).

3.3.5. Human reliability analysis

Often, human performance and reliability analysis is concerned with the qualitative and quantitative analysis of human error and its subsequent reduction. Unfortunately, prediction of human error is not an easy task. Therefore, human reliability analysis has its own difficulties. Studies of human errors must be developed to minimize large-scale accidents in complex systems such as the nuclear power, chemical, aviation and offshore industries. Often, human performance investigation is performed by a single (individual) person, who might or might not be trained in human factors. Intervention aimed at human factors is typically established by well-meaning, expert opinion or group discussions. The majority of work in this domain has come from the nuclear industry through the development of expert techniques such as SLIM (Success Likelihood Index Methodology), THERP (Technique for Human Error Rate Prediction) (Swan and Guttman, 1983) and other methods. The human reliability methods are described in reports, e.g., Chandler *et al.* (2006) and Bell and Holroy (2009); dedicated books, e.g., Kirwan (1994), Hollnagel (1998), Spurgin (2009) and Di Pasquale *et al.* (2013); and papers by Kirwan (1996) and Madonna *et al.* (2009), among others. It appears that safety due to human factors is prone to expert judgements rather than data driven. The need for expert judgement arises because of the lack of human error data.

3.3.6. Performance of human actions and decisions

Historically, "error" has been used to represent either the event itself (the action) or the outcome of the action (consequence). Different professionals view error from different perspectives. As an engineer, the Ph.D. candidate prefers to view the human operator as a system component for which success and failure can be described similarly to those of equipment. Therefore, in this study, the focus is on erroneous action or performance failure instead of on "error". The operator's action time is decomposed into RESPONSE + RECOVERY times as shown in Figure 3.13. The response time is again decomposed into three parts: identification, decision and execution. By proper means of the operator's intervention in time, an accident scenario can be prevented; if not, it is mitigated.

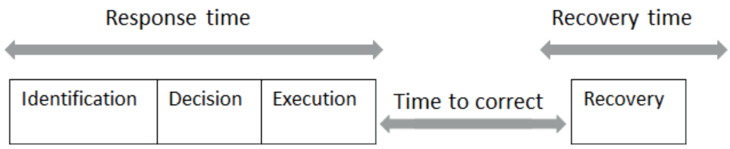

Figure 3.13: Decomposition of manual interventions (Hollnagel, 1998)

The actions are distinguished as responsive and non-responsive. The responsive action is correctly performed as shown in Figure 3.14. The non-responsive actions are distinguished into three categories: failure to perform an action, known as an omission; an unintended or unplanned action, known as a commission; and execution error. The responsive outcome is only achieved by performing a correct action and execution.

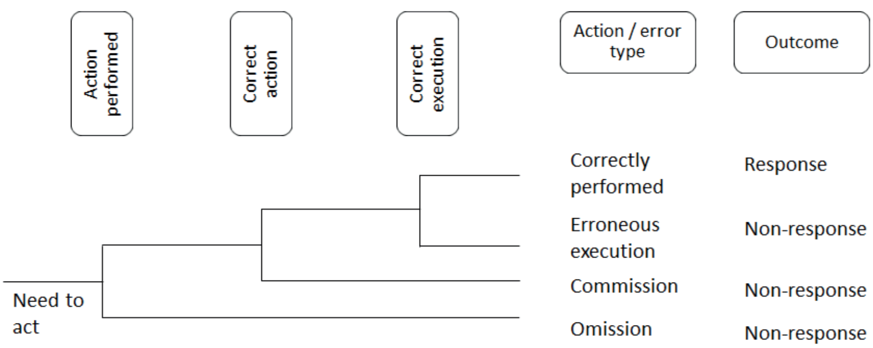

Figure 3.14: A pseudo-event tree for omission and commission (Hollnagel, 1998)

Human decisions are based on good reasons. However, these decisions might later be judged inappropriate; then, they are called errors. These reasons have a good foundation in their own world (i.e., a situation recognized by them), particularly when humans are trained experts. Without knowing how situations are recognized and what affects this recognition process, it is difficult to understand the errors.

The quality of decision-making depends on the information processing. The human information processing system is assumed to comprise a diverse range of limitations that are invoked under information processing conditions. Figure 3.15 illustrates the range of information processing during AHOs.

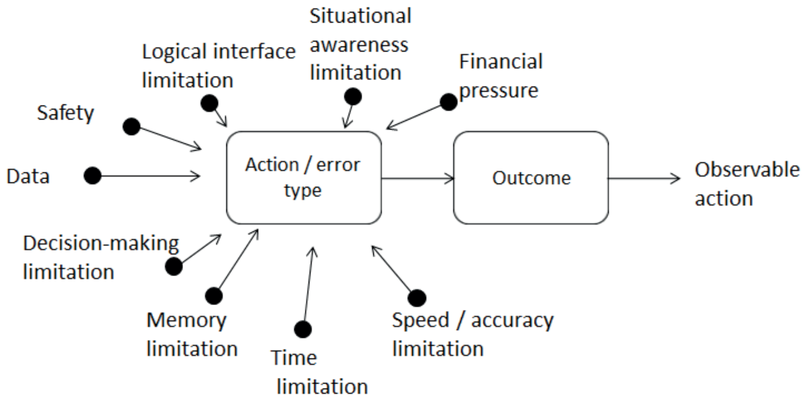

Figure 3.15: Information processing limitations in general (Hollnagel, 1998)

3.3.7. Human error mitigation strategies

Major consequences of accidents can be either avoided or reduced by taking the correct action after the accident event. Similarly, the likelihood of occurrence of an accident event can be mitigated by taking the correct actions in the design, analysis and planning, and execution phases. The contribution of human errors to accidents can be minimized by improving human performance. In general, the available time window for mitigating an accident event and its consequences is smaller in high-demand operations. To take corrective action, the operator should have sound knowledge about the system and his/her limitations, which can be achieved by improving the operator skill-based, rule-based and knowledge-based performance. The following approaches are essential for improving performance:

Situational awareness

Systems (or operations) related to situational awareness are to be established for improving situational awareness.

Training

The involved personnel are to be trained as individuals and as a team. This approach will help the involved personnel to work as a team and improve communications because they all will be in the same phase, which helps to improve efficient and effective communication between them. Furthermore, training (by means of on-board AHVs and simulators) can improve SA, which in turn can cause crew to notice errors in time so that the consequences of errors can be avoided.

Safety management system (SMS)

Accident/incident/near miss information can be utilized in the risk analysis to implement suitable risk mitigation strategies for future operations. Unfortunately, there is a lack of information on near misses' due to limited reporting, as the persons who commit errors were often blamed (or punished) even when the errors did not result in an accident. Therefore, the individual approach to reducing human error is not as effective as a system approach (SMS) for reducing errors. The SMS approach for identifying system error is comprehensive. The focus is on the individual, team, unit and organization.

Policies and procedures

In addition to the above factors, organization management policies and procedures, such as operating procedures, guidelines for crew manning, and emergency and lifesaving regulations, are helpful for improving performance. For example, the qualification of the manning requirements for personnel involved in AHOs is addressed in Section 2.3.

3.3.8. Situational awareness

Endsley (1996) has described research performed on situational awareness in the domain of medicine and the aviation industry. Endsley mentioned that situational awareness is important in complex and dynamic environments such as the maritime one. Grech *et al.* (2002) described the importance of situational awareness by mariners for better decision-making under hazardous conditions. A literature review by Grech and Horberry (2002) indicates that limited work has been performed in the maritime domain on situational awareness.

Situational awareness is being aware of what is occurring around you and understanding what that information means to you now and in the future. Crewmembers make decisions based on their perception and understanding of the environment. This perception – or situational awareness – progress varies at different levels. The formal definition of situational awareness breaks down into three separate levels (Endsley *et al*., 2003), as shown in Figure 3.16:

- Level 1: Perception of the element in the environment;
- Level 2: Comprehension of the current situation;
- Level 3: Projection of future status.

Furthermore, examining the types and causes of the human errors reveals that failures of situation assessment and awareness are exceedingly common. Figure 3.17 shows data related to the types of human errors reported in accident reports. Situational awareness is a state of knowledge that directly relates a dynamic environment to operational goals. Based on Card *et al*. (2005), situational awareness generally involves the following issues:

- Sensing and perceiving the environment;
- Assessing the environment;
- Identifying and updating immediate and long-term goals in relation to the assessment;

- Planning based on goals and the environment;
- Predicting the results of plan execution.

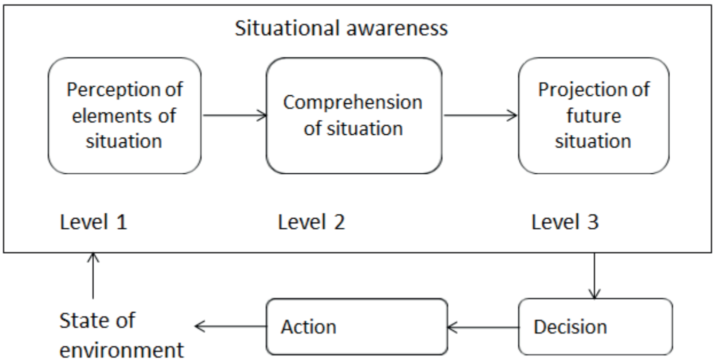

Figure 3.16: Situational awareness – levels of perception (Schaathun and Aarset, 2014)

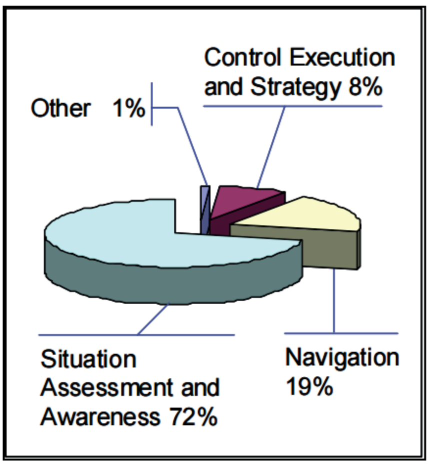

Figure 3.17: Types of human errors reported (USCG Data) (Card et al., 2005)

The information required on-board should include dynamic information such as vessel sensors, parameters related to the mooring load, and the current state of the vessel (vessel drift, bearing and stability). With the help of an appropriate on-board information system, it is possible to filter relevant information and present it effectively such that the crew on board will achieve clear situational awareness of the vessel's condition. The operational plan usually defines a number of key indicators that must be monitored, typically performance or safety parameters such as completing tasks in time and stability. Critical thresholds can be set to trigger alarm situations. The key indicators for each phase of operation are to be identified and monitored. These key indicators are crucial information for situational awareness.

3.3.9. Decision-making in a dynamic environment

Risk is always present, whether we identify it or not; the option to manage it appropriately also varies dynamically simply due to its environment (dynamic environment). This environment can be explained by the following simple relationship: Appropriate goals + Adequate Situational Awareness + Appropriate Level of Risk = Quality of Decision. The role of situational awareness in dynamic decision-making is shown in Figure 3.18. The above equation illustrates that if we change one of the inputs, then one (or both) of the others must also change for the same quality of decisions. For example, if we encounter a technical or operational problem, then to achieve the same quality of decision, we must reduce our level of risk, i.e., make our goals more conservative. This approach requires abandoning certain goals, for example, compromising on on-time completion of the operation to concentrate more on safety.

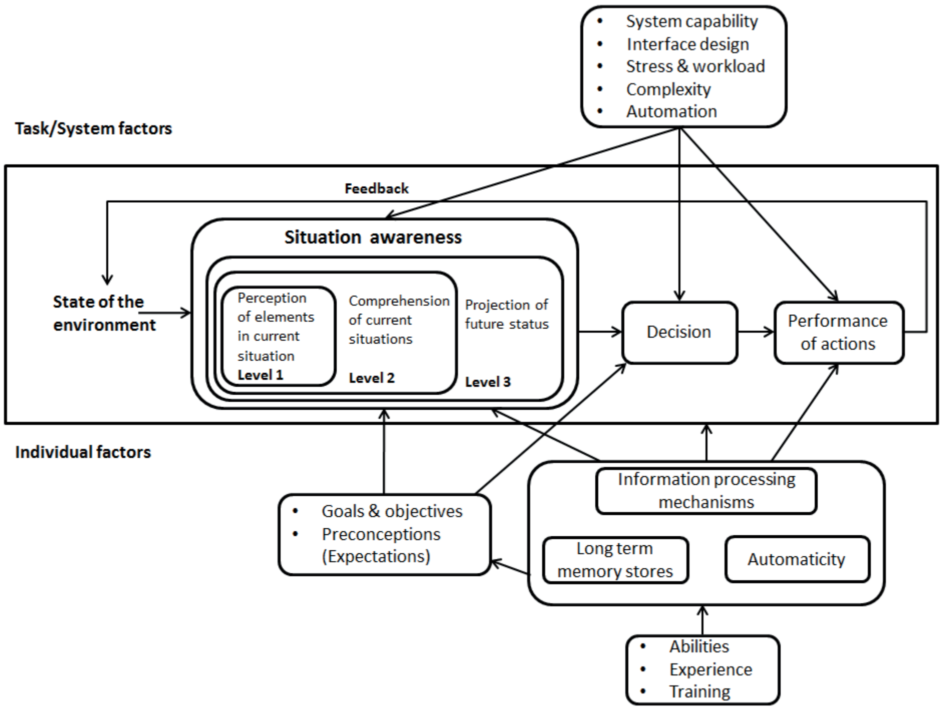

Figure 3.18: Model of situational awareness in dynamic decision-making (Endsley, 1995)

Causal factors such as inappropriate goal priorities when the situation demands change in goal selection can lead to accident situations. Some models of SA, or situational assessment to be more precise, are based on a passive ingestion of 'data elements', which we process as knowledge. What we recognize in a situation is largely a function of our goal and risk assessment. Moreover, how we view the situation also affects what 'data elements' we notice and/or search for and how they are interpreted. Therefore, situational assessment is an iterative cycle in which the operator with situational awareness guides a data search. This data search allows him/her to confirm or update his/her situational awareness. Subsequently, the updated situational awareness guides the operator on a new data search. This cyclic process is dependent on the operator's expertise. Expertise depends on experience; experts can recognize subtle clues that can be invisible to novices. Additionally, because of the experts' greater sense of what should occur, they are able to recognize quickly when things are not occurring that should; in other words, they realize that their existing assessment of the situation is incorrect or deficient. They then instigate a revised data search, including searching for non-obvious or missing data, allowing them to reach a new understanding of the situation. This revised model thus guides further information search and interpretation.

3.4. Hazards in AHOs

Anchor handling is a complex, weather-restricted operation. It is influenced by environmental, hardware, software and human factors. The present section addresses critical phases and hazards in AHOs. These issues are further discussed in subsequent sections.

3.4.1. General

Possible hazardous scenarios during AHOs involve collision with another vessel during tandem operation, collision with the rig, capsizing during tandem operation, capsizing during anchor handling, and fire. The risks associated with involved AHVs have not yet been quantified during mooring or unmooring the rig (or semisubmersible). The qualitative and quantitative risk (level) must be studied. The basic problems in assessing the risk associated with these events are the uncertainty in data due to factors such as randomness, fuzziness, incompleteness, and unpredictability.

In this study, the following questions are raised with respect to risk associated with AHOs:

- What could possible accident scenarios be?
- How does an AHV get into a hazardous scenario?
- How can getting into a hazardous scenario be prevented?
- How can a hazardous scenario be escaped?
- What were the causes of the Bourbon Dolphin accident?
- How can the risk-influencing factors related to AHOs be identified?
- Why is there a focus on the safety of AHOs?

3.4.2. Critical equipment or system failures in AHOs

Equipment or system failures that can make it difficult or even impossible to perform a safe AHO are listed below:

- Tow pins;
- Shark jaws;
- Grapple;
- Mechanical failure of safety pins;
- Work wire;
- Tugger wire;
- Losing the permanent chain chaser;

- Thrusters;
- Engine;
- Emergency releasing system;
- Propulsion;
- Direction control system;
- Navigation and communication equipment.

3.4.3. Critical phases in AHOs

From a safety and operational point of view, the following phases of an AHO can be critical:

- Collecting or delivering the anchor;
- Retrieving the anchor from the existing deployed position;
- Operating the vessel in adverse weather conditions such as wind, waves, and current;
- Vessel(s) being near the rig / platform and each other;
- Grappling activity with the help of another AHV in tandem operations;
- Engine overheating when the vessel is operating with full towing power;
- Anchor entangling with, for example, pipelines on the seabed;
- Losing control of the anchor and/or equipment on the deck;
- Breaking wire or chain when stretching;
- Lowering or picking up buoys.

3.4.4. Methods used for hazard identification in AHOs

The hazards related to AHOs are identified by the following means:

- Collation of appropriate background information and studies, such as historical incident data;
- Interpretation of 'major accident' reports;
- Observation in simulator training;
- Field observation;
- Discussion with experts.

Interpretation of 'major accident report'

The Bourbon Dolphin accident report (2008) was used for this purpose. Key findings and a summary of the report are described in Section 2.4.

Simulator observation

Simulators are indeed helpful in understanding the complexity associated with AHOs, operator behaviour during operations and the communication between personnel involved in these operations. The Ph.D. candidate has been part of simulator training at the Offshore Simulator Centre (OSC) as an observer in May 2010 at Ålesund. OSC was offering training to the Shell employees on a drilling operation north of Alaska. The training is based on the platform used for the ordinary anchor-handling course, and its focus was on teambuilding, communication and coaching. It was a great pleasure to be part of the group, which consisted of advisers, ship crew, and representatives from the operator. The group contained citizens from the USA, Canada, Russia, Sweden and

Norway (see Figure 3.19). It was a good opportunity to interact with trainers from the OSC and trainees from the Shell Company.

Figure 3.19: Simulator training team at the Offshore Simulator Centre AS in Ålesund

Field observations

A trip was made from 27.01.2011 to 21.02.2011 on board the AHV Far Sapphire (Figure 3.20). The charter hired this vessel and its crew to perform the following tasks for the Songa Delta:

- Unmoor rig at Gnatcatcher field;
- Move rig from Gnatcatcher field to Ronaldo field;
- Moor rig at Ronaldo field.

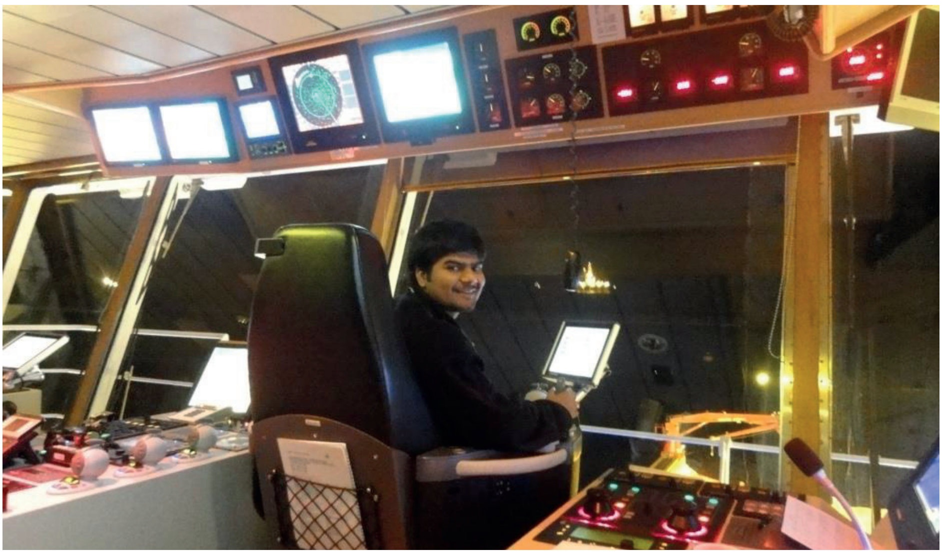

Figure 3.20: Offshore field observation from Far Sapphire

The visit summary was documented in a visit report (Gunnu, 2011). Furthermore, the knowledge gained from the field observations has been used for identifying critical hazard scenarios. The visit helped in identifying key hazards and risk-influencing factors related to anchor handling and rig move operations.

Discussion with AHO experts

When observing on board the Far Sapphire, the Ph.D. candidate also had an opportunity to discuss various hazard scenarios and risk factors associated with these operations with vessel masters, chief officers and chief engineers. Moreover, interaction with experts from Farstad (vessel's master) and Global Maritime (field surveyors, experts in rig move procedures and vessel masters with experience on AHVs) was very useful. During the anchor handling and a rig move operations seminar in Stavanger on 6-7 November 2014, Ph.D. candidate had an opportunity to communicate with experts from key stakeholders such as statutory bodies, operators, builders, consultancies, insurance companies, equipment suppliers, ship owners, and charters.

3.4.5. Hazards in AHOs

The accident reports and documents related to the Bourbon Dolphin and Stevpris accidents are reviewed. Moreover, expert opinions and state-of-the-art are used for the identification of potential hazards in AHOs. The following hazards can occur during anchor handling or supply operations:

- Dropped objects;
- Collision;
- Large static heeling angle;
- Breakdown in communication and equipment failure;
- Working on deck / or over side;
- Over-stressing equipment;
- High breakout loads;
- Vessels unable to hold position and /or heading;
- Large vessel handling (manoeuvring) forces in the transverse direction;
- Large weather forces in the transverse direction;
- Higher mooring line tension and a large angle of attack;
- Survey equipment not working, ready or setup properly;
- Entanglement of wires with vessels;
- Excessive movements of crane assemblies;
- Failure to follow procedures;
- Unable to maintain required tension.

3.4.6. Critical human actions and decisions in AHOs

During the process of AHOs, human actions can be listed in the following categories:

- Actions related to planning prior to an initiating event;
- Actions that might cause initiating events;
- Actions taken to ameliorate various accident scenarios;
- Actions that exacerbate various accident scenarios;
- Recovery actions.

3.5. Risk assessment of AHVs in AHOs

The possible hazards in AHOs are described in Section 3.4. The risk associated with AHVs is distinguished into two different modes: operational and occupational. The operational risk affects the safety of the vessel and equipment and therefore the vessel's crew, whereas the occupational risk affects the crew working on deck. Bye and Lamvik (2007) emphasize the relationship between subjective risk perception and individuals' adaption for offshore service vessels in the North Sea. Geving *et al*. (2007) and Hansen and Holmen (2011) studied physical activity level and sleep disturbance among offshore fleet workers. They found that shift work, the quality of sleep and physiological ability to perform are limiting factors for the safety of offshore operations. Hansson (2003) has developed a risk analysis model that can be used for decision support in the process of selecting the most relevant risk-reducing measures. In this section, potential risk-influencing factors related to hazards such as a large static heeling angle and vessel unable to hold position and/or direction are studied. These factors can provide an overview of the development of a hazardous event.

3.5.1. Risk assessment practices in the industry

The marine safety forum has developed a risk assessment for relocation operations of mobile offshore units (MOUs) by considering a step change in the Safety Task Risk Assessment Guide (MSF, 2011). The present practice in the industry is that, prior to the AHO, a meeting is held with all the relevant stakeholders. HAZID or HAZOP analysis is performed to identify hazards in the AHO and apply control measures in the planning phase to achieve operational safety. In addition, a pre-operation briefing is held with the vessel's crew before the operation starts. The significance of these meetings is to identify potentially high-risk operations and to establish a safe working procedure and corresponding instructions. Moreover, before the operation is about to commence, the vessel master or chief officer should perform a Safe Job Analysis (SJA) and stability calculations, which should be verified by the oil company representatives. In addition, the risks are communicated to the involved personnel. An example of risk assessment for AHOs is provided in MSF (2011). Due to the nature of AHOs, the involved personnel must be familiar with all aspects of such operations, guidelines and procedures, and equipment (see Appendix B). In addition, they should have sufficient qualification and experience.

3.5.2. Bourbon Dolphin accident analysis

The official report of the Bourbon Dolphin accident (2008) reveals that the accident did not occur only because of a coincidence of independent technical and human errors. Rather, it was due to a systematic change in the organizational behaviour of the operators, which was influenced by economic pressure in a strongly competitive environment. Various stakeholders, such as operators, shipyards, and regulatory and governmental bodies, in their respective roles are very often involved in a sequence of events leading to an accident. Possible errors made by the vessel operators are the final acts in a long and complex chain of organizational and systematic errors (i.e., the so-called latent factors).

The risk-influencing factors related to anchor handling can be identified by studying accidents and incidents related to these operations. The complete risk associated with these operations can be estimated by considering all influential factors and interactions between them. A systematic risk analysis must include effects such as interactions and decisions taken by involved stakeholders associated with the operations, the workspace, and economic pressure due to a delay in operations. For this purpose, the Bourbon Dolphin accident (2008) is analysed by considering different methods.

Failure of a barrier in the chain of events

A chain of events, often called the event sequence, is a term referring to the concept of contributing factors that typically lead to catastrophic accidents, as illustrated in Figure 3.21. This figure shows that there are two types of technical safeguards (or barriers) with respect to accident prevention and mitigation. The first one prevents an accident from occurring by reducing the probability (or frequency) of its occurrence. Similarly, the second one mitigates the effect of accidents by reducing the consequence(s) of it.

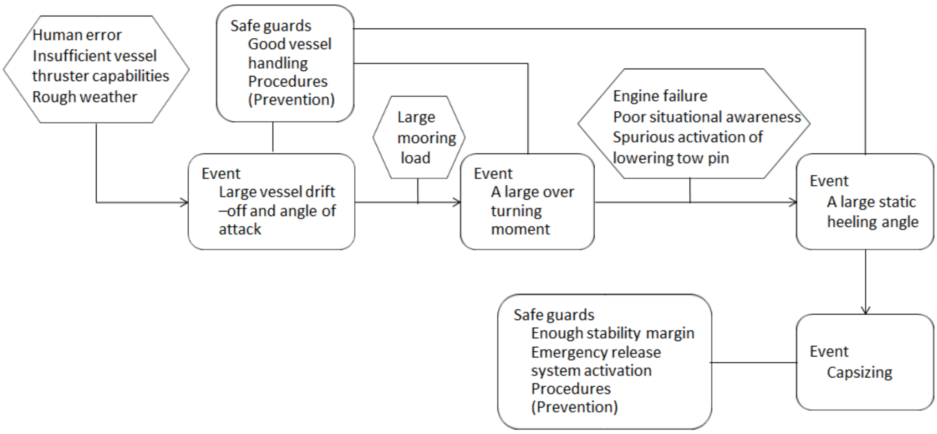

Figure 3.21: Chain of events relating to the Bourbon Dolphin vessel capsizing

Fault tree diagram for drift-off

A fault tree model for vessel horizontal behaviour is shown in Figure 3.22; the model is used for identifying the basic events related to vessel drift-off (initiating event; see Figure 3.21).

Influence diagram of AHVs capsizing in AHOs

An influence diagram for AHVs capsizing during the operational phase is shown in Figure 3.23. The influencing factors related to the Bourbon Dolphin accident and interactions between them are considered in this diagram. In addition, other factors identified from the state-of-the-art are included. This diagram illustrates how hazardous events or states can develop and interact with each other before vessel capsizing can occur. Moreover, this diagram covers interactions from the direct person-system interface at a lower level to a remote regulatory level through an organization at the upper level. This diagram is also used for identifying critical factors that are addressed to improve the safety of the AHV during AHOs.

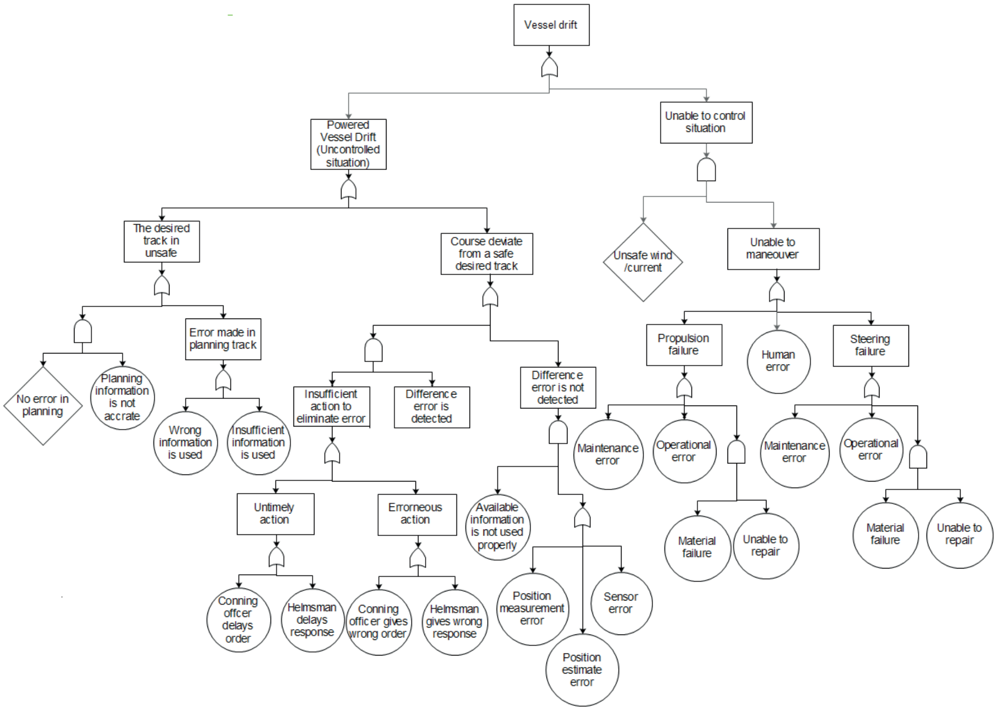

Figure 3.22: Fault tree for vessel drift-off

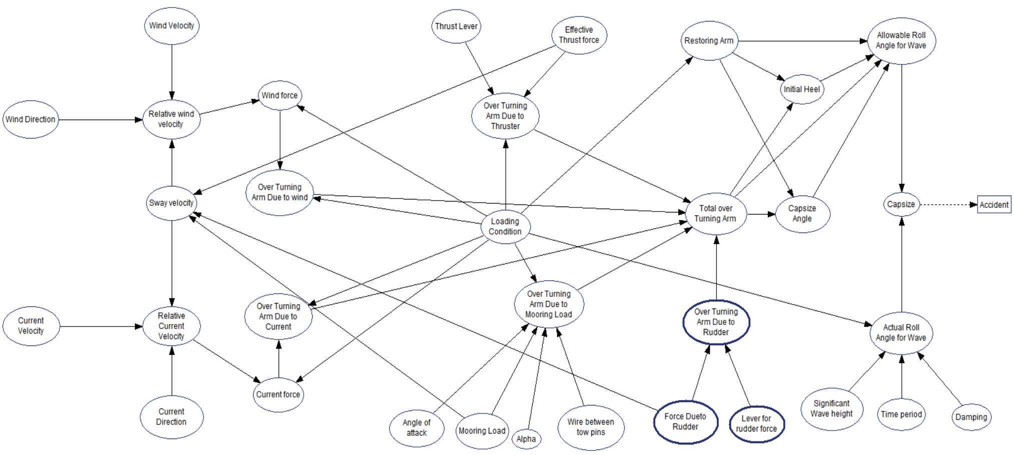

Figure 3.23: Influence diagram related to the AHV capsizing event

Conceptual model of human and organizational factors

A conceptual model of human and organizational factors for the AHV during operation is established and shown in Figure 3.24. This figure was developed based on the Ren *et al.* (2008) model.

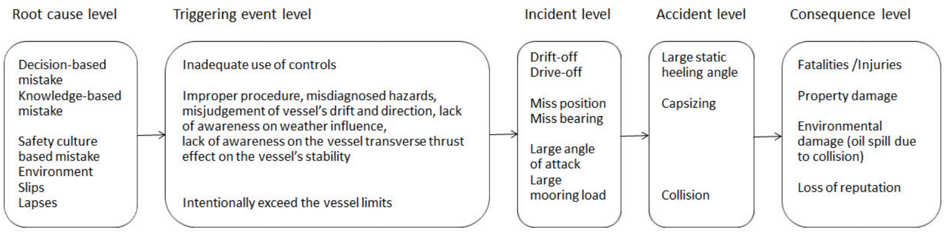

Figure 3.24: Conceptual model for human and organizational factors

3.5.3. Risk-influencing factors in AHOs

Operational safety and efficiency are affected by risk-influencing factors. Hence, it is essential to study the risk-influencing factors during AHOs, which are primarily identified using two methods. The first method is a substantial literature survey comprising technical journals, conference proceedings, design codes and guidelines, operators' manuals, incident and accident reports, procedures and manufacturer data. The second method is to gather data by consulting experts' opinions in the industry. Therefore, a potentially critical operational phase and associated hazards in AHOs are described in Section 3.4 and are identified by considering the methods described in Section 3.4.4. Then, the risk-influencing factors related to AHV capsizing and drift-off in AHOs are identified by evaluating the Bourbon Dolphin accident as a case study and are presented in Section 3.5.2. Finally, a generic model is developed to address the risk-influencing factors related to the capsizing of AHVs in AHOs (Article CP1 in Appendix A). This model is used to address the risk-influencing factors experienced during the Bourbon Dolphin accident (Article CP1 in Appendix A).

One of the primary influential factors related to the operation is high tension in the mooring line. This force causes a large heeling moment and high astern and transverse vessel motion. Moreover, these vessel motions can occur due to a high hauling speed on the anchoring winches and due to entire or partial loss of the vessel's own bollard pull. The loss of bollard pull causes the vessel to be pulled astern. At the same time, the losses of thrust force on the vessel's own propellers or fatal rudder position result in a vessel rotation, which leads to a considerable increase in transverse force and moment. In addition to the above factors, environmental conditions such as wind, waves and current influence operational safety and efficiency. The common causes behind the factors listed below are either the lack or inadequacy of human and organizational factors:

- Experience;
- Knowledge;
- Planning;
- Risk assessment;
- Communication;
- Team work;
- Awareness.

3.6. Root causes of the Bourbon Dolphin accident

The critical events and associated root causes of the Bourbon Dolphin accident are identified with the help of reviewing the official report of the accident (2008) and expert opinions. These events are the static heeling angle (initial heeling angle) and drift-off of the vessel.

3.6.1. Root causes in vessel capsizing

The stability of an AHV during anchor deployment or recovery is a complex subject. The stability is primarily dependent on vessel design, environmental conditions and forces acting on it. Unfortunately, no consistent method has yet been developed to maintain stability due to the complexity of dynamic forces involved in capsizing. The causes related to capsizing are listed below:

- Critical stability;
- Force due to heavy sea and high wind;
- Cargo shift (particularly deck cargo if lashing is not effective);
- Human factors such as lack of awareness and risk-taking behaviour;
- Organizational influence;
- External heeling moment due to wind load and mooring load;
- Cargo and ballast operation.

From a vessel stability point of view, it is essential to identify critical influencing factors during the operational phase.

3.6.2. Vessel drift

From a vessel stability point of view, the critical parameters are the magnitude of the mooring load, angle of attack (the angle between the mooring line and the vessel centreline), and angle between the mooring line and vertical axis. Vessel drift has been considered a major influencing parameter in the Bourbon Dolphin accident. Vessel characteristics, such as vessel behaviour in the horizontal plane, and operational aspects, such as basic anchor handling skills, have a significant influence on vessel position and bearing. Figure 3.25 shows the possible scenarios related to vessel drifting. The drifting scenarios occur in either a powered or disabled condition.

Drifting in powered condition (in which vessel drifts under power)

This drifting occurs when the vessel is off course and/or position, usually due to poor vessel handling skills.

Drifting in disabled condition (in which vessel is disabled)

This condition usually occurs due to technical failure along with the influence of wind and waves. Deviation in vessel drift-off and bearing can occur for the following reasons:

- Adverse weather, engine failure (vessel block out), thruster failure, and propeller failure;
- Operating in adverse weather conditions due to unreliable weather forecast and/or economic pressure;
- Delay in implementing appropriate vessel handling;
- Failures associated with vessel handling equipment;

- Operating in an environment beyond the vessel handling limitations.

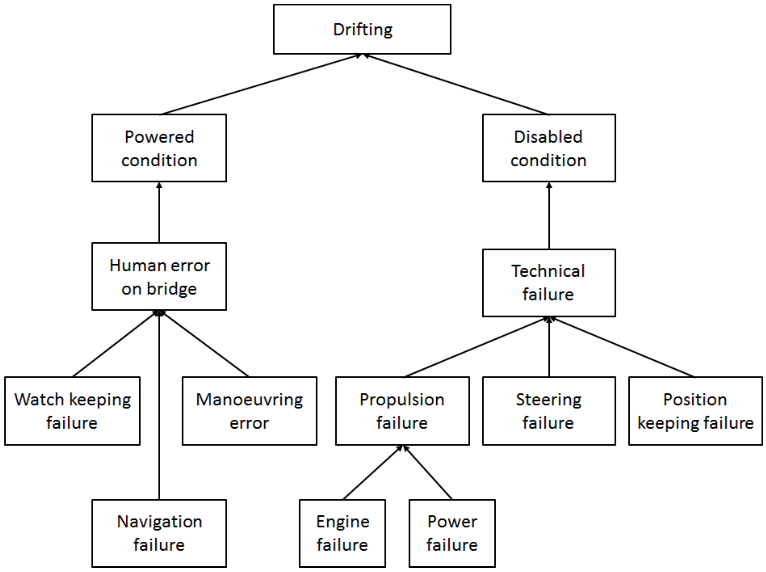

Figure 3.25: Main causes of drifting

Each of the abovementioned reasons further depends on other reasons. The reasons for a delay in implementing appropriate vessel handling and for failures associated with vessel handling equipment are described below.

Delay in implementing appropriate vessel handling

The reason behind delayed action can be delayed orders or response. A lack of situational awareness or carelessness can be a reason for a delayed order. Such hazards can be reduced by improving operator knowledge with the help of training. Limitations on system behaviour can cause a delayed response. This problem can be overcome by improving the capacity of associated vessel-handling equipment.

Failure associated with vessel handling equipment

The vessel thus has insufficient vessel handling capacity to control the vessel position and vessel heading. This situation can be avoided by either minimizing common cause failures or improving the redundancy level associated with vessel handling equipment.

3.6.3. Vessel static heeling angle

A larger static heeling angle is one of the reasons behind the Bourbon Dolphin capsizing. In recent years, there have been several discussions about the mechanics of vessel stability and capsizing. Recently, concerning structures and stability, Sano *et al*. (2012) have stated the requirements of the classification society and regulatory bodies for AHVs. The requirements primarily address the following:

- Side structure and work deck reinforcement;
- Anchor handling and towing gear;

- Static bollard pull and guidance for bollard pull test procedure;
- Stability criteria for AHOs.

Vessel capsizing in the intact condition occurs due to several causes. The effects of severe wave, wind, and mooring load can cause the vessel to heel over large angles and reduce the capsizing angle. The capsizing angle, depending on a particular case, could be the second intercept between the wind-heeling lever and GZ curve or be an obituary limiting angle, e.g., the deck submergence angle or the progress of the down flooding angle. The vessels resist capsizing through their inherent righting energy and their ability to dissipate energy by capsizing. The capsizing moment is affected by the mooring load, liquid cargo and environmental factors such as wind and wave forces and water on deck. Laranjinha *et al.* (2002) described the influence of the water on deck on the dynamic behaviour of an offshore supply vessel with a large open aft deck. It is shown that the water on deck has a significant influence on vessel roll motion; e.g., it increases the natural roll behaviour. Nilsson (2009) stated that when the vessel is subjected to beam waves, beam current and wind cause a higher heeling angle with respect to other directions. The direct and indirect causes in the Bourbon Dolphin accident that led to the larger vessel's static heeling angle are listed below:

Direct causes

- External forces from weather and current;
- Unfavourable heading of the vessel in relation to external forces;
- Machinery black out and the consequent reduction of manoeuvrability;
- Lowering the towing pin, which led to larger angle of attack;
- Loading condition and vessel stability characteristics.

Indirect causes

- Weakness in vessel design;
- Failure of systems engaged in operations.

From a stability point of view, important influencing parameters are the magnitude of the mooring load, angle of attack (the angle between the mooring line and vessel centreline), and angle between the mooring line and vertical axis. The vessel static heeling angle and capsizing angle depends on the righting moment and heeling moment (coming from the mooring parameters, current parameters and thrusters). For a given set of influencing parameters, there are fixed static heeling and capsizing angles. However, during the operation, variation in the heeling moment occurs due to variation in the influencing parameters, which leads to variation in the vessel's static heeling and capsizing angles. From a stability perspective, the vessel is safe if the vessel's actual roll angles in waves are within the limits of the allowable roll angle per the modified weather criterion.

3.7. Strategies for improving human performance

The critical components for AHV stability are classified into two categories: controllable (inside) and uncontrollable (outside) factors. Examples of controllable factors are human error and incompetent crew, whereas examples of uncontrollable factors are excessive waves, wind, current, natural hazards, and adverse environmental conditions.

According to Khamidi and Kurian (2012), the effect of inside factors can be reduced by executing the following strategies:

- Train the crew regularly to maintain their skills;
- Hire certified and capable crew;
- Employ competent crew with certifications;
- Highly supervise the crew during the operational phase.

Similarly, the effect of outside factors can be reduced by executing the following strategies:

- Conduct analysis to identify the maximum mooring load in operational conditions (by considering the dynamic effect factor to be 1.4);
- Ensure the vessel can perform the operation safely when it is subjected to the mooring load when operating in adverse weather conditions;
- Perform visual inspection of parameters such as the angle of attack and mooring tension;
- Change the vessel's heading;
- Change the vessel's thrust.

3.8. Findings and recommendations

In conclusion, the Bourbon Dolphin accident analysis facilitates understanding of the root causes and interactions between them. To improve the safety level, the following aspects should be addressed:

- Design errors;
- Poor planning and risk analysis;
- Lack of situational awareness concerning the development of the large vessel drift-off and static heeling angle;
- Lack of awareness of the effect of influencing factors on the vessel static heeling angle and stability margin;
- Lack of experience and skills in vessel handling when maintaining the balance between the vessel drift-off and static heeling angle;
- Delay in identifying corrective actions due to poor situational awareness;
- Communication gap amongst the crew;
- Human behavioural factors such as shortcuts, negligence, taking chances, working environment / work load, allowing frustrated actions and procedural errors;
- Improper training and planning.

As described in Section 3.3, among the possible vessel accident categories, capsizing is a major concern. Capsizing is a catastrophic phenomenon that can cause death to the personnel on board. It is therefore considered an accident scenario in this research work. The conclusion from the study by Gunnu *et al*. (2010) (Article CP1 in Appendix A) is that the risk of vessel capsizing can be reduced or mitigated. The following measures would either prevent accidents or reduce the risk of accidents during different phases of the operation:

- Design phase: Designing the vessel with a sufficient stability margin;

- Analysis phase: Conduct an appropriate operational risk assessment by assessing the vessel stability and positioning capability;
- Planning phase: Define risk mitigation strategies and action plans for when the vessel is operating in critical situations;
- Execution phase: Provide situational awareness on vessel stability status (stability margin with respect to criticality) and assist in reducing the overturning moment in terms of control measures (heading, transverse thrust and mooring line tension).

However, the AHV capsizing phenomenon depends on the overturning moment the vessel is subjected to, which in turn primarily depends on the magnitude of the mooring load, the angle of attack and the transverse thrust component. Typically, the vessel transverse thrust is applied to maintain vessel position and heading in line with the desired position and direction. Therefore, a methodology is proposed in Chapter 4 for assessing AHV behaviour in the horizontal plane. Furthermore, the next chapter presents positioning capability criteria, stability criteria, a condition monitoring system and a decision support system.

Chapter 4

Methodology for enhancing safety with respect to the stability of AHVs in AHOs

The first part presents an introduction and research questions addressed in this chapter. The second part of this chapter focusses on vessel drift-off, angle of attack, and stability. Moreover, it presents proposed positioning capability criteria and stability criteria. An investigation of these criteria is presented together with a case study. The third part presents a framework used for the condition monitoring system and the decision support system. The final part of this chapter presents the research contributions and the summary.

4.1. Introduction

The hazards in AHOs are summarized in Section 3.4. The key sequences of the events related to the Bourbon Dolphin accident are described in Article JP1 (see Appendix A). They are the vessel drift-off (with respect to the desired mooring line track), a large angle of attack (β), a large overturning moment, a large initial heeling angle (or static heeling angle) and capsizing. These event sequences (or progress) can be prevented or mitigated by strengthening existing safety barriers and providing additional safety barriers. To strengthen these barriers, a better vessel design, robust positioning capability and stability criteria, a suitable operational limit state, effective operational planning, better situational awareness, a decision support system, effective crew training, and statutory requirements are required.

However, suitable position capability and stability criteria are lacking for assessing vessel positioning capability and stability in AHOs. To address this drawback, such criteria and procedures are proposed in this chapter. Then, two frameworks are established to model the condition monitoring system and decision support system, which are useful in assisting the vessel's master in terms of situational awareness and an effective control strategy.

This chapter hence addresses the proposed criteria, methods and frameworks that are required to enhance safety, with emphasis on the positioning capability and stability of AHVs in AHOs.

4.2. Approaches for improving safety

In this chapter, various approaches are proposed that can be used for establishing operational criteria and statutory requirements, a better vessel design, operational planning, better vessel selection, execution, crew training and assisting key stakeholders in the decision-making process to improve the safety of the operation as a whole. These approaches are listed below:

- Stability and positioning capability criteria: In the design phase, the designer should consider vessel stability and positioning capability limitations for a designed load. Moreover, these limitations should be documented in the procedures and guidelines. This information is helpful in assisting better decision-making in later phases. However, to assess the above limitations, suitable criteria are needed. These criteria are established in this chapter: the critical static heeling angle, critical rolling angle and positioning capability criterion. The details of these criteria were discussed in Articles JP1 and JP4 (see Appendix A).
- Stability, drift-off and angle β assessment: In the analysis and planning phase, it is essential to assess vessel stability and drift-off to define the allowable limits in terms of environmental parameters and/or allowable operational loads in the operating manual. However, to assess the abovementioned allowable limits, suitable methods are needed. These methods are established in this chapter. The details of these methods were discussed in Articles CP2, CP3 and JP1 (see Appendix A).
- Condition monitoring system: During the operation phase, by applying correct decisions at the right time, the operation can be prevented from moving from a safe (or normal) condition to an intermediate phase. However, to assess the vessel stability margin during operation, a condition-monitoring system is required. Such a system is proposed in this chapter. The details can be found in Article JP2 (see Appendix A).
- Decision support system: During the operation phase, decisions are made by the vessel master to mitigate operation movement towards unsafe conditions. Typically, by making an appropriate decision, the operation can be brought back to a safe condition. However, to aid the vessel master in the decision-making process, a DSS is required. Such a DSS is proposed in this chapter. The details can be found in Article JP3 (see Appendix A).

4.3. Research questions for enhancing the safety of AHVs in AHOs

This chapter focusses on the following research questions:

- RQ2: How quickly can a larger angle of attack be developed?
- RQ3: Does the vessel have sufficient positioning capability during AHOs?
- RQ4: Are there any stability criteria that can be used in the design and analysis phase for assessing vessel stability in AHOs? If not, how can vessel stability be improved?
- RQ5: How can operational limit state criteria be developed?
- RQ6: How can the situational awareness of vessel stability during the operation be improved?

- RQ7: How can capsizing be mitigated when the vessel moves towards a dangerous zone?

4.4. Vessel drift-off assessment in AHOs

This section addresses the research question (RQ2) that involves assessing vessel behaviour in the horizontal plane (such as drift-off and angle β) during AHOs. As described in Section 3.6, vessel drift-off and a large angle β were the sequence of initiating events in the Bourbon Dolphin accident. During this accident, the current velocity increased significantly to more than the allowable limit as documented in the rig move procedure. Thus, the current force of the mooring line and hull increased significantly. Then, the vessel started drift-off away from the desired path and direction. Vessel stability assessment (Article JP1 in Appendix A) reveals that the angle β and the transverse thrust force component are significant contributing factors to the vessel's list before capsizing. Even the small magnitude of the mooring load can be critical when the vessel is subjected to a large angle β. Therefore, it is crucial to prevent or mitigate drift-off and a larger angle β during AHOs when the vessel is subjected to large environmental loads and mooring loads. Here, the angle β is a function of the vessel position and heading with respect to the rig. To assess vessel drift-off and change in vessel heading in AHOs, a methodology is required. Such a methodology is proposed in Section 4.4.1.

4.4.1. Simulation approach

Typically, during AHOs, the mooring load induced by the mooring line and the environmental forces induced by the wind, swells, waves and current act on the vessel. The total force exerted by the mooring line and the environment can be resolved into three components. The longitudinal component can either pull the vessel backward or push the vessel forward. The transverse component exerted on the ship hull drifts the vessel away from the track and heading. Thus, the vessel can be subjected to motions in the horizontal plane: surge, sway and yaw.

During the anchor deployment or recovery phase, the environment exerts environmental loads on all parts of the hull. For example, the wind exerts a drag force on the hull (above the waterline), the current exerts drag forces on the hull (below the waterline) and mooring line, and waves exert first- and second-order forces on the hull (below the waterline), all of which result in vessel drift-off from the current position and heading. Vessel drift-off is expressed as three horizontal modes of dynamic motions: surge, sway and yaw. These motions are controlled via the intervention of propellers, rudders and thrusters.

The Bourbon Dolphin accident report reveals that a larger current field existed during the operation. Thus, the vessel was affected by the larger drag force. Therefore, the AHV behaviour in the horizontal plane was studied when it was operating in the uniform current field while subjected to the mooring load. Typically, vessel position and heading are controlled by using the thrusters and propellers. Therefore, the vessel drift-off and angle β depend on the available thruster power configuration. Hence, it is essential to study the vessel drift-off and angle β variations for various power configurations.

Time-domain simulations were performed to estimate vessel drift-off and angle β relative to vessel initial position and direction. The most relevant influencing parameters considered in the model are shown in Figure 4.1. In the analysis, a typical AHO has been divided into several sub-operations with a time interval of approximately 30 mins. Each of the simulations was performed by considering a run time of approximately 30 mins. In real-time operations, there is typically a continuous intervention by the vessel master to execute control actions. The interventions depend on the master's skill, experience and knowledge. Thus, interventions vary from person to person. Moreover, each operation is different from the others. Therefore, in this study, instead of considering the vessel master's continuous intervention, a single intervention is considered. Indeed, it is represented as a change in control force and/or moment. This approach is used for assessing the vessel behaviour in the horizontal plane. A similar approach can be used in equipment failure. Nevertheless, this approach qualitatively covers the effect of human intervention or equipment failure. The detailed analysis procedure is described in Article CP3 (see Appendix A).

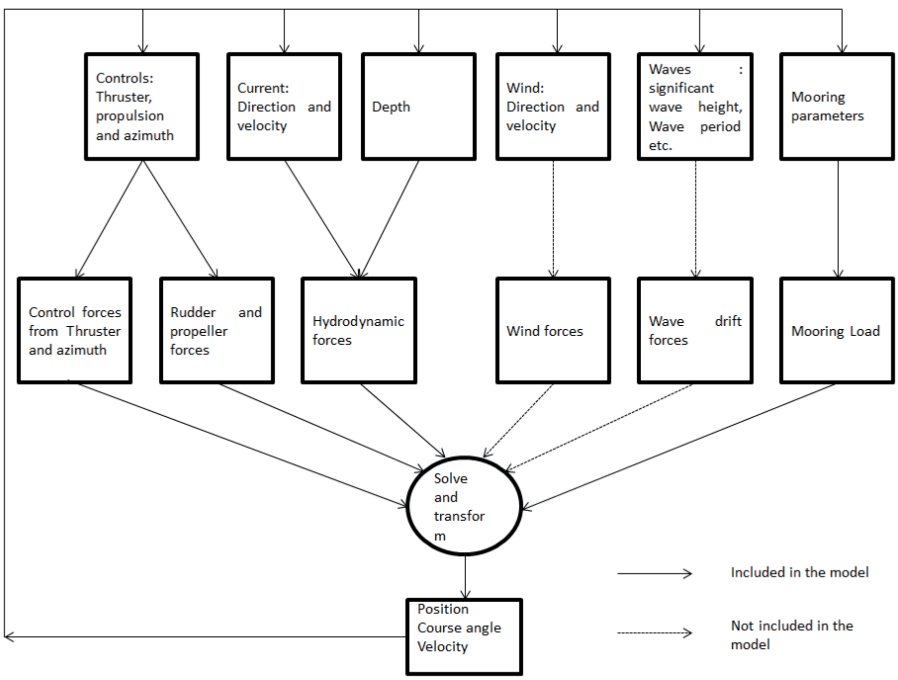

Figure 4.1: Ship, environment and control model during anchor handling operation

4.4.2. Case study

A case study was performed on the Bourbon Dolphin in the North Sea environment for a uniform current field. The parametric study was performed by considering the horizontal distance between the two ends of the chain (D), the angle between the mooring load and the vertical axis (α) for fixed parameters, such as vessel heading, and the current direction and velocity. For this purpose, the current magnitude was considered from 0.5 m/sec to

1.5 m/sec. The angle α was considered from 20 to 60 deg. The distance D was varied from 400 to 1600 m by keeping the same chain shape (i.e., the same α). Moreover, the analyses were performed for the following three failure modes:

- Resultant force due to the thrusters in the transverse direction (sway) is zero;
- Resultant moment due to the thrusters in the horizontal plane (yaw) is zero;
- Both resultant force and moment due to the thrusters are zero.

4.4.3. Key findings

The main contributions of this study were published in Article CP3 (see Appendix A). The results from the analyses illustrate how rapidly the angle β changes for various thruster capacities and for different current headings. The following findings are drawn from the analyses:

- The effective thrust force in the sway direction is important for minimizing the vessel drift-off and angle β;
- The angle β increases quite rapidly when the vessel is moving away from the rig;
- The angle β decreases with decreasing angle α;
- The vessel drift-off decreases with decreases in the distance D and angle α;
- The vessel drift-off and the angle β increase with increasing delay in action (time taken to execute action);
- Large angle β and drift-off occur when the current is from the quartering and beam directions, respectively;
- The current coming from the stern direction is more critical than the current coming from the bow direction.

This study is useful in increasing knowledge of the overall effect of the mooring load, current velocity and direction, and control forces and moment on vessel drift-off and angle β in AHOs.

4.5. Proposed positioning capability criteria

Vessel position control in the horizontal plane depends on the available thruster power configuration and vessel characteristics in the horizontal plane. To prevent large drift-off and angle β, it is essential to have an awareness of the vessel positioning capability. It appears that until now, less importance has been given to the assessment of vessel positioning capability, which is highly relevant in controlling vessel drift-off and angle β. The possible consequences of ignoring it can lead to an accident such as the Bourbon Dolphin. If there had been an industry practice concerning vessel positioning capability assessment, the Bourbon Dolphin accident would not have occurred; instead, the operation might have been delayed until fair weather. Therefore, it is essential to understand the vessel positioning capability before commencing the operation.

This section addresses the research question (RQ3) for studying whether vessels have sufficient capability for carrying out safer operations. This section further covers the positioning capability of AHVs when performing operations in deep waters. The following criteria are used in the industry when selecting AHVs for deep-water AHOs:

- Bollard pull;

- Winch capacity;
- Deck storage space;
- Anchor handling or towing winch space.

In terms of vessel positioning, capacity can be understood through thrust utilization plots. Therefore, in this study, thrust utilization plots were established for AHVs. A case study was conducted on the Bourbon Dolphin to establish thrust utilization plots for both operational and accident conditions. These plots are helpful in selecting vessels in the planning phase and defining vessel-specific limitations before commencing operations.

4.5.1. Framework

Thrust utilization plots are extensively used in vessel dynamic positioning assessment for identifying the allowable environmental parameters. The results are usually presented in the form of capability plots, which are represented in polar diagrams (IMCA, 2000). In the present research work, a new concept has been introduced for AHVs for conducting safe AHOs. A flow chart for the proposed method is shown in Figure 4.2. The details of this methodology are described in Article JP4 (see Appendix A).

4.5.2. Case study

As stated in the above section, control forces have a significant effect on achieving functional and safety requirements. Therefore, the importance of the thrust utilization plots for preventing large vessel drift-off motion during AHOs is explained by evaluating the Bourbon Dolphin as a case study. In this study, these plots are established for both normal and accident conditions by considering the respective environmental parameters (see Article JP4 in Appendix A). Furthermore, the linear shear profile and Ormen Lange current profile are considered.

4.5.3. Key findings

The main contributions of this study were published in Article JP4. As described in 0, drift-off and angle β have a significant effect on vessel safety. The Bourbon Dolphin accident report reveals that vessel drift-off was an initial event in the accident, which should have been prevented. Therefore, there is a need to establish a method to quantify the positioning capability of an anchor-handling vessel during the operational phase. Such a method is addressed in this section. The key findings are as follows:

- The results representing current loads are the most important loads in the Bourbon Dolphin accident. The contribution of the current loads (together with the current induced mooring loads) in the lateral direction is up to 69% of the total lateral loads acting on the vessel.
- The current profile has a significant influence on the mooring line loads. In the regions in which the wind driven current is dominant, the current loads on the mooring line can be neglected. In the regions in which a characteristic current profile exists, the current load on the mooring line should be considered, for instance, in the regions of the Ormen Lange field in Norwegian waters.
- The thrust-utilization plot was recognized as important in demonstrating the most critical weather direction. Predicted results show that the most unfavourable

weather direction during the accident event is 290° due to the insufficient lateral positioning capability.

- During the deployment of a very long mooring line, the limitation might come from the available propeller thrust. This limitation occurs for two reasons: the heavy mooring weight and the effectiveness of the bollard pull (after applying deduction).

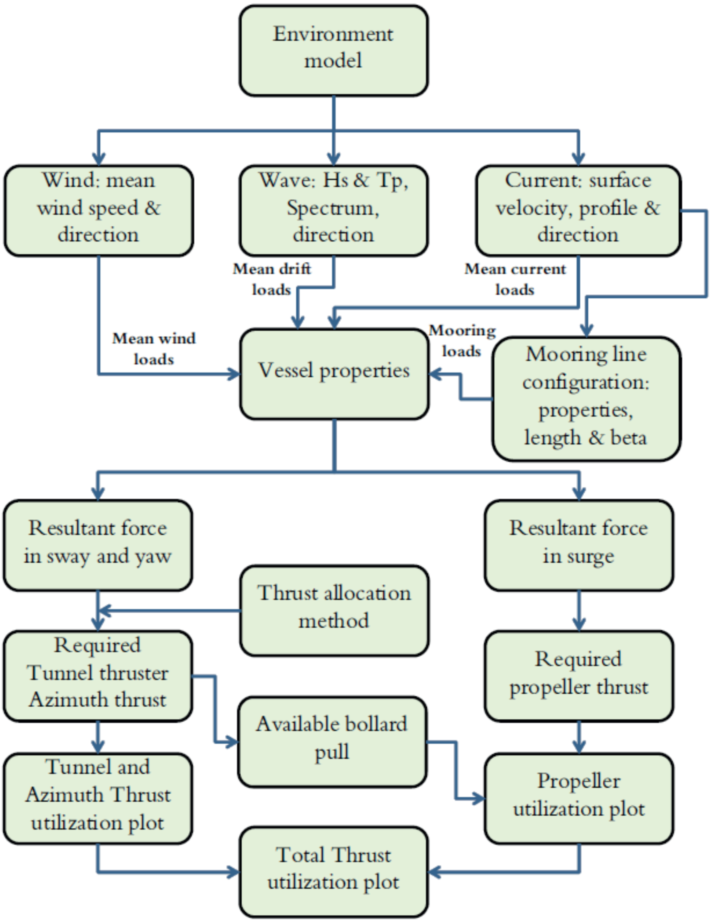

Figure 4.2: Flow chart for the proposed method

4.6. Review of existing stability criteria

The major historical work on the stability of ships was studied by Rahola in 1939. Rahola's work involved a detailed analysis of the Baltic ship capsize and included a proposal for a GZ-based criterion. Based on recommendations from the 1960 International Conference on the Safety of Life at Sea (SOLAS 60), the IMCO subcommittee on Subdivision and Stability was formed in 1962. The first international stability criterion, Resolution A.167, largely based on Rahola's GZ criterion, was adopted by the IMO in 1968 for ships under 100 m. The IMO assembly adopted Resolution A.562 in 1985. This resolution is an energy balance criterion but also includes a wind heel recommendation and is to be used as a supplement to A.167. This section describes widely used existing stability criteria and recommendations for assessing AHV stability. These criteria and recommendations are the IMO A 167 Intact Stability Criteria, IMO 749 Intact Stability Criteria for Non-Passenger Ships, IMO Severe Wind and Weather Criteria, IMO A 469 Intact Stability Criteria for Offshore Supply Vessels and NMD recommendations after the Bourbon Dolphin accident.

4.6.1. IMO A 167 Intact Stability Criteria

These criteria are developed based on the righting arm (GZ) or quasi-dynamic stability method. The statistical stability criteria are originally included in resolutions A.167 (ES.IV) and A.168 (ES.IV). They are developed because of the discussions conducted in several sessions of the subcommittee on Subdivision and Stability Problems (STAB), a forerunner of the SLF subcommittee and the Working Group on Intact Stability (IS). Ships that come under the IMO A 167 Intact Stability Criteria should satisfy the criteria shown in Figure 4.3. There was general agreement that the criteria must be developed based on the statistical analysis of stability parameters of ships that had suffered casualties and ships that were operating safely. Detailed discussions of the work of these IMO bodies and of the method used in the development of stability standards were reported in the following papers: Nadeinski and Jens (1968) and Thomson and Tope (1970), to which reference is made. The IMO intact stability criteria are listed below:

- A- area under the GZ curve up to 30 deg. > 0.055;
- B- area under the GZ curve up to 40 deg. or down flooding angle > 0.09;
- C- area under the GZ curve between 30 and 40 deg. or down flooding angle > 0.03;
- E- maximum GZ to be at least 0.20 m at 30 deg. or above;
- F- initial GM to be at least 0.15 m;
- Maximum GZ to be at an angle > 25 deg.

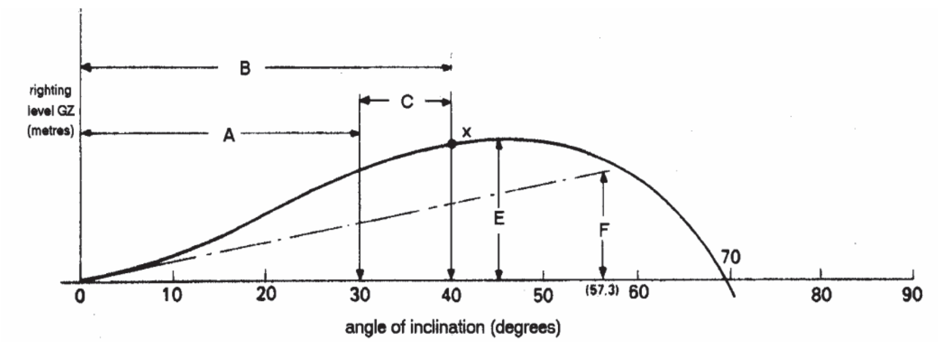

Figure 4.3: Intact stability criteria

4.6.2. IMO A 469 Intact Stability Criteria for Offshore Supply Vessels

Prior to the Bourbon Dolphin accident, there were no special rules for AHVs. Moreover, in accordance with the IS Code (IMO, 2008), the weather criterion is not mandatory for AHVs in operation mode. Thus, in practice, AHV stability is treated similarly to OSV stability in transport mode. The ship-specific rules associated with the OSVs are covered by the IMO (2007) Guidelines for the Design and Construction of Offshore Supply Vessels. The intact stability criteria for supply vessels are listed below:

- The area under the curve of the righting lever (GZ) should not be less than 0.070 m-rad. up to an angle of 15 deg. where the maximum righting lever occurs at 15 deg. and 0.0555 m-rad. up to an angle where the maximum righting lever (GZ) occurs at 30 deg. or above.
- When the maximum righting lever occurs at an angle of heel between 15 deg. and 30 deg., the area under the curve of the righting levers (GZ) up to the angle of maximum righting lever (θ_{max}) should be determined using a formula. Area (m-rad.) $= 0.055 + 0.001 \times (30 - \theta_{max})$.
- The area under the curve of the righting lever between 30 and 40 deg. angle of heel or between 30 deg. and θ_f, if θ_f is less than 40 deg., should not be less than 0.030 m-rad., where θ_f is the angle of heel at which the lower edge of any openings in the hull, superstructure or deck houses that cannot be closed watertight is immersed.
- The righting lever (GZ) should be at least 0.20 m at an angle of heel equal to or greater than 30 deg.
- The maximum righting lever shall occur at an angle of heel not less than 15 deg.
- The initial transverse metacentric height (GM) shall not be less than 0.15 m.

4.6.3. IMO Severe Wind and Weather Criteria

The weather criterion evaluates the ability of the vessel to withstand the combined effect of beam wind and waves. It is developed based on the energy balance method (IMO, 2009, 1985), which is that restoring energy must be equal to or greater than the capsizing energy. Integration of the righting arm curve is interpreted to represent the righting or restoring energy. An example of an energy balance criterion is IMO resolution A.562. This criterion is recommended for all ships over 75 m and was approved by the IMO in 1985. However, it does not apply to special-purpose ships such as AHVs. The details of these criteria were discussed in Article CP2 (see Appendix A).

4.6.4. IMO 749 Intact Stability Criteria for Non-Passenger Ships

This criterion is nothing but a combination of the intact stability criteria and weather criteria and is applicable to non-passenger ships. The criteria are as follows:

- Area under GZ curve up to 30 deg. > 0.055;
- Area under GZ curve from 30 to 40 deg. or down flooding angle > 0.03;
- Area under GZ curve up to 40 deg. or down flooding angle > 0.09;
- Initial GM to be at least 0.15 m;
- GZ to be at least 0.20 m at an angle > 30 deg.;
- Max GZ to be at an angle > 30 deg.;
- IMO Weather Criterion (Maximum initial angle of heel);

- IMO Weather Criterion (Areas).

4.6.5. NMD recommendations after the Bourbon Dolphin accident

Major disasters motivate authorities to introduce and upgrade regulations. For example, the Bourbon Dolphin disaster led to improvement in AHV stability rules and regulations. Because of this accident, after consultation with the industry, shipmasters, and the Director General of Shipping and Navigation, the NMD issued various actions for immediate implementation on all Norwegian-flagged AHTS vessels and other vessels working within Norwegian waters. The circulars are the following:

- NIS/NOR Circular 7/2007, 7 September 2007 (NMD, 2007);
- NMD Circular - Series V, RSV 04-2008, 14 July 2008.

Stability requirements for supply and towing vessels allow for the angle of heeling at which the maximum righting arm (GZ_{max}) appears to be less than 20 deg. but not less than 15 deg. (NMD, 2008). In other words, even a slight heeling can be critical. Moreover, the angle of flooding, which results in water on the aft deck, occurs before the vessel reaches the angle for maximum righting arm (GZ_{max}). The astern trimming reduces the angle of flooding further. In accordance with the above requirements, the stability booklet should include the acceptable vertical and horizontal transverse force/tension to which the vessel can be exposed during the operation. Furthermore, it should include a sketch of the GZ curve and a table of the force/tensions that provide the maximum acceptable heeling moment. Calculations must show the maximum acceptable tension on wire/chain, including the transverse force that can be accepted for vessel maximum heeling, to be limited by one of the following angles (Figure 4.4):

- Heeling angle equivalent to a GZ value equal to 50% of GZ max;
- The angle of flooding of the work deck – i.e., the angle that results in water on the working deck when the deck is flat;
- 15 deg.

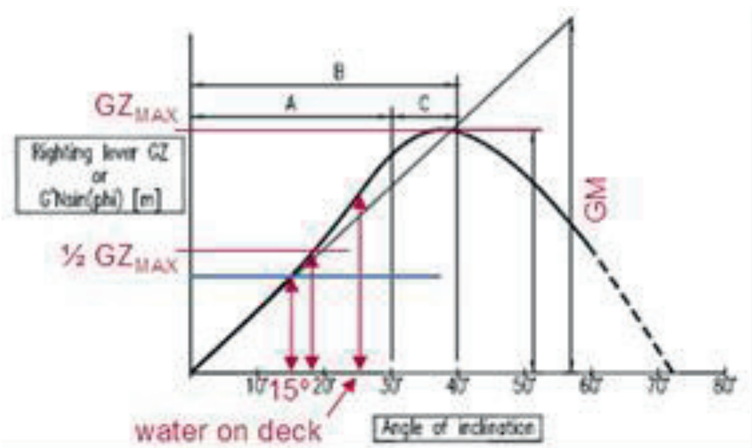

Figure 4.4: NMD criteria for the maximum heeling angle

The calculation should then be made to show the maximum force from the wire/chain, acting down at the stern roller and transversely to the outer pins that would be acceptable without taking the vessel beyond the angles stated previously. The heeling moment based on the transverse bollard pull must also be shown and allowed for. The NMD anchor handling guidelines suggest that the vertical component be taken as the distance (vertically) from the deck at the tow pins to the centre of the stern thruster or propeller shaft, whichever is the lower. The torque arm of the horizontal components shall be calculated as the distance from the height of the work deck at the guide pins to the centre of the main propulsion propeller or to the centre of the stern side propeller if the latter projects more deeply; see Figure 4.5. The torque arm of the vertical components shall be calculated from the centre of the outer edge of the stern roller to a vertical straining point on the upper edge of the stern roller; see Figure 4.6.

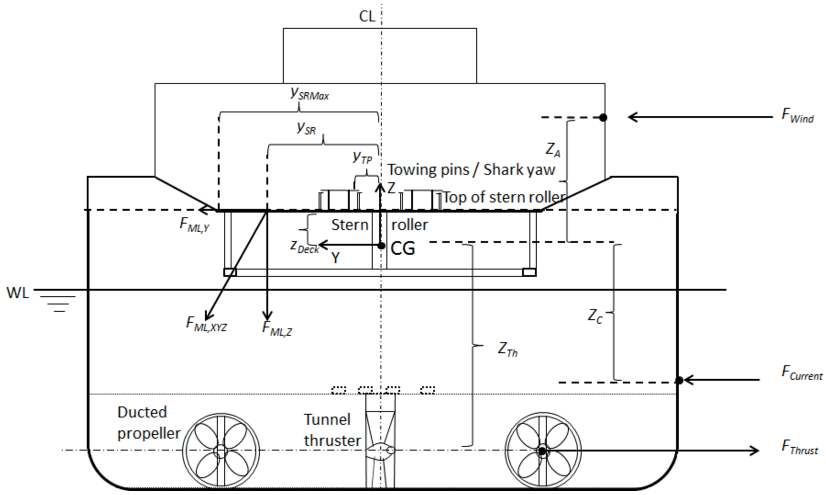

Figure 4.5: Transom of an AHV viewed from aft

4.7. Proposed stability criteria

This section addresses research questions RQ4 and RQ5, which are described in Section 4.3. It was found that the existing stability criteria do not cover AHV stability when it is subject to a mooring load and other operational parameters during the AHO. To address this drawback, two safety criteria (or limit state formulations) are proposed in this section.

4.7.1. Limit state

Floating structures, such as AHVs, have a range of design limit states. Crossing the limit state from the safe side to the unsafe side can move the vessel into hazardous conditions or unwanted events. The limit state function $f(x)$ can be expressed as follows:

$f(x) = f(x_1, x_2, \dots . x_n)$
$f(x) > 0$ in the safe domain
$f(x) = 0$ on the limit surface
$f(x) < 0$in the unsafe domain

The limit states related to AHVs can be broadly classified as, for example, stability, structural integrity, positioning and direction capability, and extreme motions. Here, the Ph.D. candidate have listed some of these limits associated with AHOs:

- Stability – the vessel must resist the capsizing phenomenon. This limit state can be expressed as a maximum allowable dynamic rolling angle or an allowable static heeling angle.
- Structural integrity – the mooring line must resist exerted external tension. This limit state can be expressed as the allowable breaking strength of the material used for the mooring line.
- Positioning and heading capability – for maintaining position and heading, the vessel must resist the external forces exerted by the environment and mooring line. This limit state can be expressed in terms of the maximum allowable weather conditions.
- Extreme motions – certain motions can cause problems with vessel equipment and discomfort to the personnel working on the deck. The limit state can be expressed as a function of weather conditions and weather directions.

In this study, the limit states for vessel stability during AHOs are defined by considering the mooring parameters along with other operational parameters. These limit states are established using a modified version of the existing weather criteria. For further details, refer to Articles CP2 and JP1 (see Appendix A). With the help of these limit states, we can confirm whether the vessel is within the safety limit for any anticipated operational situations.

4.7.2. Framework

Criteria proposed in this section are referred to as the critical rolling angle criterion and the critical static heeling angle criterion, which are expressed as a function of the vessel dynamic rolling angle and static heeling angle. These criteria are developed based on the existing IMO "weather criteria". The methodology for the development of these criteria is explained in Figure 4.6 (see Article JP1 in Appendix A). In this model, the effects of the wind-exerted drag force on the hull (due to the mean wind and gust wind on the projected area above the waterline), the current-exerted drag force on the hull (projected area below the waterline) and mooring load on the vessel static heeling angle are considered. Moreover, the effect of vessel drift-off due to the environmental loads and the thrusters in the transverse direction is considered. In addition, the vessel dynamic rolling angle in the operating sea state is accounted for. The details of this methodology are described in Article JP1 (see Appendix A).

4.7.3. Case study

A case study was performed on the Bourbon Dolphin to assess vessel stability during AHOs (see Article JP1 in Appendix A). The parametric study was conducted by considering the variation in the operational parameters (see Article JP1 in Appendix A). From this analysis, the relationships between the vessel static heeling angle and capsizing angle and between the maximum critical rolling angle and static heeling angle are established, which are shown in Figure 4.7(a) and Figure 4.7(b), respectively.

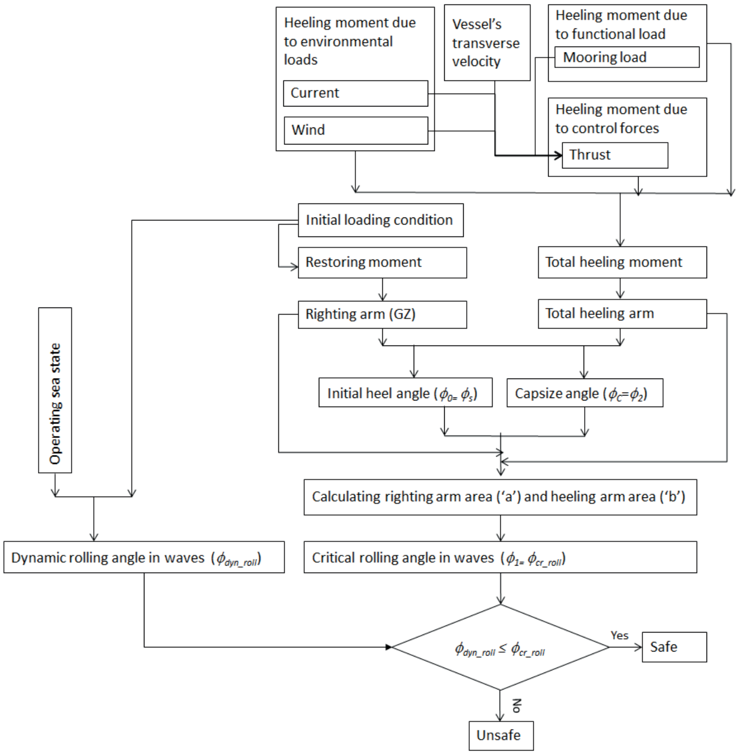

Figure 4.6: Procedure to calculate the critical rolling angle criteria

4.7.4. Criteria to assess AHV stability in the design and analysis phase

The environmental forces exerted by the wind, waves and current are sensitive to the wind velocity, current velocity and operating sea state, respectively. Furthermore, these forces are sensitive to the relative direction between the vessel and the environment. Therefore, for operational applications, it is useful to find those combinations of influencing parameters that represent the limit between "safe" and "unsafe". By using the abovementioned stability criteria, the designer can assess vessel stability in the design phase and define vessel-specific limitations in terms of operational parameters. Similarly, in the analysis and planning phase for the available (or selected) vessels, stability can be assessed for the estimated operational loads. By conducting a parametric study on the Bourbon Dolphin, key influencing factors related to vessel stability are obtained. The results are elaborated in Articles CP2 and JP1. Key conclusions from the results are the order of these key influencing parameters, which are magnitude of the mooring load, angle β, transverse component of the mooring load, and angle between the vertical line and mooring load.

4.7.5. Criteria to assess AHV stability in the operation phase

This subsection addresses RQ5, which is helpful for studying vessel stability during the operation phase. To address this question, an operational limit state is established that is called the critical static heeling angle criterion. This limit state criterion is developed based on the modified weather criterion, which is described in Articles CP1 and JP2 (see Appendix A). In addition, a parametric study is conducted to establish the relationships between the vessel capsizing angle and the static heeling angle and between the critical rolling angle in the waves and the static heeling angle. The details corresponding to this study can be found in Article JP2. This criterion can be used as an aid to assist designers, operators and masters in achieving vessel safety during operations.

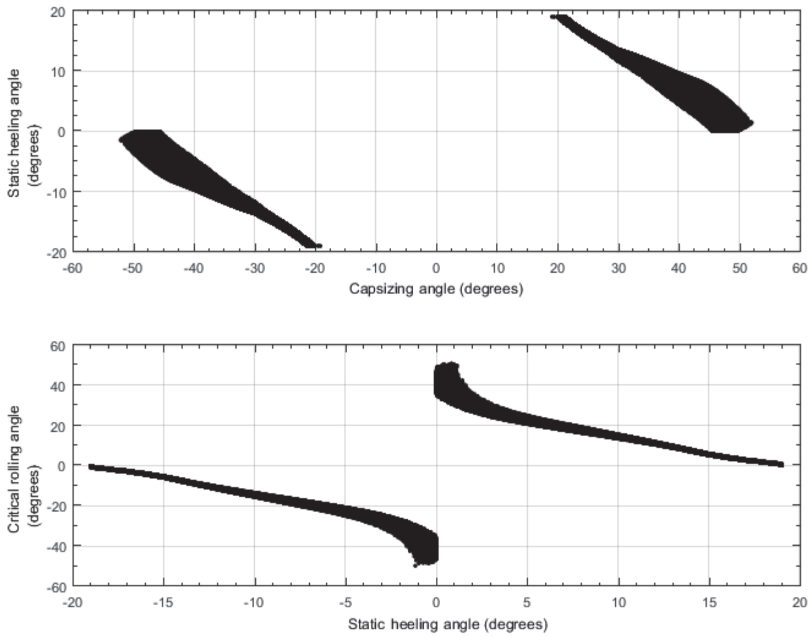

Figure 4.7: (a) The relationship between the vessel capsizing angles and the static heeling angles. (b) The relationship between the critical rolling angles in the waves and the static heeling angles

4.7.6. Section summary and remarks

The main contributions related to this section are published in Articles CP2 and JP1 (see Appendix A). The proposed stability criteria are convenient for use in assessing AHV stability in the design phase, analysis and planning phase, and operation phase. Moreover, the proposed criteria can be used for preparing the operating guidance and simulator training. In addition, the relationship between the operational parameters and vessel static heeling angle can be used for developing the vessel-specific on-board condition monitoring system and decision support systems that are established in Section 4.8 and Section 4.9, respectively.

4.8. Framework for the condition monitoring system

In this section, the author established an ANN-based system identification methodology to estimate the AHV static heeling angle during AHOs. This framework consists of two blocks: 1) a mathematical model for assessing the vessel static heeling angle and 2) an ANN-based model for estimating the vessel static heeling angle.

4.8.1. Mathematical model for assessing the vessel static heeling angle

In this block, a mathematical model is established for assessing vessel stability, i.e., the vessel static heeling angle in terms of operational parameters (see Figure 4.8). This model is elaborated in Article JP1 (see Appendix A).

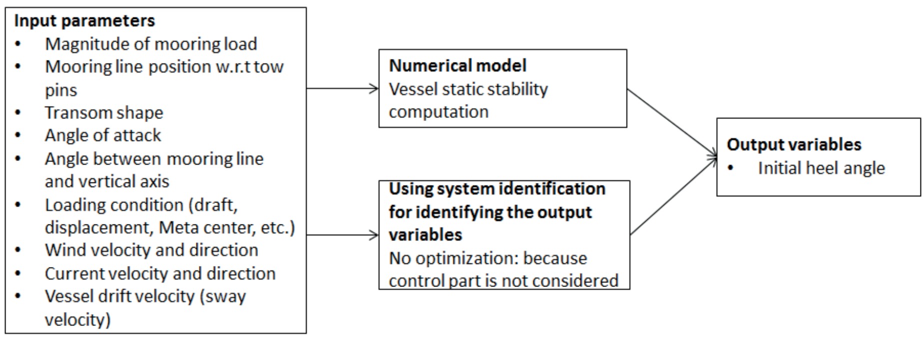

Figure 4.8: Outline of the integrated monitoring system for assessing the AHV stability margin during AHOs

4.8.2. ANN-based model for estimating the vessel static heeling angle

In real-time applications, it is essential to collect raw input data (i.e., the influencing parameter) instantaneously from the sensors and on-board monitors and to subsequently estimate useful information (i.e., vessel static heeling angle). Therefore, processing data related to the influencing parameters from the respective monitors is crucial for estimating the static heeling angle. However, in real-time applications, it is difficult to predict the static heeling angle based on the model described in Section 4.8.1. Therefore, it is essential to develop a model that can configure and manage resources in real time for estimating the static heeling angle. With this requirement in mind, an ANN-based system identification model is here established for estimating the static heeling angle in terms of operational parameters (see Figure 4.8). This model is elaborated in Article JP2 (see Appendix A).

4.8.3. Section summary and remarks

By having this system, situational awareness related to the vessel stability margin during AHOs can be achieved. The proposed condition monitoring system can assist key personnel both onshore and offshore during the planning and operation phases in the following:

- To identify hazards in AHOs;
- To assess vessel stability margin in AHOs;
- To assess the risk associated with AHOs;
- To identify where operational control can be improved.

4.9. Framework for the DSS model

The proposed DSS framework is depicted in Figure 4.9 and Article JP3 (see Appendix A). Figure 4.9 illustrates how to obtain information on the influencing parameters and vessel static heeling angle for real-time operations. Furthermore, it illustrates how to predict the vessel stability margin and suggest control strategies. This framework consists of two blocks: 1) estimation of the vessel stability margin and 2) optimization-based prediction of the best control strategies. This framework is designed such that the key influencing parameters' effect on vessel stability is considered. In addition, the decisions are suggested based on the best operational practices in the industry. Overall, the proposed framework is an integration of the ANN-based condition monitoring system and knowledge-based optimized system to offer an intelligent decision for assisting the AHV's master during AHOs. This integration is achieved by the following:

- Transforming and representing the data, information and knowledge in ways that assist the master to make a correct decision;
- Making suggestions in a form that is close to how a human user would interpret them manually;
- Pre-setting the relevant data, models, reasoning and results in ways that are easy for the user to understand.

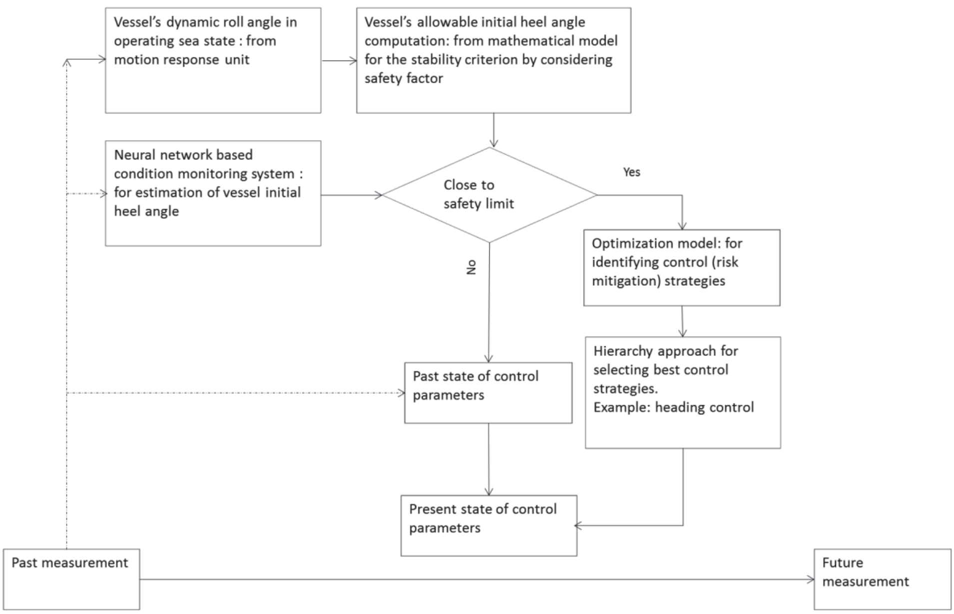

Figure 4.9: Illustration of the proposed decision support system

4.9.1. Estimation of vessel stability margin

The objective of this block is to estimate the vessel static heeling angle (refer to Section 4.8), and it compares this estimate with the defined allowable static heeling angle. This block first estimates the vessel static heeling angle based on the model described in Section 4.8.2. In this study, for demonstrating the framework, the vessel allowable static heeling angle is considered as 5 deg. This value is obtained from the experts' opinion. However, in real-time applications, the vessel dynamic rolling angle can be predicted for an operating sea state (combination of H_S and T_P). Then, the vessel allowable static heeling angle can be derived, a process described in Article JP1 (see Appendix A).

4.9.2. Optimization model

This block predicts the best control strategy and recommends control parameters to the vessel's master for maintaining the vessel static heeling angle within the allowable static heeling angle (or target angle). The control strategy identification comprises three steps: 1) establish an objective function, 2) predict possible control strategies, and 3) choose the best control strategy.

In the first step, the objective function (J) is established (see Article JP3 in Appendix A) as a function of the static heeling angle (θ_i) and target heeling angle $\left(\theta_{i,t}\right)$. In most of the control applications, a quadratic form is used for the objective function. In this study, it is expressed as $J = \left(\theta_i - \theta_{i,t}\right)^2$.

In the second step, the SQP optimization technique is used to predict the possible set of control inputs, which are identified by optimizing the objective function. The target heeling angle in the objective function can be different from operation to operation. To obtain the optimal set of control variables, the objective function is minimized. In this study, MATLAB's Optimal Toolbox function fmincon is used, which is an SQP implementation. This function allows addressing either an unconstrained or a constrained optimization problem. Moreover, it allows imposing constraints with respect to the value of the control input such as upper or lower bounds, which are often required in practice. Further details on the implementation of this algorithm for this problem are discussed in Article JP3 (see Appendix A).

In the final step, once the possible set of control inputs is identified, the next step is choosing the best control strategy based on the operational context, a process described in Article JP3 (see Appendix A).

4.9.3. Concluding remarks on the DSS

In the present study, the DSS framework is developed to assist the vessel's master in maintaining vessel stability during AHOs, but a similar system can be developed for controlling vessel drift-off and direction. Then, the above two DSSs can be integrated together into a single DSS, which would be beneficial for achieving both the functional and safety goals during AHOs without compromising any one of them.

The benefit of the DSS is to assist key personnel in making decisions. The DSS proposed in this section can be integrated into the simulators for crew training purposes. In addition, the proposed DSS is helpful in preparing guidance. For practical applications, this system initially should be incorporated into the simulator. It can subsequently be established on board an AHV as a trial run. Once this system has proved its effectiveness and efficiency, it can be used on board AHVs as a DSS.

4.10. Main research contributions in this chapter

The contributions from this chapter are published in Articles JP1, JP2, JP3 and JP4 and are presented in Articles CP2 and CP3. As a summary, the main research contributions are the following:

- A methodology has been established for assessing vessel drift-off and angle of attack in AHOs.
- A methodology has been established for assessing the vessel positioning capability for a given set of thruster and propeller configurations.
- A stability criterion is proposed for assessing vessel stability in the design phase and the analysis and planning phase;
- A stability criterion is proposed for assessing vessel stability in the operation phase;
- By conducting a parametric study on vessel stability, key influencing factors are identified;
- A mathematical framework is proposed for establishing a condition monitoring system that can be used for obtaining situational awareness during the operation, providing a vessel stability margin;
- A mathematical framework is proposed for establishing a decision support system to be used for aiding the vessel's master in the decision-making process during the execution phase of the operation.

4.11. Summary

As a summary, this chapter presents the procedures, methods and techniques used in this research work to enhance the safety of AHVs in AHOs. This chapter focusses on finding solutions to improve the safety of the AHV through the following:

- improving vessel design considering the positioning capability and stability criteria;
- establishing vessel thresholds by considering the positioning capability and stability margin related to operational and environmental loads in the vessel design phase;
- assessing the required vessel positioning capability and stability margin in the analysis phase;
- assisting in vessel selection considering the operational loads and operational limitations in the planning phase;
- describing critical operational scenarios and control strategies in the operational manual (rig move procedure) in the planning phase;
- continuously estimating the vessel stability margin in the operation phase;
- aiding the vessel's master with effective control strategies in the execution phase;

- assessing vessel positioning capability and stability in the design and analysis phase;
- estimating the vessel stability margin in the operation phase;
- identifying critical scenarios and developing case studies for implementation in simulators for crew training;
- establishing safety procedures, guidance, rules and regulations.

Chapter 5

Conclusion and recommendations

This chapter summarizes the thesis, with an emphasis on findings and contributions, and outlines directions for future research.

5.1. Overall summary of the thesis

The main motivation for this thesis, motivated by the Bourbon Dolphin accident, is to develop methods and criteria to enhance the safety of anchor handling operations and to prevent capsizing. From the literature survey, it was noticed that further research was required to improve the safety of AHOs. However, AHO is a wide domain involving AHVs, rigs, anchoring systems and interactions between key personnel. Therefore, in this study, emphasis was given to the stability of AHVs in AHOs. The focus was on how to improve the safety of AHVs through the proper design, planning, and execution of the operation. To improve the safety of AHVs, new positioning and stability criteria were proposed and investigated in a case study. Moreover, a condition monitoring system and a decision support system framework were developed.

The main contributions of this research work are summarized in this chapter. Moreover, recommendations for future work in this area are proposed.

5.2. Summary of thesis contributions

5.2.1. Main contributions and their relevance

The main contributions of the thesis are summarized as follows:

- *A numerical model was established to assess vessel drift-off and angle of attack in a uniform current field.*

  An excessive drift-off from the planned anchor track was an initiating event in the Bourbon Dolphin accident. To hold the vessel in position, the vessel started using its two lateral thrusters at full capacity. Subsequently, the vessel manoeuvred towards the actual line direction to return to the desired line position and direction. Thus, the angle of attack was increased significantly. However, the thrusters were overheated. Thus, a thruster breakdown occurred. Then, the vessel listed towards the port side. Consequently, the vessel capsized. Therefore, in this model, the effect of effective control force and moment due to human intervention and/or propeller or thruster failures was also considered. Moreover, the effectiveness of this model was demonstrated by a case study. This case study shows how the vessel drift-off and angle of attack vary when the vessel is operated in a uniform current field while it is subjected to faults (available thrust and power).

This numerical model is useful for analysing vessel drift-off and angle of attack in the analysis and planning phase. These analysis results are useful for selecting the operating scenario and defining its limits in the rig move procedure.

- *A positioning capability criterion was proposed.*

  Thrust utilization plots were established to evaluate AHV positioning capability in AHOs.

  A case study was conducted on the Bourbon Dolphin's positioning capability, which demonstrated that she had been in the most unfavourable weather direction during the accident.

  This criterion can be used to aid the vessel's designer in two ways during the vessel design: 1) to define the positioning capabilities for given propulsion and thruster capacities and 2) to select the propulsion and thruster configurations for the given environment and mooring loads. Moreover, this criterion can be useful in the analysis and planning phase in two ways: 1) to define the AHV-specific positioning capability limits, which can be expressed in terms of the operational parameters, and 2) to select a vessel with sufficient propulsion and thruster configurations to maintain its position and direction for an estimated set of operational parameters.

- *A numerical model was established to assess vessel stability when it is subjected to operational parameters during AHOs.*

  A large static heeling angle was the event preceding the capsizing in the Bourbon Dolphin accident. The angle is influenced by the mooring load and other operational parameters. Therefore, in this model, the effect of operational parameters on vessel stability was considered.

  This numerical model is useful for analysing vessel stability in the analysis and planning phase. These analysis results are useful for selecting the operating scenario and defining its limits in the rig move procedure.

- *Stability criteria were proposed.*

  Two stability criteria were proposed: 1) the critical static heeling angle criterion and 2) the critical rolling angle criterion.

  A case study was conducted on the Bourbon Dolphin's stability, which demonstrated that the magnitude of the mooring load, the angle of attack and the transverse component of the thrust and the mooring line position with respect to the tow pin were high-influencing parameters during the accident.

  These criteria can be used to aid the vessel's designer during the vessel design to define the vessel-specific limits in terms of its operational parameters or to change the vessel's design to accommodate the defined operational parameters. Moreover, these criteria can be useful in the analysis and planning phase in two ways: 1) to define the AHV-specific stability limits, which can be expressed in terms of the operational parameters, and 2) to select a vessel with a sufficient stability margin to maintain vessel stability for a set of estimated operational parameters.

- *A framework for a condition monitoring system was developed.*

  A lack of situational awareness of the vessel's stability margin can lead to capsizing. To improve vessel situational awareness, a neural network-based condition monitoring system was proposed.

  A case study was conducted to discuss and demonstrate how network parameters, such as the number of hidden layers and length of training data, can affect the network performance.

  This monitoring system can assist the vessel's master in predicting the vessel stability margin during AHOs.

- *A framework for a decision support system was developed.*

  In this thesis, a human was considered an additional safety barrier. To strengthen this barrier, a condition monitoring system and a decision support system were proposed. The developed DSS framework predicts the best control strategy and recommends control parameters to the vessel's master for maintaining the vessel static heeling angle within the allowable static heeling angle (or target angle).

  A case study was conducted to discuss and demonstrate the effectiveness of the proposed decision support system.

  The benefit of this system is that it can be used to assist the crew on board and personnel on shore during the operation. Thus, the operations can be easily executed and abandoned (if required) by the operator without further hesitation. Moreover, the system saves time and resources for the master by being able to anticipate the vessel's status at any given point of time and by knowing what type of action must be taken.

5.2.2. Secondary contributions

The secondary contributions in the thesis are summarized as follows:

- A comprehensive literature review on AHVs and AHOs has been given in 0;
- The risk-influencing factors related to the AHV's capsizing and drift-off in AHOs were identified;
- Hazardous scenarios and root causes related to AHV accidents in AHOs were identified;
- The proposed models can be helpful for identifying ship-specific operating limits;

- The proposed models can be used for predicting vessel-specific operability by considering the vessel's performance limitations;
- The proposed condition monitoring system can be used to obtain better situational awareness related to the vessel stability margin during the operation;
- The proposed models can be used for developing ship-specific operating procedures and guidance;
- The proposed models can be helpful for developing vessel benchmarking;
- The proposed models can be used for identifying critical scenarios, and further, these scenarios can be used for developing case studies for implementation in simulators for crew training;
- The methods proposed in this thesis can contribute to the development of rules and regulations for vessels and equipment, requirements, and training procedures for on-board personnel and to the establishment of thresholds for vessel safety linked to operational and environmental demands.

5.3. Suggestions for future work

The research never ends; the methodologies developed in this thesis serve as a set of powerful tools to improve the safety of AHVs in AHOs. A brief account of some opportunities for immediate improvements and long-term improvements are described in Section 5.3.1 and Section 5.3.2, respectively.

5.3.1. Short term or immediate improvements or level 1

Possible immediate extensions of the methodologies established in the present work are as follows:

- *Guidance on AHVs*

  Many stakeholders are involved in various phases of the AHO, for example, designers, shipping companies, operators, statutory bodies, governmental bodies, and insurance companies. These stakeholders have a role in minimizing risk and operational cost. Therefore, it is essential to develop guidance to assist key personnel when making decisions during different phases of the operation. The research findings and state-of-the-art established in this thesis can be used to establish such guidance. Therefore, future work should focus on identifying possible critical scenarios during AHOs and a sequence of possible events. If an accident event escalates, what can occur? Moreover, to prevent the escalation of these events, what actions or decisions should be taken? The answer to this question should be developed in collaboration with the experts in this domain.

- *Establishing critical scenarios for training purposes*

  With the help of extensive training and operational procedures, the AHOs can be better handled. The skills of the abovementioned key personnel can be improved with the help of on-board, classroom or simulator training. Prior to the AHOs, it is possible to simulate a specific AHO in the simulator, which is helpful for training these personnel and developing safety procedures. The critical operational scenarios should be covered in the training procedures. The methods and frameworks developed in this thesis can be used for this purpose. However, further research along these lines is required to integrate these methods and frameworks into the simulator.

- *Validation of stability criteria*

  Stability criteria were developed based on the existing IMO weather criterion. The effectiveness of the suggested criteria was demonstrated in a case study. Including the operational parameters, there are other parameters that can affect vessel stability, such as the loading condition (e.g., vessel draft and centre of gravity) and vessel design parameters. The vessel is safe as long as the actual static heeling angle remains within the limits of the allowable initial heeling angle. Therefore, the criteria should be tested for other vessel loading conditions. Due to safety concerns, it is essential to investigate this criterion further before it can be used in industrial applications.

  In this thesis, the extreme roll response was considered the basis for the vessel's stability criterion. This rolling angle is a function of the vessel heading, loading condition, speed and operating sea state and is not extensively covered here. Moreover, the operational parameters that affect the vessel dynamic rolling angle were not included. Therefore, further investigations are needed for a better assessment of the vessel dynamic rolling angle.

  It is challenging numerically to model the capsizing phenomena. However, it is essential to evaluate these criteria before the model is implemented in industrial applications. Therefore, the proposed stability criteria should be validated with an experimental analysis or advanced time-domain simulations. To summarize, future work should focus on further improvements of these criteria and on final implementation.

- *Safety factors for stability*

  It is essential to consider the effect of the uncertainties when defining the allowable dynamic rolling angle and the allowable static heeling angle. Therefore, to obtain the safety factors between the vessel critical static heeling angle and the allowable static heeling angle and between the vessel critical dynamic rolling angle and the allowable rolling angle, uncertainty analysis must be conducted. Further research along these lines is required to obtain these safety factors.

- *Further validation of the ANN-based condition monitoring system framework*

  An artificial neural network-based condition monitoring system was developed for estimating the vessel stability margin during operation but was studied for only one vessel loading condition. Therefore, the effectiveness of this system should be investigated for other loading conditions and other AHVs. Moreover, other approaches could be studied and compared with the results obtained by this ANN model.

- *Further validation of the DSS framework*

  A decision support system was developed for assisting the vessel's master to maintain vessel stability in the execution phase of the operation, which is a theoretical approach. In this study, a comprehensive list using a hierarchy approach was used for selecting an optimal control strategy. The state-of-the-art and experts' opinion were used for identifying these control strategies for a given operational scenario (or the context of the operation). Further work should be conducted on the experts' opinion for establishing a better context-based decision support system.

  Typically, when performing AHOs, uncertainties in information and goals can occur that can lead to conflict when achieving the objectives. In these situations, the use of fuzzy set theory might help in better decision-making. Therefore, further research should be performed in this direction.

- *Extension of this study to other AHVs*

  This thesis has demonstrated new methods for assessing vessel stability and positioning capability. Thus far, the effectiveness of the proposed stability and positioning capability criteria has been demonstrated for only one AHV – that is, the Bourbon Dolphin. It would be of great interest to study the effectiveness of these criteria for other AHVs, which could demonstrate the performance of these criteria.

5.3.2. Long-term suggestions or level 2

Several long-term extensions of this thesis have been identified:

- *Development of a better model for vessel drift assessment*

  With respect to the operational requirements, vessel drift-off is an important parameter to control. This parameter is highly dependent on the current magnitude. Vessel drift-off, angle of attack, and positioning capabilities were studied using a simplified approach. To some extent, this approach can be used in the planning phase. However, the industry requires a better manoeuvring model that can consider all other parameter effects on vessel drift-off and angle of attack. Therefore, future research should be conducted along these lines to develop a manoeuvring model to assess a vessel's drift-off when it is subjected to environmental loads, mooring loads, control forces and moments, and human interventions during AHOs.

- *Development of a real-time condition monitoring system*

  The condition monitoring system framework developed in this thesis should be extended to real-time applications. Moreover, the efficiency of this model should be investigated for real-time applications. Therefore, future work should focus on acquiring quality on-line real-time data (that is, input and output data related to the neural network) and on processing these data into the proposed mathematical model. Finally, this model should be integrated into the on-board condition monitoring system.

- *Development of an integrated drift-off and stability-oriented real-time decision support system*

  The DSS framework developed in this thesis should be extended to real-time applications. Moreover, future work should focus on including vessel drift-off and angle of attack control in this framework. Then, this framework should be integrated into the on-board environment and should be tested for real-time operations.

- *Development of a capsizing avoidance system*

  The existence of an adequate capsizing avoidance system might have averted the Bourbon Dolphin accident. Prevention would not occur only because of the presence of such a system. However, capsizing can be prevented in two phases. The first phase activates the automatic alarm, and the second phase automatically activates the emergency releasing system.

  Existing industry practice in emergency situations is that the vessel's master or the operator in charge (during the shift) activates the alarm and emergency release system (or quick emergency release system). Due to the lack of situational awareness on vessel stability, he/she might react slowly. This situation is dangerous for both the vessel and its crew. Once the false proof decision support system is established, it can be integrated with the alarm and the emergency release system. Thus, human intervention can be minimized. However, such a system requires ship-specific critical threshold limits. Therefore, further research should be conducted in this direction.

- *AHV operability study*

  During AHOs, the stability and positioning capabilities of an AHV have an important influence on vessel operability limits. The practice in the industry is that AHOs are not conducted in sea states with a significant wave height greater than 3.5 m and a mean wind velocity above 40 knots. Due to this practice, even when operators choose a vessel with high stability margin (for the same operational loads) and positioning capability, the vessels are not operated beyond these limits. Thus, the vessel operability is less than its actual potential. Conversely, due to the lack of awareness, vessels with lower capacities also operate with the same limits.

Thus, accidents such as the Bourbon Dolphin capsizing can occur during AHOs. The models proposed in this thesis are useful for establishing vessel-specific limits. These limits can be useful for predicting vessel operability for a given set of metocean data and operational loads. Therefore, further research should be conducted to study various AHV's operability.

- *AHV benchmarking study*

  At present, no methods are available to benchmark a vessel by considering its performance limits. Operators who do follow good safety practices are prone to less risk-taking behaviour. Thus, they choose AHVs with higher capacities, a choice that leads to higher operating cost. Conversely, the operators who do not follow good safety practices are prone to higher risk-taking behaviour. Thus, the operation cost can be less, but the operation can be risky. Hence, the need to develop a methodology for selecting an AHV to conduct safe and cost-efficient AHOs exists.

  Benchmarking vessels against each other by considering the vessel-specific limits is the best approach to assist the operator in vessel selection. Therefore, further research should be conducted to develop a methodology for benchmarking the vessels.

5.4. Final remarks

In summary, a new approach was developed in this thesis to address vessel stability and drift-off, situational awareness and control strategies for improving the safety of AHVs in AHOs. Moreover, this approach is useful for improving vessel performance and operability. Thus, the AHVs will be more cost effective and safer. It is my sincere hope that this work provides useful insight for key personnel related to AHOs. Although this thesis is focussed on the safety of AHVs in AHOs, this approach can be extended to other vessels involved in other marine operations such as fishing trawling, pipe laying, and crane operation.

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Appendix A

Appended papers

A.1. Paper 1

Risk influencing factors related to capsizing of anchor handling vessels in view of the Bourbon Dolphin accident

Authors: Giri Rajasekhar Gunnu, Torgeir Moan, Haibo Chen

Published in Proceedings of Systems engineering in ship and offshore design, Royal Institution of Naval Architects, Bath, UK, 2010.

Is not included due to copyright

A.2. Paper 2

Stability assessment of anchor handling vessel during operation considering wind loads and wave-induced roll motions

Authors: Giri Rajasekhar Gunnu, Torgeir Moan

Published in Proceedings of 22nd ISOPE, The International Society of Offshore and Polar Engineers, Rhodes, Greece, June 17–22, 2012.

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A.3. Paper 3

Stability assessment of anchor handling vessels during operations

Authors: Giri Rajasekhar Gunnu, Torgeir Moan

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A.4. Paper 4

An assessment of AHV stability during anchor handling operations using a method of artificial neural network

Authors: Giri Rajasekhar Gunnu, Torgeir Moan

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An assessment of anchor handling vessel stability during anchor handling operations using the method of artificial neural networks

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ABSTRACT

The risk of vessel capsizing is inherent to anchor handling operations (AHOs). Lessons learned from the Bourbon Dolphin accident reveal that the large static heeling angle could not be prevented due to the lack of awareness of the vessel's stability status, which can be improved with the help of a suitable on-board monitoring system. Therefore, an on-board monitoring system is proposed for assessing stability in terms of the static heeling angle. However, a complete mathematical model is not available for estimating a static heeling angle as a function of operational parameters. Therefore, an artificial neural network (ANN)-based functional relationship has been established between the operational parameters and the static heeling angle. Furthermore, a parametric study has been performed to investigate the effect of neural network topology on network performance. The results show that an ANN topology that contains one hidden-layer is efficient enough to predict a static heeling angle. The correlation coefficient between the ANN model predictions and the target values is 0.999. This result shows that the ANN provides an accurate estimate of the static heeling angle as a function of the operational parameters. Therefore, the proposed mathematical model can be used for assessing a vessel's stability during AHOs.

1. Introduction

Offshore floating structures are widely used in oilfield exploration, production and accommodation. These structures are usually held in position by means of mooring systems. Typically, these mooring systems consist of components such as mooring lines (which may be a combination of chains, wires and synthetic rope) and anchors. The operations of floating structures involve de-positioning (anchor recovery from the seabed); move (towing the floating structures to a new location) and positioning (deployment of anchors into the seabed) are defined as anchor handling operations (AHOs). These operations are performed with the help of dedicated vessels called anchor handling vessels (AHV), which conduct activities such as handling mooring lines and deploying or recovering anchors. These AHOs are applied to other floating systems that are used in the offshore wind energy and aquaculture industries. However, this paper focuses mainly on AHOs that are associated with mobile drilling rigs. In practice, to ensure safe operations, the allowable weather conditions are defined in the rig move procedures.

The performance of AHVs during AHOs is judged based on two objectives, namely, the economy and safety. In this work, the latter objective is studied. Even though, to date, there have been only two accidents (Lyng et al., 2008; Nielsen, 2004) related to AHVs during AHOs, AHOs are considered to be highly risky. The risk of a vessel capsizing is an inherent part of these operations, and it is not possible to eliminate this risk, but it is possible to reduce. The risk associated with AHVs in AHOs can be managed by improving the rules and regulations, and providing the information related to the vessel's stability and control strategies to the crew based on the condition monitoring system and decision support system, respectively. More than these additional efforts are required for controlling the risk during AHOs which are like training the vessel's crew, etc.

In the aftermath of the tragic Bourbon dolphin vessel accident (Lyng et al., 2008) the IMO Sub-committee on Ship Design and Construction meeting (MSC 88/23/2) decided to establish a new international standard for the safe design and operation of tugs and anchor handling vessels, for inclusion in part B of the 2008 IS Code. The committee agreed to include criteria for anchor handling operations in their meeting at MSC 95 (June 2015). During the discussion at SDC 3 (IMO SDC 3/WP5, 2016), the working group agreed the amendments and further stated that these amendments should enter into force on 1 January 2020. The proposed amendments did not consider the wind and the current force effect on the vessel's static heeling angle and the vessel's dynamic rolling angle. To address these

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drawbacks, Gunnu and Moan (2016) proposed two stability criteria, which are 1) the critical static heeling angle criterion and 2) the critical rolling angle criterion. For a given AHV and loading condition, the above mentioned criteria depend on the vessel's dynamic rolling angle (in waves), static heeling angel and the capsizing angle. These angles depend on the operational parameters, such as the magnitude of the mooring load, the angle between the vertical axis and the mooring line, the angle of attack (the angle between the mooring line and the vessel's centreline), the control forces (exerted by the thruster and rudders in the transverse directions) and the environmental loads (due to current, wind and waves). The assessment of these angles in the analysis and planning phase could be helpful in defining the safety limits in the operating manual. Moreover, by varying these operational parameters the relationship between the vessel's static heeling angle and capsizing angle, and between the maximum critical rolling angle and static heeling angle were established.

In this study, a condition monitoring is proposed to provide the information related to the vessel's stability margin to the crew. The risk of a vessel capsizing can be mitigated by continuous monitoring of the vessel's stability margin during the operating phase and implementing correct control strategies during the execution phase of the operation which are discussed in Appendix A. Therefore, awareness of the vessel's stability status and safety margin well in advance is essential for conducting safe operations. This information is useful for the vessel's master in deciding whether to continue the operation or not. Moreover, this information is useful for making the correct decisions at the correct time. These decisions are possible to achieve by making use of a proposed on-board monitoring system that accounts for the operational parameters' effect on the vessel's stability.

An appropriate on-board monitoring system will play a major role in assessing and mitigating vessel capsizing scenarios during the operation. Currently, there are several on-board monitoring systems that are available for AHVs assessing operational parameters such environmental parameters (wind parameters from wind sensors and wave information from the rig/other resource), mooring line tension (winch monitor), the vessel position and heading, and vessel drift-off (position reference system), the vessel's heading and position with respect to the rig and target location (navigational monitor), the vessel power distribution (power monitor system), stability in loading condition (Loadicator), video screens, and more. However, none of these factors are useful for assessing the vessel's stability status when it is subjected to a mooring load during AHOs. Hence, in the present practice of AHOs, the vessel's master assesses the vessel's stability margin and further conducts the necessary actions for continuing the operation or preventing (and mitigating) critical scenarios. The efficiency of the stability prediction and the success of the actions depends on the skill, knowledge and experience of the vessel's master. Even an experienced master might not have faced all of the possible critical scenarios that are related to AHOs in his/her service. Therefore, relying only on the master's skills is not an appropriate approach. Hence, a solution to overcome this problem is currently needed. In this study, the vessel's static heeling angle is considered to be a monitoring parameter that is useful to understand or/and monitor the vessel's stability during the execution phase of the operation. This estimated vessel's static heeling angle can be compared with the vessel's critical static heeling angle (for an operating sea state) for assessing the vessel's safety margin during AHOs. This critical static heeling is possible to estimate for a given operating sea state. With this approach, the vessel's dynamic rolling angle effect on the vessel's safety is considered. However, in this study, the dynamic rolling effect is not considered. The vessel's static angle is influenced by operational parameters, such as the magnitude of the mooring load; the angle between the vertical axis and mooring load; the angle of attack (the angle between the mooring line and vessel centreline); the wind and current velocity in the transverse direction; the vessel's transverse drift velocity and the mooring line position with respect to the tow pins. During AHOs, the operational parameters vary significantly, which implies variation in the vessel's static heeling angle. However, a complete mathematical model is not available for estimating the vessel's static heeling angle as a function of the operational parameters during the operation.

Therefore, in this paper, a method has been proposed for estimating the vessel's static heeling angle during the AHOs when the vessel is subjected to the heeling moment induced by the operational parameters and the vessel's righting moment. In the present study, artificial neural networks (Golden, 1996; Haykin, 2009; Lippmann, 1987; Mehrotra et al., 1997) are used to establish the functional relationship (function approximation modelling) between the vessel's static heeling angle and the operational parameters during anchor handling operations. The ability of ANNs to compute has been proven in the field of prediction and estimation. They are suitable for modelling and solving complex problems that are difficult to solve and model with classical mathematics and traditional procedures.

The results of this study can be useful for the vessel's master and other involved personnel to understand the vessel's stability (vessels' heel) status and margin during operations. Furthermore, the proposed mathematical model can be helpful for recognizing faults by understanding the progress of the events and the factors that can have an impact on the vessel's performance in terms of safety. To prevent accidental events, the system can be set to give an alarm when the vessel's stability reaches its limit state. In real-time applications, the vessel's stability is assessed by feeding the information on the operational parameters to on-board monitoring systems. This approach saves time and resources for the vessel's master by producing an estimate of the vessel's stability status at any point in time.

This paper is organized into six sections. The next section contains a literature review of AHOs. The neural network approach is presented in Section 3. A case study is described in Section 4, and the results and discussion are given in Section 5. Finally, the conclusions of the obtained results are presented in Section 6.

2. Anchor handling operations

A typical range of AHOs and a sequence of steps associated with them are described in the operating manuals, e.g., Vryhof Anchors (1999), and dedicated books, e.g., Gibson (1999); Hancox (1994); Maudsley (1995); Ritchie (2007). These operations depend on a number of factors, such as the site location, the infrastructure on the seabed, the number of vessels, the type of mooring equipment and the weather conditions (such as significant wave height, wave period, wind velocity and direction, and the current velocity and direction). As mentioned above, one of the major accident scenarios during AHOs is vessel capsizing. The risk associated with capsizing can be prevented or mitigated by means of an appropriate vessel design, operational planning, and efficient execution of the operation.

An earlier study of accidents such as the Bourbon Dolphin (Lyng et al., 2008) and Stevns Power (Nielsen, 2004) incidents and near-misses has helped in understanding the influential factors that are related to a vessel's capsizing during AHOs. The key sequence of events related to the Bourbon Dolphin accident are discussed in Appendix A. Fig. 1 presents the influencing factors that are related to AHVs capsizing based on the study by Gunnu et al. (2010) on the Bourbon Dolphin (2008) vessel accident. As seen in Fig. 1, the main reason that causes vessel capsizing is a large angle of attack (the angle between the mooring line and the vessel centreline). This large angel of attack along with the mooring line tension and poor manoeuvring causes the vessel to develop a large static heeling angle of approximately 5 degrees, and along with this, large waves can lead to capsizing. The angle of attack depends on the vessel's position and bearing (direction) with respect to the rig. Operational features such as the vessel's behaviour in the horizontal plane, manoeuvring and tow pin handling influence these parameters. Gunnu and Moan (2012) studied how the angle of attack rapidly changes in various thruster capacities and current headings.

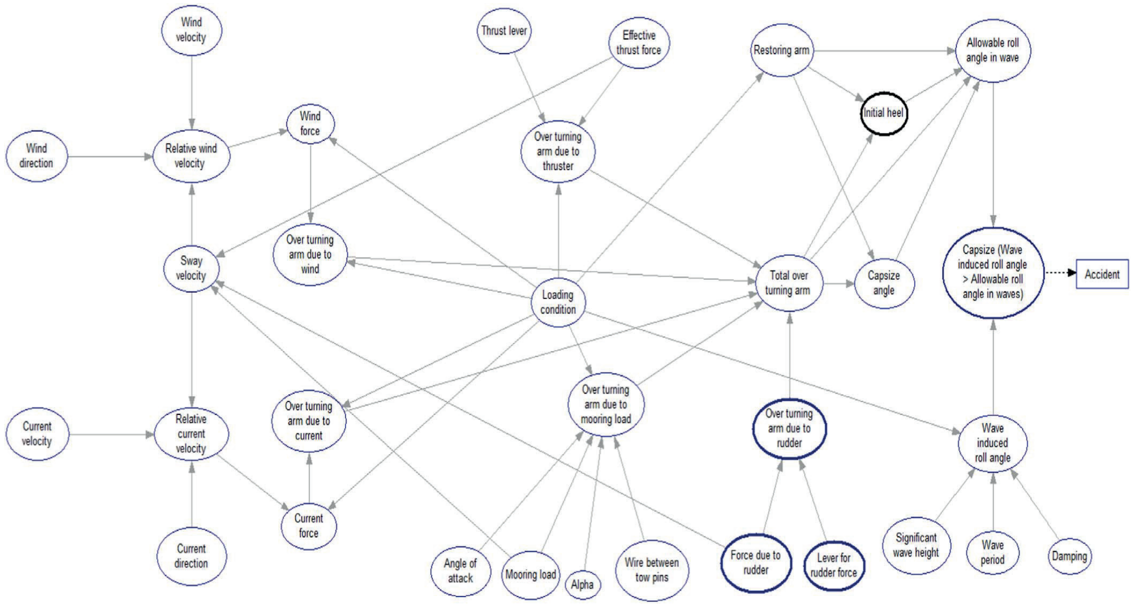

Fig. 1. Influence diagram related to the anchor handling vessel's stability in anchor handling operations.

The results show that the maximum angle of attack occurs when the current is coming from a quartering sea. Moreover, the results show that the vessel's drift and angle of attack increase when there is an increased delay in time before taking the action. Furthermore, Wu et al. (2015) stated in their earlier study that the vessel's drift motion and angle of attack depend on the vessel's positioning capability. Gunnu and Moan (2016) also investigated the effect of the angle of attack on the vessel's static heeling angle. This study shows that even a small magnitude of mooring load can cause a large static heeling angle when the vessel is subjected to a large angle of attack. The large angle of attack along with the higher mooring load leads to a large static heeling angle, which in turn leads to capsizing. A large angle of attack is therefore critical for the transverse stability of the vessel.

To prevent this large angle of attack, an ideal situation during the operations is to keep the mooring line along the centreline of the vessel. However, due to the lateral transverse environmental load, the vessel is difficult to maintain a mooring line along the centreline during AHOs. One way of addressing this situation is by increasing the knowledge and skills of the vessel master in doing his job. Therefore, good vessel handling skills are eminent for a safe execution of the operation. One of the aspects that is associated with the vessel master handling skills is situational awareness. Thor Hukkelås and Andreassen (2013) proposed a new anchor handling concept to increase the safety, wherein situational awareness is vital. The current practices related to AHOs do not provide awareness of the risk that is associated with these operations and the involved vessels. For this reason, the personnel involved in these operations face two key challenges. One is to identify limiting states related to vessel capsizing. Another is the optimal control of the mitigating vessel tending toward a capsizing scenario during AHOs.

Typically, these challenges are addressed in operational procedures in the planning phase. Moreover, these challenges are presented for personnel who are involved in the operations by means of a briefing before the operation begins. Furthermore, to mitigate the capsizing scenario during the AHOs, it is essential to provide relevant and safety-critical information continuously on board the vessel while conducting the operation. This information is helpful for reducing the risk level during the execution phase of the operation.

Because the vessel's stability is fundamental for a safe operation, providing information that is related to a safety margin against capsizing through an on-board monitoring system is very important for preventing capsizing scenarios during AHOs. Therefore, prediction of the vessel's stability during AHOs is very important. This type of prediction depends on the forces and moments that are induced by the environment, mooring load and thrusters. Gunnu and Moan (2016) described that the vessel's stability can be assessed by assessing the vessel's static heeling angle (static heeling angle) and comparing it with the critical static heeling angle or the vessel's dynamic rolling angle and comparing it with the vessel's critical rolling angle. The vessel's critical static heeling angle is considered to be a limit state in this study. During AHOs, the vessel master requires precise and easily understandable information on the current vessel's situation, such as a vessel's static heeling angle. This information is useful for assessing the vessel's safety margin with respect to the vessel's critical heeling angle for a given maximum possible dynamic rolling angle in the waves (for a given set of operating sea states). Further, this information is useful for making good decisions for preventing critical scenarios. Compared to the current situation on-board of the AHVs, the vessel's static heeling angle information can be predicted with the help of an on-board integrated monitoring system. The authors are not aware of published information about an on-board integrated monitoring system for assessing the vessel's stability during AHOs. Hence, an on-board condition monitoring is currently needed for predicting the vessel's stability during AHOs. In the present study, an integrated monitoring system (see Fig. 2) has been proposed for assessing the vessel's static heeling angle (based on monitoring operational parameters) during AHOs. The vessel's stability margin was calculated with the help of the proposed on-board integrated monitoring system, which provides the master with more information on the vessel's stability than ever before. This innovation helps the master to make better rational decisions.

3. Neural network methodology

In many engineering applications, two basic modelling approaches

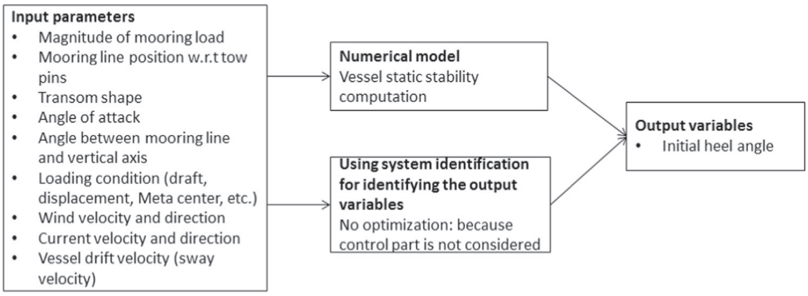

Fig. 2. Outline of the integrated monitoring system for AHV stability during the operation phase.

have been widely used, namely, analytical methods based on first principles and empirical methods. To model the vessel's stability, analytical models are too difficult to construct due to the complexity that is involved. Empirical models are developed based on the input and output data collected through experiments or numerical simulations. These models establish the functional relationship between the input and output data. Prediction based on empirical models can be quite useful and accurate. Zhou (2002) described that empirical models are further divided into statistical models (e.g., polynomial form, regression model) and artificial neural network (ANN) models. Statistical models established by the Rahola (1939) serve as the basis for the current IMO stability regulations for conventional vessels which are used for cargo and passenger transport. These models were established by taking into account of the accidents category related to the vessel's stability between the last quarter of the 19th century and early 20th century. However, AHV's stability during AHOs have differed from that of the conventional vessel's stability in the transport mode. In lack of relevant experience data, in this study, ANN model is used to establish the relationship between relevant variables (operational parameters) and the vessel's stability parameters which is the vessel's static heeling angle.

The popularity of ANNs has been demonstrated in many applications in different sectors such as engineering, military, marine, economics, and medicine. ANN methods are very flexible and have been applied in data modelling, classification, identification, optimization, prediction, forecasting, data and image compression, pattern recognition, and control of complex systems, and especially in establishing nonlinear functional relations (functional approximation) between input and output variables. Shao and Murotsu (1997) used a neural network to develop a limit state function for estimating the reliability of a structural system. Similarly, a limit state function that is related to the stability of AHVs can be established for estimating the safety margin of the vessel while conducting AHOs. In this study, an ANN based modelling approach has been used to establish a relation between the vessel's static heeling angle and operational parameters.

3.1. Review of neural network applications

An artificial neural network is a representation of the human brain that attempts to simulate its learning processes (Dzemyda et al., 2012; Haykin, 2009; Lippmann, 1987). The ANN is often called a “Neural Network” or simple neural net. An ANN usually consists of a large number of simple processing elements and interconnections. These processing elements are called neurons, and each neuron has multiple input signals and a single output signal. The output is typically a nonlinear function that is the sum of the weighted input signals of that neuron. According to Rao et al. (2014), ANNs are adequately characterized as computational models that have properties such as the ability to adapt, learn, generalize, and/or cluster, and the ability to organize data in which an operation is based on parallel processing. The learning process within the ANN is achieved by altering the network's weights and bias so that the network can efficiently perform a task. Once the learning process is completed, the trained neural network with the updated optimal weights are capable of predicting an output within the desired accuracy corresponding to an input. In general, the training process is known to be computationally expensive and time consuming. A wide range of algorithms is available for training the network, each of them have their own advantages and disadvantages. These learning algorithms fall into three groups, which are supervised learning, unsupervised learning and reinforcement learning. In this study, the ANN is used for establishing the functional relationship between input and output. For this type of problem, supervised learning technique is considered to be the best technique for training purposes and hence used in this study. Theoretical concepts that are related to ANNs and its learning process are described in dedicated books, e.g., Freeman and Skapura (1991), Golden (1996), Hagan et al. (1996), Hassoun (1995), Haykin (2009); Lippmann (1987), Mehrotra et al. (1997), Principe et al. (1999), Wu (1994), and Zurada (1992).

ANNs have also been used for applications in naval architecture and marine engineering (Ray et al., 1996; Reich and Barai, 2000), oceanography and meteorology (Jain and Deo, 2007), and offshore industries (Chang et al., 2009). Lisowski et al. (2000) proposed a neural network-based classifier that is supportive of the navigator in the process of determining the ship's domain. By using a neural network, Alkan et al. (2004) determined a fishing vessel's initial stability particulars, such as the vertical centre of gravity (KG), the height of the transverse metacentre above keel (KM) and the vertical centre of buoyancy (KB) during the preliminary design stage. Xu and Haddara (2001) developed a hull response monitoring system by considering a multilayer neural network and a back-propagation learning algorithm (Freeman and Skapura, 1991). They concluded that the neural network model is capable of estimating an instantaneous wave-induced vertical bending moment from heave and pitch measurements. Filippo et al. (2012) used ANNs to predict the forecasting of sea level variations. Hashemi et al. (1995) modelled vessel accidents for different combinations of navigating conditions on the lower Mississippi River. They concluded that predictions by an ANN are better than those from multiple discriminate analysis and logistic regression analysis. Van de Ven et al. (2005) used ANNs for the identification of underwater vehicle dynamics. Kamranzad et al. (2011) used ANNs to conduct the forecasting of wave heights in Dayyer of the Persian Gulf for the next 3, 6, 12 and 24 h by using the previous 3 h of data on the wind speed, direction and wave height. Lopes and Ebecken (1997) developed an ANN-based fatigue monitoring system for fixed offshore structures. The monitoring system has been used to assess the accumulated fatigue damage of the structures through an installed on-board data acquisition and processing system.

3.2. Feed-forward neural network

Many types of ANN methods exist, and the most commonly used

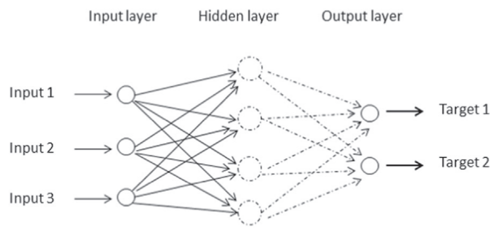

Fig. 3. Structure of the neural network.

type is the feed-forward neural network (Hassoun, 1995). The multilayer feed-forward network consists of multiple layers. These networks have been successfully applied for modelling nonlinear problems (Bishop, 1995; Haykin, 2009). The architecture of this class of network has one or more hidden layers besides the input and output layers. The neurons that are associated with the hidden layers are called hidden neurons. A typical architecture of a multilayer feed-forward neural network is shown in Fig. 3. The circles here represent the neurons, while the arrows represent the weights. The number of neurons in the input and output layers are equal to the number of respective input and output variables. Apart from the training, there are no backward links in the feed-forward neural network. The links proceed from the input nodes to the hidden nodes and similarly from the hidden nodes to the output nodes. A network can have any number of layers, neurons per layer, network inputs and network targets. Each neuron in the network consists of three basic components, i.e., the weights, thresholds, and signal activation function. The weights are nothing but the strength of the input vector. Each input is multiplied by the corresponding weight of the neuron connection. The *+ve* weight excites (stimulates), and the *−ve* weight inhibits the node output. The activation function performs a mathematical operation on the signal output. The network is initialized by choosing arbitrary weights. Before comparing the performance of different ANN architectures, it is important to note that the performance of the same architecture with the same trained dataset can produce dissimilar outputs. This circumstance occurs due to the influence of the initialization weights, which are randomly defined at the beginning of the training process (Hagan et al., 1996). These weights are successively adjusted through an iterative process until the relationship between the set of inputs and outputs is established. This goal is achieved with the help of a training algorithm. During the iterative process, the set of input data is assigned to the input nodes of the network. Moreover, the set of input data propagates forward through the network to the output nodes. The difference between the ANN model predictions and the target values at each output node represents an error that is propagated back through the network to adjust the weights. This is the reason the feed-forward neural network is also called as the backpropagation network. The iterative process continues until it reaches any one of the network parameters, i.e., the mean square error, number of iterations, etc.

3.3. ANN model performance evaluation criteria

The performance of the network model is generally assessed based on the predicted values from the model and the target values. Typical performance measures are the mean square error (MSE), bias (upper and lower bounds), mean average error (MAE), average mean square error ($AMSE$), mean square relative error ($MSRE$), root mean square error ($RMSE$), average absolute error (AAE), mean absolute relative error ($MARE$), standard deviation of error ($St.\,Dev.$), correlation coefficient (PCC), scatter index (SI), index of agreement (I_a), discrepancy ratio (DR) and the coefficient of determination (R^2). In this paper, the bias (from Eq. (11)), $RMSE$ (from Eq. (12)) and CC (from Eq. (13)) were used as the performance measures.

The accuracy of the ANN model can be assessed by plotting the correlation between the target and predicted values using Pearson's coefficient of correlation (PCC). In general, the Pearson correlation coefficient is a linear correlation between two variables and is used as a measure of the degree of linear dependence between two variables. The higher the PCC value is, the better the agreement between the ANN prediction and the target values. If the PCC value is +1, then the model can be considered to be a good model. Furthermore, the present work proposes an extra performance measure, which is the chance (probability) of exceeding a certain level of error magnitude.

Table 1
Operational parameters.

Category	Parameter
Mooring load	Magnitude of mooring load Angle of attack Angle between mooring load and centre plane
Environment	Relative velocity between wind and ship Relative velocity between current and ship
Operational	Vessel sway velocity Mooring line position with respect to tow pins

$$Bias = y_k^{(ANN)} - y_k^{(T)} \tag{1}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(y_k^{(T)} - y_k^{(ANN)})^2} \tag{2}$$

$$PCC = \frac{\sum_{k=1}^{N}(y_k^{(T)} - \bar{y}^{(T)})(y_k^{(ANN)} - \bar{y}^{(ANN)})}{\sqrt{\sum_{k=1}^{N}(y_k^{(T)} - \bar{y}^{(T)})^2}\sqrt{\sum_{k=1}^{N}(y_k^{(ANN)} - \bar{y}^{(ANN)})^2}} \tag{3}$$

4. Neural networks have aided a vessel's stability assessment during AHOs and applications

The vessel's static heeling angle is considered to be a monitored parameter for assessing the vessel's stability margin when the vessel is subjected to operational parameters (see Table 1) during AHOs. These parameters were classified into three main categories, as described in Table 1. A vessel's stability estimation (or prediction) during AHOs depends on the relationship between the operational parameters and the vessel's static heeling angle.

4.1. ANN applied in the study of vessel stability assessments during AHOs

4.1.1. The ANN's vessel's static heeling angle model for stability prediction

The multilayer neural network model consists of the input, multiple hidden and output layers, which are chosen for the network model in this study. The reason for this section is that the multilayer models can extract higher order statistics from the data (Haykin, 2009) relative to the single layer model. In other words, they have better generalization capabilities for establishing a functional relationship (function approximation modelling) in complex relations, e.g., the vessel's static heeling angle estimation while subjected to the operational parameters during AHOs. Preliminary investigation of the number of hidden layers reveals that one hidden layer is efficient enough and appropriate for this application. Accordingly, a network topology with one hidden layer was considered in this study (see Fig. 4), i.e., the network topology was composed of three layers (input, output and one hidden). In the considered network topology, the number of neurons in the input and output layer were equal to the same respective number of input and output variables. The present study considers seven input neurons and one output neuron. Furthermore, the hidden layer (or middle

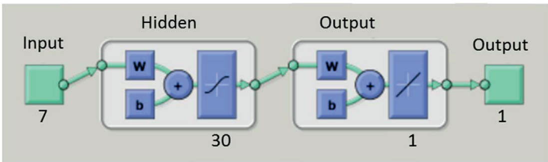

Fig. 4. Optimized neural network topology.

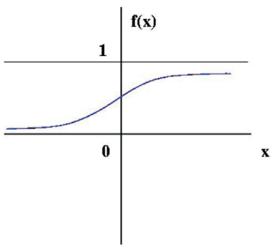

Fig. 5. Log sigmoidal and unipolar threshold.

layer) consists of m neurons. The ANN model efficiency depends on the number of neurons in the hidden layer and their sigmoidal functions. Unfortunately, there is no general rule (or algorithm) for finding the optimal number of neurons and their sigmoidal functions. In general, the number of neurons in the hidden layer, M, must be found from the method of trial and error (Pu and Mesbahi, 2006).

4.1.2. Selection of input and output variables

The neuron in the output layer shown in Fig. 4 represents the vessel's static heeling angle. The major operational parameters that can affect the vessel's static heeling angle (described in Table 1) are the magnitude of the mooring load; the angle between the vertical axis and mooring load; the angle of attack; the wind, the current, and the vessel's drift velocities in the transverse direction; as well as the tow-pin configurations. These parameters are called network input variables, and the corresponding information processing nodes are called neurons in the input layer. Symbolically, these components are described below:

- Network input parameters:
- Network output parameter: y_k= vessel's static heeling angle (ϕ_0).

The relationship between the neurons of the input and hidden layers are defined as follows:

$$a_j = \sum_{i=1}^{7} w_{ji}^{(i)} x_i + w_{j0}^{(1)} \tag{4}$$

where $i = 1,2, \ldots 7$ indicate the number of neurons in the input layer (the same as the network input parameters x_1 to x_7), $j = 1,2, \ldots m$ indicate the number of neurons in the hidden layer (m= 30, as shown in Fig. 4), superscript (1) indicates the parameters between the first layer (input layer neurons) and hidden layer, w_{ji} refers to the weights between the neurons of the input and hidden layers, w_{j0} refers to the biases, and a_j is an input to the hidden layer. The activation quantities, i.e., the outputs of the hidden layer neurons (z_j), are expressed in Eq. (2):

$$z_j = h(a_j) \tag{5}$$

where z_j is an output from a neuron in the hidden layer, and h is the activation function.

The relationship between the neurons of the hidden and output layers is defined as follows:

$$b_k = \sum_{j=1}^{m} w_{kj}^{(2)} z_j + w_{k0}^{(2)} \tag{6}$$

where $k = 1,2\ldots, K$ ($k = 1$, as shown in the Fig. 4) refer to the number of neurons in the output layer, superscript (2) indicates the parameters between the hidden layer and output layer neuron, w_{kj} refers to the weights between the hidden layer neurons and output layer neuron, w_{k0} refers to the biases, and b_k is an input to the output layer. The activation quantities, i.e., the output from the output layer neuron (y_k), are expressed in Eq. (8):

$$y_k = \sigma(b_k) = b_k \tag{7}$$

where y_k is output from the neuron of the output layer, and σ is the activation function, which is linear. Eq. (8) can be redefined as follows:

$$\begin{aligned} y_k(x, w) &= \sigma\left(\sum_{j=1}^{m} w_{kj}^{(2)} h\left(\sum_{i=1}^{7} w_{ji}^{(1)} x_i + w_{j0}^{(1)}\right) + w_{k0}^{(2)}\right) \\ &= \sum_{j=1}^{m} w_{kj}^{(2)} h\left(\sum_{i=1}^{7} w_{ji}^{(1)} x_i + w_{j0}^{(1)}\right) + w_{k0}^{(2)} \end{aligned} \tag{8}$$

where w is the set of all weights and bias parameters, x_i is an input variable, and y_k is an output variable.

4.1.3. Activation function

The choice of activation function (transfer function) is strongly influenced by the complexity and performance of the neural network and plays an important role in the convergence of the algorithm (Chandra and Singh, 2004; Duch and Jankowski, 2001, 1999; Singh and Chandra, 2003). The most commonly used activation functions are the linear, tangent hyperbolic and sigmoidal (S-shaped) functions. The activation function limits the amplitude of the output of a neuron, which is usually called the squashing function (Cybenko, 1989; Lippmann, 1987). It squashes the permissible amplitude range of the output signal to some finite value. The most actively used squashing functions for solving nonlinear problems are the Uni-polar sigmoid (log sigmoid in Matlab), Bi-polar sigmoid, Tanh (tan-sigmoid in Matlab), Conic Section and Radial Bases Function (RBF).

In this study, continuous nonlinear functions are chosen as the activation functions, which are the logistic sigmoidal function (Eq. (6)) and tangential hyperbolic function (Eq. (8)). These functions are differentiable with respect to the parameters of the model. The differentiated logistic sigmoidal and tangential hyperbolic functions are shown in Eqs. (7) and (8), respectively. As shown in Fig. 5, the logistic sigmoidal function has lower and upper bound values of zero and 1, respectively. This sigmoidal function means that the range of the function is [0,1]. The logistic sigmoid function has the following mathematical formulation:

$$h(a_j) = (1+e^{-a_j})^{-1} \tag{9}$$

The derivative of the logistic sigmoid function is

$$\frac{dh(a_j)}{da} = h(a_j)(1-h(a_j)) = z_j(1-z_j) \tag{10}$$

Similarly, as shown in Fig. 6, the tangential hyperbolic sigmoidal

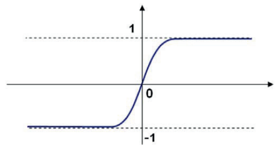

Fig. 6. Tan sigmoidal and Bi-polar threshold.

Table 2
Principle particulars of the AHV.

Overall length	L_{OA} = 75.20 m
Length between particulars	L_{BP} = 64.91 m
Breadth	B = 17.00 m
Draft (mean)	T = 6.50 m
Displacement	Δ = 5332 t
Depth	D = 8.00 m
Bollard pull capacity	180 t
Winch capacity	400 t
Nearby down flooding points	Portside: (0.3, 7.56,8.86) m Starboard side: (0.3, −7.56,8.86) m

Table 3
Vessel stability characteristics without a mooring load.

Displacement	4540.100 t
Centre of gravity	(32.03,0, 6.9) m
Draft at mid ship	5.74 m
Initial trim	0.11 deg. (forward)
Metacentre	1.05 m
Initial heeling angle	0 deg.
Down flooding angle	22.75 deg.
Vanishing angle	48.12 deg.
Maximum righting arm (GZMax)	0.29 m
Angle at maximum GZ occurs	19 deg.
Block coefficient	0.68

function has the lower and upper values of −1 and 1. This sigmoidal function means that the range of the function is [−1, 1]. The tangent hyperbolic sigmoid function has the following mathematical formulation:

$$h(a_j) = \frac{(e^{a_j} - e^{-a_j})}{(e^{a_j} + e^{-a_j})} \tag{11}$$

The derivative of the tangent hyperbolic sigmoidal function is

$$\frac{dh(a_j)}{da} = 0.\ 5(1+h(a_j))(1-h(a_j)) = 0.\ 5.\ (1+z_j).\ (1-z_j) \tag{12}$$

4.1.4. Back-propagation training or error back-propagation algorithm

The training process is also called the ANN learning process. A three-layer fully connected feed-forward neural network that has been widely used for establishing functional relationships between input and output variables has been considered in this study. These networks are very flexible and can be used for data modelling, classification, forecasting, control, and other goals. These feed-forward neural networks were trained with the back-propagation learning algorithm (Freeman and Skapura, 1991; Haykin, 2009; Mehrotra et al., 1997; Patterson, 1998; Zurada, 1992). The neurons in the back-propagation artificial neural networks can be fully or partially interconnected. The term back-propagation refers to the way that the error that is computed at the output layer is propagated backward from the output layer to the input layer through the hidden layer. The algorithm then adjusts the weights and bias. This algorithm is one of the reasons that neural networks have gained popularity. The details of various available training algorithms that are related to the back-propagation and their description can be seen in many books, e.g., Wu (1994), among others. The Levenberg-Marquardt (LM), which is the most commonly used back-propagation algorithm, is considered for training purposes. This algorithm is available as the TRAINLM function in the MATLAB (2015) neural network Toolbox. The initial weights and bias values were generated as random numbers, which were then optimized for a chosen set of training data (which contains a set of inputs and outputs). The training terminates when any one of the following conditions is met:

- The network reaches any one of the network training parameters (such as the number of epochs);
- The maximum amount of time is exceeded;
- The network performance reaches the target error value.

The target error used in this study for training purposes is *MSE*, as described in Eq. (10):

$$MSE = \frac{1}{N}\sum_{k=1}^{N}(y_k^{(T)} - y_k^{(ANN)})^2 \tag{13}$$

where $y_k^{(T)}$ represents the target value of a neuron in the output layer, $y_k^{(ANN)}$ represents the ANN model's predicted value of the neuron in the output layer, and N is a number of data points in the given data set.

In Eq. (13), because the errors are squared before they are averaged, there will be a high dominance of large errors. The *MSE* ranges from zero to ∞. It is known that the lower values of the *MSE* indicate better performance of the network model. In the present study, the termination criteria considered for the network training are the following: the *MSE* is equal to 0.001, and the number of epochs is equal to 5000.

Table 4
Simulation data with input ranges.

Parameter	Data range	Number of parameter values
M_{ML}	75, 90, 110, 130, 145, 160, 170, and 180	8
A	20, 25, 30, 35, 38, 40, 45, 50, 55 and 60	10
B	−85, −75, −65, −55, −45, −35, −25, −15, −5	9
v_w	−40,−35,−30,−20, −10,0,10,20,30,35 and 40	11
v_c	−4, −3, −2, −1, 0, 1, 2, 3 and 4	9
Tow pin configuration	PSO-PSI, PSO-SBI, PSO-SBO, PSI-SBI, PSI-SBO and SBI-SBO.	6
V	−4, −3, −2, −1, 0, 1, 2, 3 and 4	9
Total simulations		3,849,120

4.1.5. Training data resource

In general, the ANN model does not use physical equations of actual models, but instead requires reliable data. Typically, experimental or field data (real-time data) for a sufficient range of events are required to establish the neural network topology. It is difficult and expensive to obtain these data. To establish a methodology, numerically simulated data can be used as the training and testing data. However, it is vital that this simulated data correctly reproduces the important features of the real-time data. Therefore, in this study, the data were obtained from the numerical model developed by the authors Gunnu and Moan (2016) in their earlier study. The data set was generated by using the principle particulars of the Bourbon Dolphin (BD) vessel, which contains a set of input and output data. Table 2 outlines these particulars of the vessel. As was mentioned previously in Section 4.1.2, the present study considers seven input parameters and one output parameter. The input parameters are M_{ML},α, β,v_w, v_c,v and the tow pin configuration. The output parameter is the vessel's static heeling angle. These data are used for training (and testing) the network, i.e., solely for optimizing the weights and bias in the network topology. A well-optimized neural network is said to arise only when the input–output mapping that is computed by the network is correct not only for the training data but also for the testing data (i.e., the data that is not used in creating or training the network).

In this study, the vessel's loading condition 2.1 (condition without a roll reduction tank) from the BD accident report (2008) has been considered to be the initial loading condition. For simplification, the

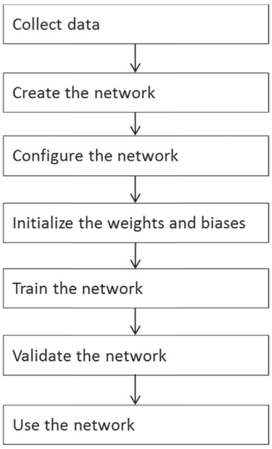

Fig. 7. Flow chart of neural network-based prediction.

free surface correction was kept constant for all of the simulation cases. The static stability characteristics that are associated with the initial loading condition are summarized in Table 3. Based on the mathematical model described by Gunnu and Moan (2016), the vessel's static heeling angle was computed for all of the 7 operational parameters. The input data set covers a wide range of operational parameters, which is listed in Table 4. The generated data was used for both training and testing the network.

4.1.6. Design case

This section describes the construction of ANN models for establishing a functional relationship between input and output variables. A wide range of learning algorithms is used for training ANNs (Bishop, 1995; Principe et al., 1999). Several guidelines and algorithms have been developed for transforming the input data into a form that is more suitable for training the ANN. The training process includes variable selection for determining the optimum number of hidden processing neurons, the specification of the size and the composition of the training, as well as the validation of the network and test sets. In summary, the construction of a neural network model involves data selection, data transformation, variable selection, network building, network training and evaluation. In this study, the operational parameters have been considered to be the input variables, while the vessel's static heeling angle has been considered to be the output variable. For simulating and establishing the neural network topology, MATLAB (2015) with the Neural Network Toolbox was used. A varying number of neurons in the hidden layer can create different network topologies, and the sigmoidal function is related to the neurons in the hidden layer. All of the networks have been developed considering one hidden layer and the vessel's static heeling angle as the only output neuron. Fig. 4 illustrates the structure of the proposed ANN model. The feed-forward neural network with one hidden layer was selected due to its ability to perform a functional relationship between the input and output variables, as described in Section 4.1.2. While selecting the training data, care has been taken to avoid bias to any one of the input parameters. Note that the conditions that were related to the vessel's capsizing were not considered for training purposes because capsizing is not influenced by the static heeling angle of 5 deg. which is considered to be a limit state in this study.

As mentioned before, the ANN model in this work was established by using Neural Network Toolbox 8.4 of MATLAB (2015). For the given set of training data, the neural network updates the weights and bias values with a learning algorithm until the network reaches its network performance parameters. The updating of the network weights between successive training cycles (epochs) depends on the defined learning rule. There are four basic types of rules (Hassoun, 1995; Haykin, 2009). The present work uses a multilayer feed-forward network with the most commonly used back-propagation algorithm (Freeman and Skapura, 1991). The network is trained to contain all of the necessary information from the training data set, which allows it to take considerably less storage space. The trained network can be used to generalize and predict the parameters that the network was not

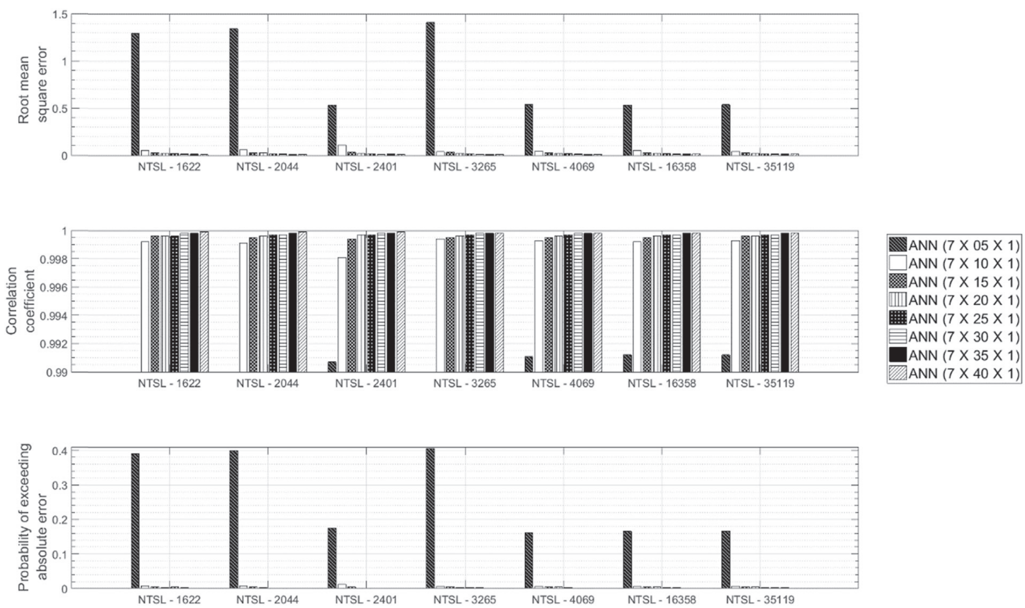

Fig. 8. (a) Root mean square error ($RMSE$), (b) The correlation coefficient (PCC), and (c) The probability of exceeding the absolute error (error < -1 and error > 1) for a training data set with a different trained network topology by considering tan-sigmoidal as a sigmoidal function.

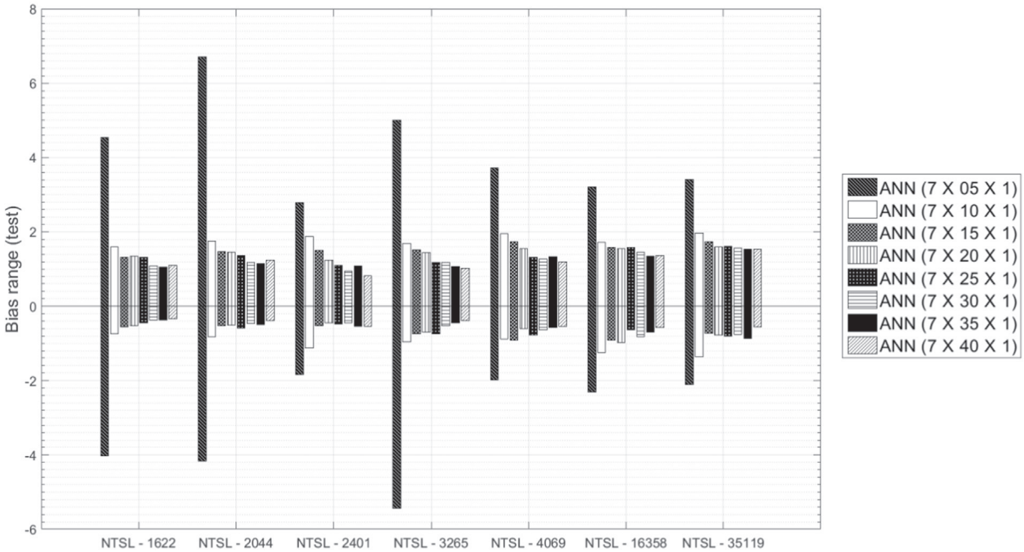

Fig. 9. The error range for a training data set with a different trained network topology by considering the tan-sigmoidal as a sigmoidal function.

exposed to earlier. The success of neural network training depends on various network topology parameters such as the number of hidden layers, the number of neurons associated with each hidden layer, the learning algorithm, the activation function of the neurons and the training data set. However, it is difficult to predict the best combination of network parameters. As the number of hidden layers increases, the neural network is capable of extracting higher order statistics from the data that it obtains (Haykin, 2009). Furthermore, the advantage of choosing a particular activation function (or transfer function) over another is not thus far theoretically understood (Hassoun, 1995). Therefore, a parametric study was conducted for determining the best combination of these parameters. The steps that are associated with the neural network based vessel's static heeling angle predictions are depicted in Fig. 7.

5. Design of the appropriate neural network topology

As mentioned before, the performance of the ANN model depends on the network topology parameters, such as the hidden layers, the number of training iterations (epochs), the learning factors, the number of neurons in the hidden layers and the sigmoidal functions related to the neurons. To establish an efficient network topology, a

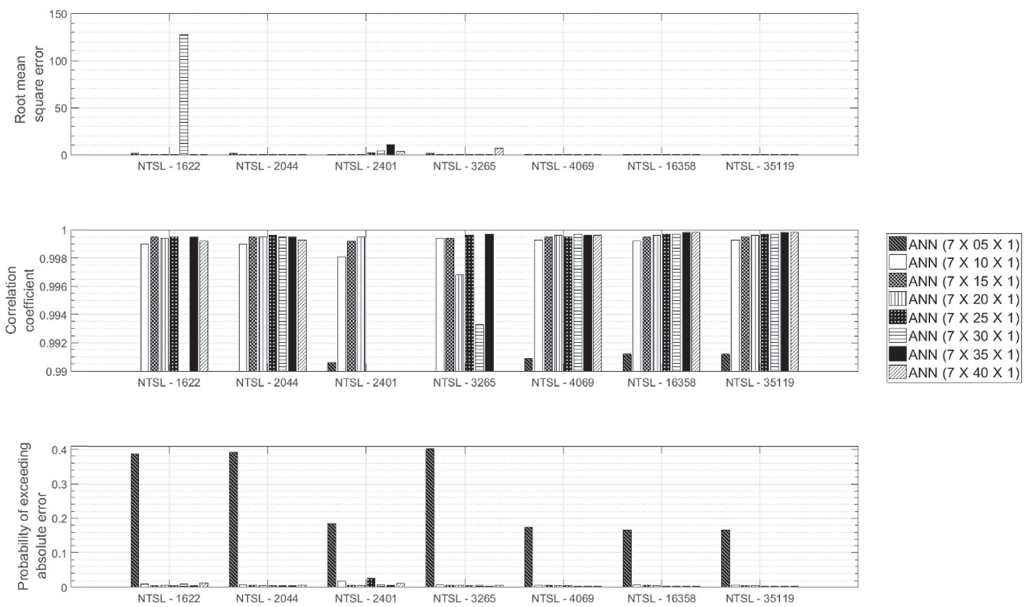

Fig. 10. (a) Root mean square error (*RMSE*), (b) Correlation coefficient (*PCC*), and (c) Probability of exceeding the absolute error (error < -1 and error > 1) for a test data set with a different trained network topology by considering the tan-sigmoidal as a sigmoidal function.

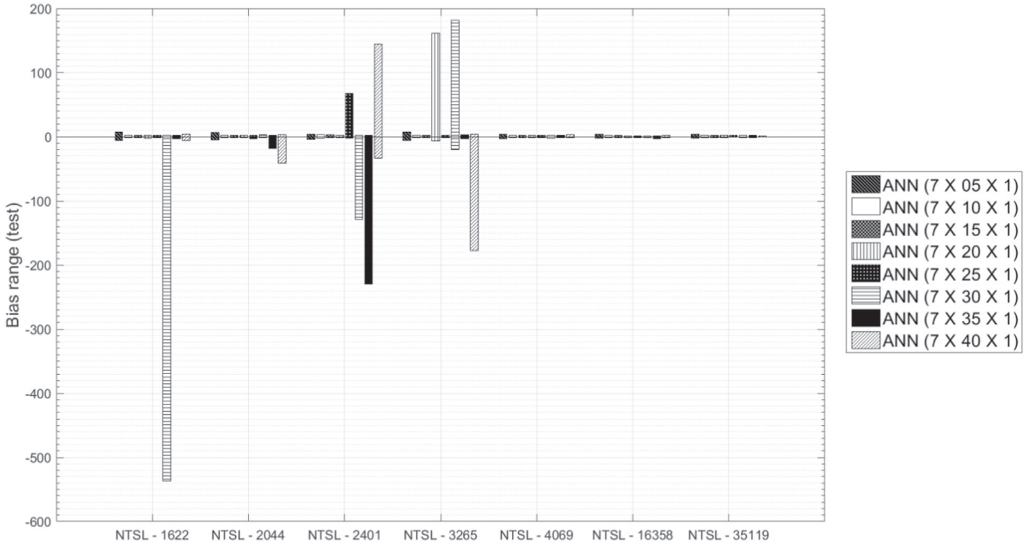

Fig. 11. The error range for a test data set with a different trained network topology by considering the tan-sigmoidal as a sigmoidal function.

series of neural network simulations was performed. These network topology parameters were found by the method of trial and error. The training and testing data sets were obtained from the data generated by the numerical simulation model (3,849,120 data points in total), as described in Gunnu and Moan (2016). The ANN model was used for establishing the relationship between the physical parameters, such as the operational parameters and the vessel's static heeling angle. Sufficient and well-distributed input data selection is a basic requirement for establishing an efficient ANN model. The chosen length of the data set of training cases varied from 1622 to 35,119 data points (0.0519% to 1.1239% of the available data from the mathematical model, after removing the data related to capsizing conditions). The testing data set contains 3,124,678 (100%) data points (after removing the data related to capsizing conditions). The network topology parameters, such as the number of neurons and the activation function, were varied until a global least error was achieved. The network performance was quantitatively compared with statistical parameters such as bias, $RMSE$, PCC and chance of exceeding the error by absolute 1 deg. This error is acceptable for engineering applications. The prediction of the vessel's static heeling angle for given operational parameters depends on the network topology. As discussed before, the network topology ($ANN - 7 \times M \times 1$) consists of seven neurons in the

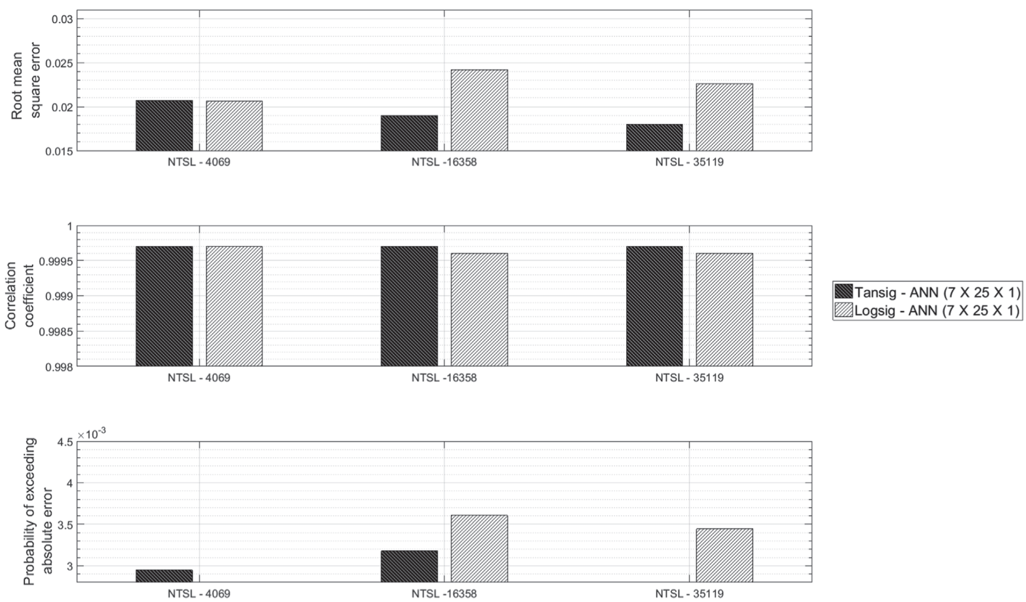

Fig. 12. (a) Root mean square error ($RMSE$), (b) Correlation coefficient (PCC), and (c) Probability of exceeding the absolute error (error < -1 and error > 1) for a training data set with a trained network topology ($\mathrm{ANN} - 7 \times 25 \times 1$).

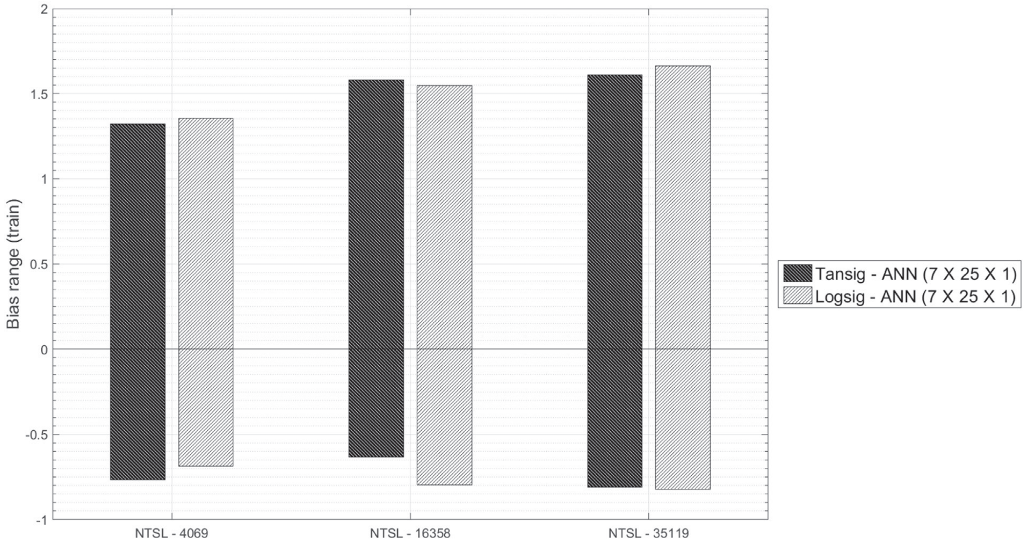

Fig. 13. The error range of the training data set for a network topology (ANN $-$ 7 $\times$ 25 $\times$ 1).

input layer, one neuron in the output layer and one hidden layer. The hidden layer has M neurons, which have variable sigmoidal functions. The optimal combination of the above-mentioned variable neurons and sigmoidal functions were studied in this section.

5.1. Effect of the number of hidden layer neurons on the network performance

The first parametric study that is related to the network topology investigates the effect of the number of neurons in the hidden layer (M) on the network performance, while considering the variable number of data points (N) in the training set and the tan-sigmoidal function as an activation function for all of the neurons in the hidden layer. Fig. 8(a) shows that for a chosen number of data points N =35,119 and given that the number of neurons in the hidden layer M ranges from 5 to 40, the root mean square error ($RMSE$) reduces from 0.54 deg. to 0.01 deg. Similarly, Fig. 8(b) and Fig. 8(c) show that the correlation coefficient (PCC) increases from 0.9912 to 0.9998 and the probability of exceeding the error reduces from 0.166 to 0.014. Several simulations were performed for testing the neural network model. For testing the case of a given N =35,119 and M ranging from 5 to 40, Fig. 10 shows that the $RMSE$ reduces from 0.54 deg. to 0.01 deg., the PCC increases from 0.9912 to 0.9998, and the probability of exceeding the error reduces from 0.166 to 0.018. From the results, it is clear that the network

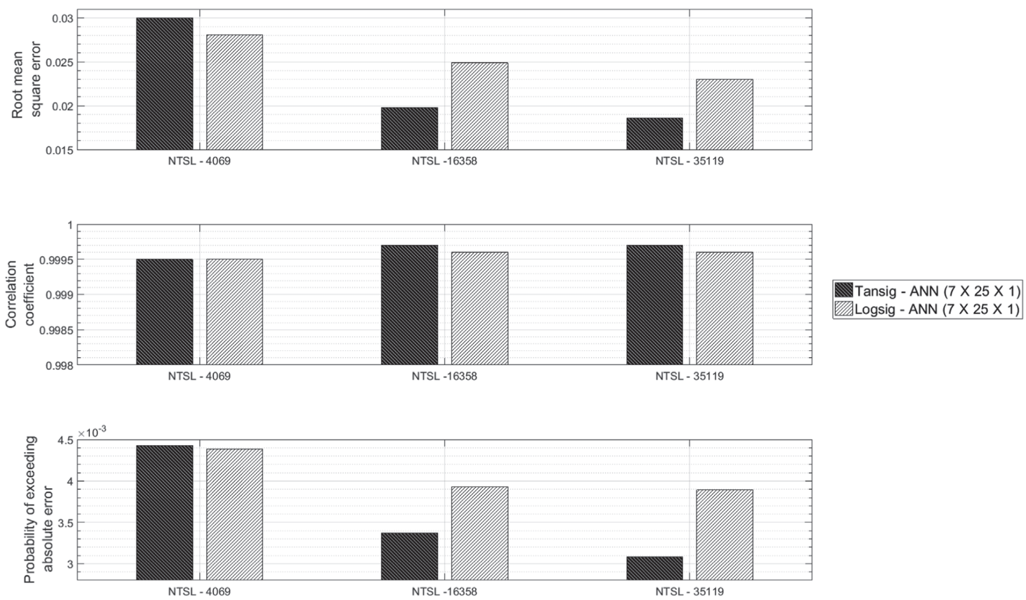

Fig. 14. (a) Root mean square error ($RMSE$), (b) Correlation coefficient (PCC), and (c) Probability of exceeding the absolute error (error < -1 and error > 1) for a test data set with a trained network topology (ANN $-$ 7 $\times$ 25 $\times$ 1).

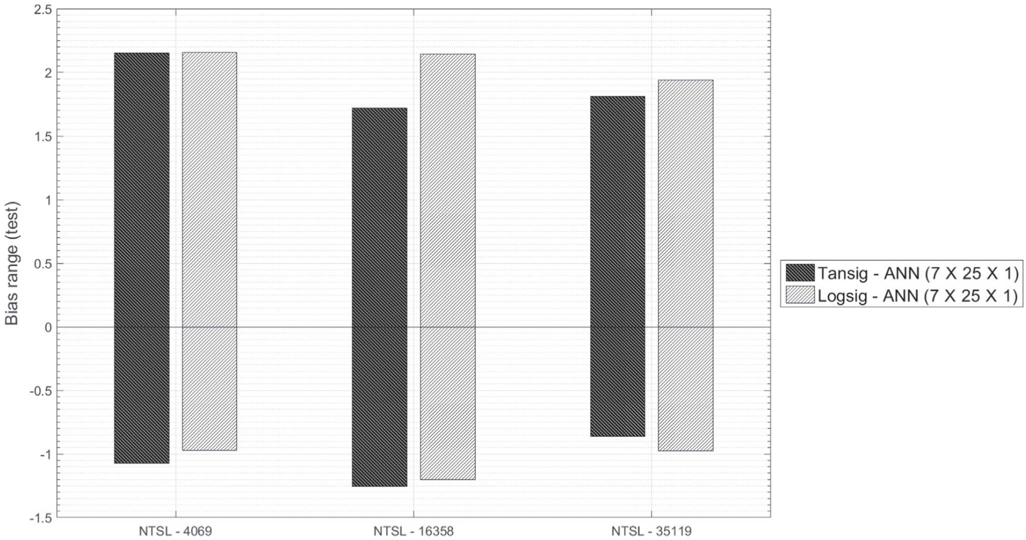

Fig. 15. The error range of the test data set for a network topology (ANN − 7 × 25 × 1).

performance increases with an increased number of neurons in the hidden layer. However, Fig. 9 and Fig. 11 do not show any trends that involve bias.

5.2. Effect of the lengths of the training data sets on the network performance

The second parametric study examines the effect of the number of data points (N) in the training data set on the network performance while considering the variable number of neurons in the hidden layer (M) and tan-sigmoidal function as an activation function for all of the neurons in the hidden layer. Fig. 8 shows that the root mean square error (*RMSE*), the correlation coefficient (*PCC*) and the probability of exceeding the error do not follow any particular trend for a number of data points in the training data set N ranging from 1622 to 35,119 points. In the case of testing, it can be noted from Fig. 11 that the error range is acceptable when N exceeds 4069 points. A possible reason behind this finding is that the ANN performance depends on the quality of data that is used for the training along with the number of points in the data set. On the other hand, the time required for training the network increases with the increased number of data points in the training set. Based on the results, it can be included that an optimal network can be achieved based on the network performance and network training duration.

5.3. Effect of the hidden layer sigmoidal function on the network performance

Similarly, the third parametric study related to the network topology investigates the effect of the sigmoidal function in the hidden layer neurons on the network performance while considering the variable number of data points (N) in the training set and a constant number of neurons in the hidden layer (M=25). Fig. 12(b) and Fig. 14(b) show that both the tan and log sigmoidal functions yield almost the same predictions of the correlation coefficient (*PCC*). Fig. 13 and Fig. 15 show a similar effect on the error range for the training and testing cases, respectively. For the training case of given number of data points N =35,119 points, Fig. 12(a) shows the *RMSE* error values 0.0180 deg. and 0.0226 deg. for the transfer functions of the tan-sigmoidal and log sigmoidal, respectively. For these functions,

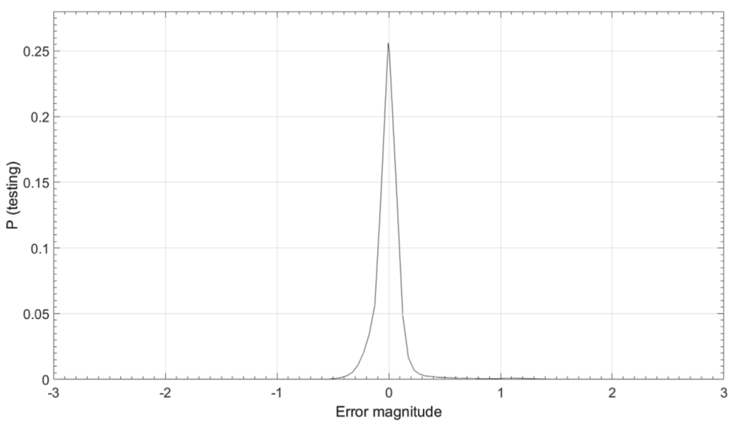

Fig. 16. Probability error distribution of the test data with a training network topology ANN − 7 × 30 × 1, tan-sigmoidal function and training data set with 35,119 data points.

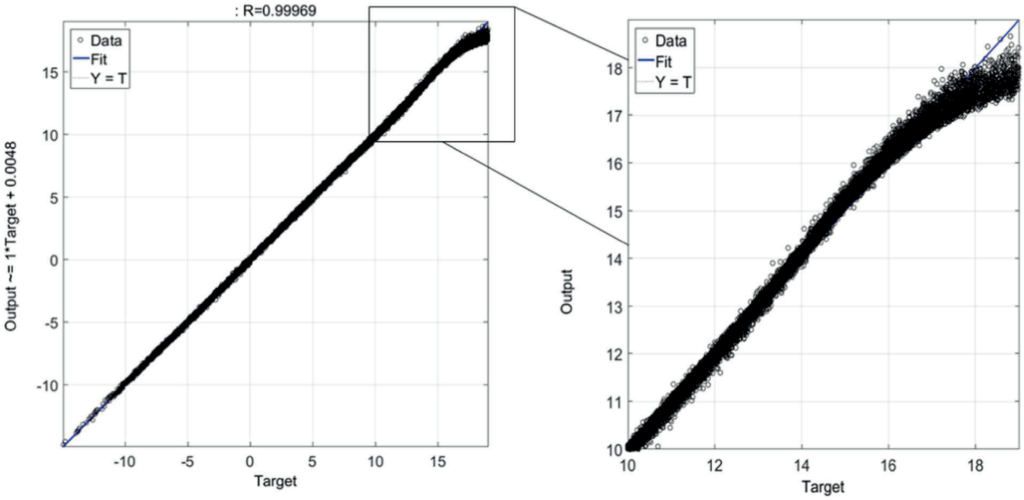

Fig. 17. Comparison between the target (mathematical model) and output (ANN – 7 × 30 × 1 model with a tan-sigmoidal function and training data set with 35,119 data points) prediction on the vessel's static heeling angle.

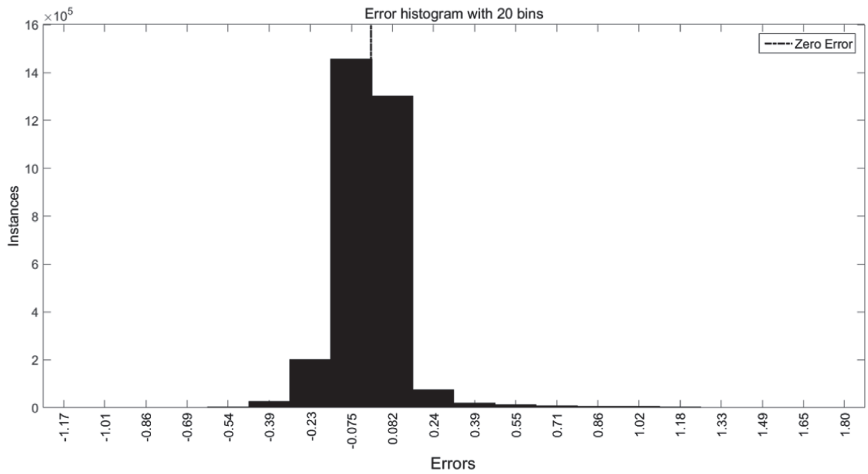

Fig. 18. The error histogram of the vessel's static heeling angle for test data with a training network topology ANN – 7 × 30 × 1, tan-sigmoidal function and training data set with 35,119 data points.

the values of the probability of exceeding the error are 0.00027 and 0.0034, as shown in Fig. 12(c). It can be noted from Fig. 12(c) that the tan-sigmoidal function is more effective than the log sigmoidal. The model with $N = 4069$ points is considered to be the base model obtained from network training and is used for testing. Fig. 14 presents the results from the testing cases and further shows that the tan-sigmoidal function is more effective.

5.4. Optimal network topology

The best network topology for predicting the vessel's static heeling angle was identified with the help of a parametric study described in Sections 5.1–5.3, which is ANN – 7 × 30 × 1 (as shown in Fig. 4). The transverse function in the hidden layer for this network topology is tan-sigmoidal function. This network performed well compared to the other network topologies that were considered in this study. The performance of this network was evaluated by considering the number of data points N = 35,119 in the network training. For a test case, the predicted values of *PCC* and RMSE are 0.09997 and 0.016, respectively. Fig. 16 shows that the bias of the static heeling angle is in the range of −1.12 deg. to 1.79 deg. and the probability of exceeding the bias is 0.0024. These results indicate that there is an acceptable fit between the estimated and actual static heeling angles. Although the statistical analysis shows a good correlation between the ANN and the actual value, Fig. 17 shows a large bias between the prediction of the ANN model and the target values wherever the static heeling angles are larger (static heeling angles > 10 deg.). However, our interest is that the vessel's static heeling angle is within the range of −5 deg. to 5 deg., and the bias that occurs at a larger static heeling angle can be disregarded. The error distribution from Fig. 18 shows that the error is typically within the range of ±0.5 deg. The error statistics within this range are acceptable for engineering applications. Based on these results, it can be concluded that the proposed methodology can be used for an on-board monitoring system for assessing the AHVs stability during the operational phase.

6. Concluding remarks

Condition monitoring is essential to ensuring safety during an anchor handling operation. The static heeling angle is the main parameter for characterizing the stability of an anchor-handling vessel. The static heeling angle depends on the operational parameters, such as the mooring load, the angle between the vertical axis and the mooring load, the angle of attack (the angle between the mooring line and the vessel's centreline), and the forces caused by the thrusters; the wind and current can be of influence during the operation. A reliable on-board monitoring system is essential for assisting the vessel master at making a reliable decision for preventing capsizing. Even though there are several on-board monitoring systems that are available, none of them can predict the vessel's stability margin during AHOs. Therefore, it is necessary to integrate the available on-board condition monitoring system for assisting the vessel's stability status. This action will provide benefits such as an early indication of capsizing scenario assessment, which makes it possible to achieve better stability control of the vessel, optimal performance of the vessel, cost efficiency and easy readability. However, a complete mathematical model is still not available for establishing the condition monitoring. Therefore, the purpose of this study has been to establish an estimate of the vessel's static heeling angle as a function of the operational parameters during AHOs.

In the present work, ANN methodology is applied to establish a functional relationship between the operational parameters and the vessel's static heeling angle. The efficiency of the ANN model depends on the network topology and its training. The optimization of the neural network topology depends on the number of hidden layers, the number of neurons associated with each layer, the choice of the hidden activation function associated with the neurons, and the data used for training the network (the number of training data points and its distribution). The network performance was assessed by statistical parameters such as the bias, root mean square error, correlation coefficient and probability of exceeding the error. The numerical simulation of the training and test data demonstrated the effectiveness of the ANN approach in terms of these statistical parameters (the network performance measures). The following conclusions are drawn from this study:

- The network topology that contains one hidden layer is efficient and accurate enough to predict the vessel's static heeling angle.
- The network performance can be enhanced by increasing the number of well-distributed data points in the training data set.
- The correlation between the predictions of the ANN model and the target values is improved by increasing the number of neurons in the hidden layer. However, the error range could be increased slightly by increasing the number of nodes due to the "over fitting".
- The mean square error depends on the activation function for a given ANN topology and the training data. This relationship occurs because the network learning rate and momentum depend on the activation function.
- The best activation function depends on the training data set that is used for the training. In the current case, the tan-sigmoidal function was found to be more efficient than the log-sigmoidal function.

In the current study, the vessel's stability was analysed by using the proposed method with a combination of neural network and numerically simulated data. The optimized neural network topology and hidden layer neuron sigmoidal functions were identified, which are ANN – $7 \times 30 \times 1$ and tan-sigmoidal. For this network topology, the predicted results yield a correlation coefficient of 0.999 between the neural network model output and the target values. This finding demonstrates that the neural network model is efficient for predicting an AHV's static heeling angle with an acceptable accuracy.

This study is especially focussed on a numerically simulated data set (for training and testing) that was obtained using the particulars of the Bourbon Dolphin vessel. For the robustness and accuracy of the model predictions, it is recommended that in the future, we investigate the model efficiency by using data sets from other vessels. In addition, refined conclusions with respect to the efficiency of the model can be drawn by evaluating the model against the real-time applications data.

The ANN based condition monitoring system proposed in this study itself would not prevent capsizing event. But the proposed system can be used as a tool to assist the vessel's master in terms of the vessel's stability margin (as it is a function of the vessel's static heeling angle) to avoid accidental events like the one experienced on the Bourbon Dolphin accident.

Acknowledgments

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Appendix A. A review of the Bourbon Dolphin accident

A1. Accident background

The Bourbon Dolphin capsized with a crew of 15 west of Shetland, while performing anchor handling work at the Transocean Rather on 12 April 2007 (Gibson, 2008; Lyng et al., 2008) eight lives were lost. The official report of the Bourbon Dolphin accident (2008) reveals that the accident did not occur only because of a coincidence of independent technical and human errors. Rather, it was due to a systematic change in the organizational behaviour of the operators, which was influenced by economic pressure in a strongly competitive environment. Various stakeholders such as operator, shipyard, regulatory and governmental bodies in their respective roles are involved in a sequence of events leading to this accident. Possible errors made by the vessel operators are the final acts in a long and complex chain of organizational and systematic errors (i.e., the so called latent factors). Besides that, the lack of suitable operational safety limit, safety evaluation, situational awareness, condition monitoring systems and decision-making are the main causes behind this accident.

A2. Sequence of events related to the accident from a physical and technical point of view

The key sequence of events (see Fig. A.1) illustration related to the Bourbon Dolphin accident is as follows: vessel drift-off (with respect to the desired mooring line track), resulting in a large angle of attack of the mooring line, a large overturning moment due to the large forces acting in the vessel's transverse direction, a large initial heeling angle (or static heeling angle) and eventually the vessel capsizing. First, the excessive drift-off from the planned anchor track is an initiating event related to this accident. During this accident, the current velocity increased and exceeded the

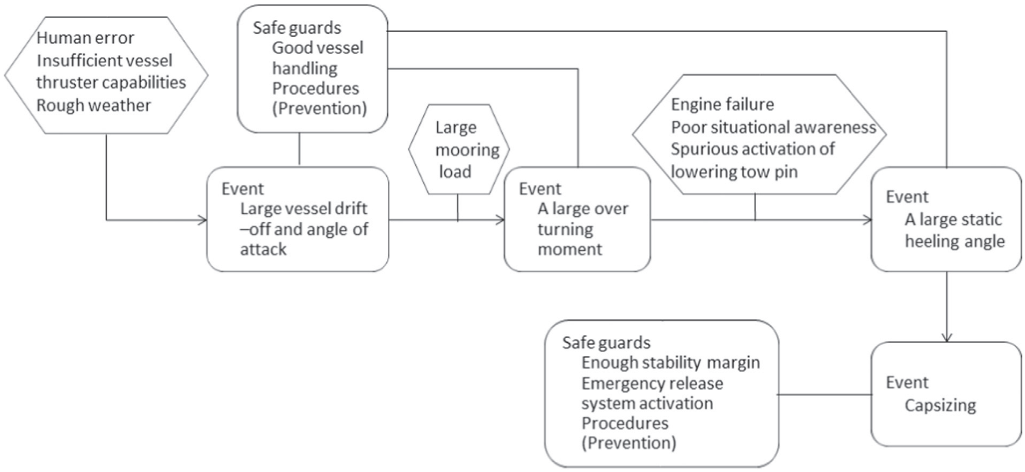

Fig. A.1. Sequence of events relating to the Bourbon Dolphin vessel capsizing.

allowable limit as documented in the rig move procedure. Thus, the current force of the mooring line and hull increased significantly. Moreover, the vessel was lacking sufficient thruster capacity to maintain the vessel position and direction in line with the planned track. Then, the vessel started drift-off away from the desired path and direction. As a result, the vessel's drift-off and angle of attack increased. The vessel did not have enough stability margin to resist the large force acting in the vessel's transverse direction due to the large angle of attack, leading to capsizing.

However, the accident could have been prevented if the vessel's master either had stopped the operation before commencing it, or had executed an effective control measure before moving the vessel into an accidental situation. To act in time, the master should have a clear idea before abandoning or delaying the operation due to its negative result on the cost of the project. According to the present practice of executing the operation (from the starting to last stages), the AHV's master continuously checks the available information on board, such as environmental parameters (wind parameters from wind sensors and wave information from the rig/other resource), the magnitude of the mooring load at the winch monitor, the vessel position and heading, and vessel drift-off. Moreover, the master must monitor vessel heading and position with respect to the rig and target location (Navigation software is used for this purpose). However, the existing systems do not provide assistance to the master regarding the vessel's condition (stability margin) during the decision-making process.

These event sequences can be prevented or mitigated by strengthening existing safety barriers and/ or providing additional safety barriers. To strengthen these barriers, a better vessel design, robust positioning capability and stability criteria, a suitable operational limit state, effective operational planning, better situational awareness (through condition monitoring system), a decision support system, effective crew training, and statutory requirements are required.

A3. Causes of the accident

The direct and indirect causes connected to the sequence of events in the Bourbon Dolphin accident are listed below:

Direct causes.

- External forces from weather and current;
- Unfavourable heading of the vessel in relation to external forces;
- Machinery black out and the consequent reduction of manoeuvrability;
- Lowering the towing pin, which led to larger angle of attack;
- Loading condition and vessel stability characteristics.

Indirect causes.

- Weakness in vessel design;
- Poor planning and absence of an effective risk analysis;
- Lack of situational awareness concerning the development of the large vessel drift-off and static heeling angle;
- Lack of awareness of the effect of influencing factors on the vessel static heeling angle and stability margin;
- Lack of experience and skills in vessel handling when maintaining the balance between the vessel drift-off and static heeling angle;
- Delay in identifying corrective actions due to poor situational awareness;
- Human behavioural factors such as shortcuts, negligence, taking chances, working environment / work load, allowing frustrated actions and procedural errors;
- Improper training and planning;
- Failure of systems engaged in operations.

A4. Key conclusions from the investigation report

The Bourbon Dolphin accident was investigated by the UK Health and Safety Executive, the Norwegian maritime authorities and a Norwegian Royal Inquiry Commission, which reported their findings on 28 March 2008. This report (Lyng et al., 2008) describes how a series of problems and misunderstandings caused the oil rig support AHV to capsize. All aspects of the operation up to and after capsizing were investigated in depth by the Commission, Transocean (the owners of the rig), and Chevron (the operator, that hired the vessels). It is clear from the accident report that vessel stability is an issue, and it had been paramount in the minds of the crew of the ship. If the vessel master (or person in charge of a vessel during an AHO) had been provided with appropriate information timely, there would not have been a capsizing event.

Key conclusions of the accident report (Lyng et al., 2008) findings are listed below:

- The vessel was built and equipped as an all-round AHSV (Anchor Handling Supply Vessel). Uniting these functions poses special challenges. In addition to bollard pull, anchor-handling demands thruster capacity, powerful winches, large drums and equipment for handling chains. Supply and cargo operations demand the largest possible, and flexible, cargo capacities both on deck and in tanks. The “Bourbon Dolphin” was a relatively small and compact vessel, in which all of these requirements were to be united.
- The company had no previous experience with the A 102 design and ought therefore to have undertaken more critical assessments of the vessel's characteristics, equipment and, not least, operational limitations during both her construction and her subsequent operations under various conditions. The company did not notice that the vessel had experienced an unexpected stability-critical incident approximately two months after delivery.
- The vessel's stability-related challenges were not clearly communicated from the shipyard to the company and onwards to those who were to operate the vessel.
- Under given load conditions, the vessel did not have sufficient stability to handle lateral forces. The winch's pulling power was over-dimensioned in relation to what the vessel could actually withstand concerning stability.
- The anchor-handling conditions prepared by the shipyard were not realistic, nor did the Norwegian Maritime Directorate's regulatory system make any requirement that these conditions be approved.
- The International Safety Management (ISM) Code demands procedures for the key operations that the vessel is to perform. However, despite the fact that anchor handling was the vessel's main function, there was no vessel-specific anchor-handling procedure for the “Bourbon Dolphin”.
- The company did not follow the ISM code's requirement that all risk should be identified.
- The company did not specify sufficient requirements for the crew's qualifications for the demanding operations. The crew's lack of experience was not compensated for by involving experienced personnel.
- The master was given 1½ hours to familiarize himself with the crew and vessel and the ongoing operation. In its safety management system, the company has a requirement that new crews shall be familiarized with (inducted into) the vessel before they can take up their duties on board. In practice, the master familiarizes himself by overlapping with another master who knows the vessel before he himself is given the command.
- Neither the company nor the operator ensured that sufficient time was made available for handover in the crew change.
- The vessel was marketed with a continuous bollard pull of 180 t. During an anchor-handling operation, thrusters are always used in practice for manoeuvring and dynamic positioning. The real bollard pull is then materially reduced. The company did not itself investigate whether the vessel was suited to the operation, but left this decision to the master.
- The company did not see to the acquisition of information about the content and scope of the assignment the “Bourbon Dolphin” was set to perform. The company did not itself do any review of the Rig Move Procedure (RMP) with a view to risk exposure for crew and vessel. The company was thus not in a position to offer guidance.
- The Norwegian classification society Det Norske Veritas (now DNVGL) and the Norwegian Maritime Directorate were unable to detect the failures in the company's systems through their audits.
- In specifying the vessel, the operator did not consider that the real bollard pull would be materially reduced by using thrusters. In practice, the “Bourbon Dolphin” was unsuited to addressing the great forces to which the vessel was exposed.
- The mooring system and the deployment method chosen were demanding to handle and vulnerable in relation to environmental forces.
- Planning of the RMP was incomplete. The procedure lacked fundamental and concrete risk assessments. Weather criteria were not defined, and the forces were calculated for better weather conditions than those operated in. Defined safety barriers were lacking. It was left to the discretion of the rig and the vessels whether operations should start or be suspended.
- In advance of the operation, no start-up meeting with all involved stakeholders was held. The vessels did not receive sufficient information about what could be expected of them, and the master misunderstood the vessel's role.
- The procedure demanded the use of two vessels that had to operate at close quarters in different phases during the recovery and deployment of anchors. The increased risk exposure of the vessels was not reflected in the procedure.
- The procedure lacked provisions for alternative measures (contingency planning), for example, in uncontrollable drifting from the run-out line, nor were there guidelines for when and how such alternative measures should be implemented and what, if any, risk these measures would involve.
- The deployment of anchor No. 2 was commenced before the considerable drifting during the deployment of diagonal anchor No. 6 had been evaluated.
- Human error occurred on the part of the rig and the vessels during the performance of the operation.
- Communication and coordination between the rig and the vessel was defective during the last phase of the operation.
- Lack of involvement occurred on the part of the rig when the “Bourbon Dolphin” drifted.
- The roll reduction tank was most likely in use at the time of the accident.
- The inner starboard towing pin had been depressed, and the chain was lying against the outer starboard towing pin. The chain, thereby acquired a changed angle of attack.

A5. Recommendations for preventing AHVs accidents in future AHOs

The following measures would either prevent accidents or reduce the risk of accidents during different phases of the operation:

- Design phase: Designing the vessel with a sufficient stability margin;
- Analysis phase: Conduct an appropriate operational risk assessment by considering the vessel stability and positioning capability;
- Planning phase: Define risk mitigation strategies and action plans for when the vessel is operating in critical situations;
- Execution phase: Provide situational awareness on vessel stability status (stability margin with respect to criticality) and assist in reducing the overturning moment in terms of control measures (heading, transverse thrust and mooring line tension).

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A.5. Paper 5

Decision Support System for ensuring the stability of anchor handling vessels during operations

Authors: Giri Rajasekhar Gunnu, Torgeir Moan

Manuscript phase.

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A.6. Paper 6

Anchor Handling Vessel Behavior in Horizontal Plane in a Uniform Current Field During Operation

Authors: Giri Rajasekhar Gunnu, Xiaopeng Wu, Torgeir Moan

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A.7. Paper 7

Positioning capability of anchor handling vessels in deep water during anchor deployment

Authors: Xiaopeng Wu, Giri Rajasekhar Gunnu, Torgeir Moan

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ORIGINAL ARTICLE

Positioning capability of anchor handling vessels in deep water during anchor deployment

Xiaopeng Wu · Giri Raja Sekhar Gunnu · Torgeir Moan

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Abstract The aim of this paper is to study anchor handling vessel (AHV) thrust capacity during anchor deployment, especially in a deep water situation when high external forces are expected. The focus is on obtaining realistic external forces and evaluating the positioning capability of an AHV. Wind, wave and current loads on the AHV are considered. Current load on the mooring line, which is usually excluded in practice, is included in the model as well. The thrust utilisation plot, a concept widely used in the Dynamic Positioning system, is proposed to illustrate the positioning capability of an AHV. The Bourbon Dolphin accident was investigated as a case study using the proposed model and methodology. First, load analysis was performed. The results indicated the importance of applying a reasonable current profile and taking the mooring line effect into account. Then, thrust utilisation plots for normal and accident conditions were compared. The comparison showed that the Bourbon Dolphin might have been in the most unfavourable weather direction in terms of position capability during the accident event. Finally, the effect of mooring line configuration was studied. The results signified that a very long mooring line might challenge the propeller thrust capacity and the propeller thrust loss due to lateral thrust usage needs to be considered. Such an analysis and documentation prior to the commencement of the operation can be used for defining vessel specific limitations and selecting the proper vessel for a specific task.

Keywords Anchor handling · Drifting · Positioning capability · Thrust utilisation plot · Current profile

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1 Introduction

Anchor handling operation (AHO) is considered to be one of the potentially most hazardous and demanding marine operations in the offshore industry. Characterised by bad weather, long working hours and high-tension load, AHOs are inherently dangerous, especially in a deep water situation when high external forces are expected. Meanwhile, the AHOs have a significant economical influence on the offshore projects. According to Saasen et al. [1], AHOs may carry 10–20 % of the total well exploitation cost because hiring the anchor handling vessel (AHV) is expensive. Considering daily hire rates on the spot market, costs may be as high as 900,000 Norwegian krones. The safety and economic factors make the AHO even more important.

The planning and execution of AHO are of significance. Skilled crew and well-designed vessels are needed to fulfil the tasks. Any miscalculation or misjudgment prior or during the operation might lead to project delay and economic loss. In the extreme cases, miscalculation or misjudgment can lead to casualties. The risk associated with AHO was recently demonstrated by the Bourbon Dolphin accident in 2007 [2], which claimed eight lives. The vessel lost stability due to a series of complex circumstances during the job in the Rosebank oilfield. Another loss of AHV was reported in 2003 [3]. The Danish vessel “Stevns Power” lost stability during an anchor retrieval operation. Eleven people died in this accident. Both of the above accidents were characterised by a short time window before the vessel capsized. Despite only two instances of capsizing AHVs in the past decade, the consequences are fatal. How to enhance the safety level of the AHOs remains a challenging topic for all relevant societies, companies and research institutes.

To date, the AHVs are still treated as normal supply vessels with respect to stability requirements. These requirements are not sufficient to address the complexity and the forces involved in the AHOs. Due to huge mooring loads and the constraint of the mooring line hanging over the stern, these vessels face a high risk of capsizing. Taking the mooring line effect into account is indeed necessary, and how to modify the existing rules and regulations or establish related criteria would be of interest. For example, Gunnu and Moan [4] proposed a modified stability criterion for AHVs in the operational phase, in which the initial heel of the vessel due to mooring load was considered.

Situation awareness can also help to reduce the risk level. The AHOs are usually under tight schedules. The desire to be on schedule could hamper the safety of the operations. Both of the two notable accidents mentioned had shown such a desire, which might be one cause of the misjudgement. The master on board needs condensed and easily understood information about the situation to make good decisions. Hukkelås [5] proposed a new anchor handling concept to increase the safety. Situation awareness is the key in this concept. The stability margin is calculated and visualised in real time, which provides the master much more information about the vessel stability than before. Therefore, the master has a higher chance of making rational decisions.

Because the AHO is a series of complex activities, it would be difficult to secure safety for just one or two measures. More risk-mitigation measures need to be developed and added into the overall picture of the operation. For example, the risk influencing factors associated with the Bourbon Dolphin accident have been addressed by Gunnu et al. [6]. The considerable vessel drift during the AHO is considered as an initiating event for this accident. The track plot for the Bourbon Dolphin before the accident is shown in Fig. 1. The red line in the figure indicates the track for the Bourbon Dolphin from the commencement of deploying mooring line no. 2 until the accident. It is shown that in the early stage the vessel was capable of following the planned path of the mooring line. However, the vessel began to drift gradually and continually, paying out more mooring line under unfavourable weather conditions. The blue line shows the track for another AHV at the site that tried to help the Bourbon Dolphin. The black arrows are added by the authors to indicate the mooring line orientation and weather direction. This information will be explained further in the paper.

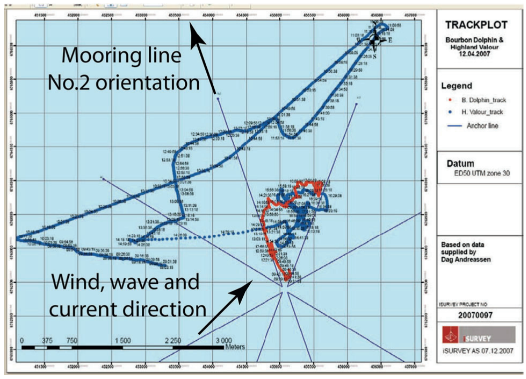


Fig. 1 Track plot of the Bourbon Dolphin (*red line*) [2] (colour figure online)

Extensive drift for the AHV can be unfavourable and even hazardous. First, extensive drift compromises the functionality requirement of the vessel, which is to deliver the mooring line in the desired position. Moreover, extensive drift could compromise safety, which requires maintaining the stability of the vessel. When the master tries to regain the correct course from an extensive drifting condition, it will be very tempting for him to manoeuvre the vessel in a way that develops a large angle of attack (β, the angle between the mooring line and the ship centre line). A plan view of an AHV drifting off course and trying to get back to course is illustrated in Fig. 2. A larger angle of attack means a larger lever arm for the vertical component of the morning load and a larger transverse component of the morning load. The combination of these two leads to larger overturning moment on the vessel which can be hazardous from the vessel stability perspective. Therefore, it is crucial to prevent significant drift and a large angle of attack during AHO, especially in deep water operations due to higher external loads and mooring loads are expected in these operations.

The hazardous conditions related to vessel stability can be averted by means of taking proper decisions and by executing appropriate ship handling skills. In practice, according to the opinions expressed by AHV masters, the hazardous misaligned mooring load can be handled either

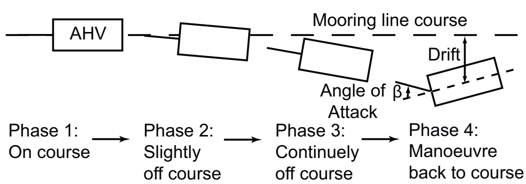


Fig. 2 Off course

by means of reducing the angle of attack (the vessel heading is adjusted such that the misaligned mooring line is in line with vessel heading) or by reducing the mooring line tension. Usually, the master will give priority to the former one because this is an optimised solution at this phase to fulfil both functional and safety requirements. This is achieved by correcting AHV heading first so that the angle of attack will be small and the AHV will be in the phase 1 condition in Fig. 2 in a normal operation. However, lack of ship handing capacity (poor ship positioning capability), or poor ship handling skills (incorrect maneuvering action), or a combination of these two can lead to an extensive drift condition. This might subsequently lead to the phase 4 condition in Fig. 2 when the master try to regain the correct course. The safety, i.e. the stability of the AHV, will then become more important at this stage and the functionality requirement shall become less significant. In such a hazardous situation, the master might reduce the propulsion thrust to reduce the mooring line tension, or even release the mooring line (by activating emergency releasing or quick releasing system) so that the AHV capsize situation can be avoided.

To prevent the unfavourable consequence or hazardous situation caused by the extensive drift, it is essential to have an awareness on the vessel positioning capability. When selecting the proper vessel for an anchor handling task, however, the major concern is normally put on available bollard pull (the maximum pulling force that a vessel can exert on another vessel or object), winch capacity and deck storage space. It seems that the positioning capability is not treated with enough care. The possible consequence is demonstrated in the Bourbon Dolphin accident. If the positioning capability of the vessel was well understood before the operation commenced, the master might have decided to delay the operation until more favourable weather condition came. As a result, there is a need to study the positioning capability of the AHV during anchor deployment. A method needs to be developed to evaluate the positioning capability of the AHV to help all parties involved in the operation gain a better picture before the operation commences. Useful information about the vessel position capability can then be generated, and operation limitation can be obtained. On the basis of this information, critical scenarios can be established as an input to simulator training.

The aim of this paper is to establish and use a detailed numerical model to study AHO during anchor deployment. Focus is put on obtaining realistic external forces on the vessel and evaluating the positioning capability of an AHV. The thrust utilisation plot is proposed to demonstrate the AHV positioning capability. The remainder of the article is organised as follows. The next section gives a detailed description of the main scenario and the flow chart in this work. In Sect. 3, the numerical methodology involved are addressed. Then the Bourbon Dolphin is studied as a case. Analysis and results are presented in Sect. 4. Finally, some conclusions are drawn in Sect. 5.

2 Scenario description and flow chart

There are various types of AHOs, depending on location, equipment on vessel, mooring methods, etc. The practical aspects of AHOs are discussed extensively by Ritchie [7] and Gibson [8]. Among different practical means, one basic method uses the permanent chaser pendant (PCP) system which mainly includes a wire hanging permanently attached to the rig used for chasing out anchors, and a ring fitted over the anchor line connected to the pendant wire. The mooring line can be handled by the rig or by the anchor handling vessel through this system. This method is the least complex method in anchor handling.

Within a PCP anchor handling operation, one common scenario is that the AHV delivers the mooring line to the desired location while the rig pays out the mooring line. This basic but important scenario is illustrated in Fig. 3. During this phase, the vessel is subjected to environmental forces coming from wind, swell, wave and current. In addition, the vessel carries mooring load coming from the mooring line. The magnitude and orientation of the mooring load vary during the whole operation, based on the total pay-out length of the line, the shape of the line, the speed of the vessel and the environmental conditions. The more mooring line has been paid out, the higher the force that will be exerted on the vessel. The vessel should have sufficient bollard pull to counteract the mooring load and provide propulsion forward. To maintain the desired heading, the lateral forces should be balanced by the thrusters and azimuth.

The Bourbon accident happened in this scenario, which makes the scenario very typical and worth studying. According to the accident report, there were several deficiencies in the rig move procedure relevant to this scenario. First, the current load on the mooring line was not included when estimating the static loads on the vessel, resulting in the underestimation of the static loads on the vessel and might be leading to the considerable drift. In fact, the vertical current profile, as will be discussed in this paper,

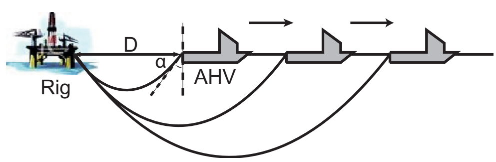


Fig. 3 Typical anchor handling operation

has a significant influence on the mooring line loads. Second, when the side thrusts are running at full capacity, the vessel bollard pull would show a significant drop. The vessel could then be pulled backward by the huge mooring load and could not finish the task. To overcome the deficiencies mentioned above, the thrust utilisation plot which is a concept in the Dynamic Positioning (DP) system, is introduced in this study.

DP capability analysis is an important part in the design of DP vessels as well as DP-related operations. The results are usually presented in the form of capability plots, which are polar plots indicating the limiting mean wind speed envelope for the vessel. More details about the basics of DP capability plots can be found in [9]. When the design sea state is predefined, the DP capability can be presented by means of a thrust utilisation plot, which shows the ratio envelope between the required thrust and the maximum available thrust [10]. The purpose of the DP capability plots and the thrust utilisation plots is to determine the position keeping ability of the vessel under various environmental conditions. In the guidelines for the safe operation of DP vessels, it is mentioned that the DP capability plots should be used in the risk assessment process to determine the safe working limits at offshore installations (see [11]). Because in AHO, the operation weather limit is usually predefined, the thrust utilisation plot is more suitable in this study.

The DP function, except when very small tolerance of positioning is required, is normally not activated by masters during anchor deployment, possibly due to that the vessel being in constant motion and the continued communication between different parties. The masters are normally controlling the vessel manually or keeping the auto head condition. However, every master has his own experience and consequently different control strategy. As a result, it will be difficult to propose a general model to simulate the actions of the masters. The aim of the thrust utilisation plot in this paper, is to propose a reasonable measurement to estimate the capacity of the AHV in the planning stage, but not to look into details of a specific control strategy of a specific master.

In general, the typical AHV forward speed during anchor deployment is about 2–5 knots. Such a speed is considered to be quite low. In an unfavourable weather condition, when maintaining vessel position becomes the main task, the speed could be even lower. Moreover, as mentioned, the master will try to keep the AHV heading in line with the mooring orientation to avoid large angle of attack in a normal operation. Based on these two facts, the forward speed effect is therefore neglected and the angle of attack is assumed to be zero.

The flow chart of the proposed method is presented in Fig. 4. First, based on the given environmental conditions, which are normally given by sea-keeping analysis of the AHV, the mean environmental loads on the AHV can be estimated. Current-induced mooring loads, which can be influenced by current profiles and mooring line configuration, should also be considered. Then the resultant static external force on the vessel in the horizontal plane (surge, sway and yaw) can be obtained. The resultant lateral forces in sway and the resultant yaw moment are supposed to be balanced by the side tunnel thrusters and azimuth thrusters. The resultant longitudinal force in surge is supposed to be withstood by the main propellers. A thrust allocation method should then be applied to obtain the required thrust of the tunnel thrusters and azimuth thrusters, based on the lateral force and yaw moment. Comparing the required thrust with the available thrust, the tunnel and azimuth thrust utilisation plot can be established. The propeller thrust utilisation plot can be generated in a similar manner, except that the available bollard pull will be affected by side thrust usage and needs to be adjusted. Finally, the total thrust utilisation plot can be obtained by combining both the tunnel and azimuth thrust utilisation plot and the propeller thrust utilisation plot.

The main aim of this paper is to:

- Develop a numerical model suitable to simulate the anchor handling scenario in static analysis

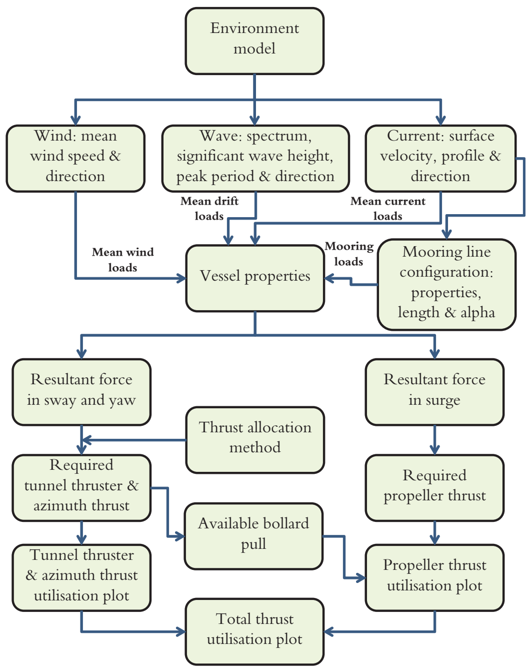


Fig. 4 Flow chart of the proposed method

- Estimate forces acting on the vessel and establish the thrust utilisation plot
- Apply the proposed method to the Bourbon Dolphin accident as a case study.

3 Theory background

Thrust utilisation plots represent the analysis of the equilibrium of the steady-state forces and moments of an AHV during anchor deployment in this study. The main concern is to estimate the external loads acting on the AHV correctly. The forces and moments in the horizontal plane are of interest. Components that have a high influence on the static external loads on the AHV are mean wave drift load, mean wind drift load, current load on the vessel and mooring load (see Fig. 4). Among these loads, the current load on the mooring line are not studied in previous limited open publications on an AHV. Augusto and Andrade [12] proposed a planning methodology for deep-water anchor deployment aimed at operational resource optimisation. Wennersberg [13] developed and implemented an anchor handling simulator based on the MSS toolbox [14]. The mooring line model in both studies was based on the catenary equation, which did not take the current forces acting on the mooring line into account. In practice, the current effect on the mooring line is usually not accounted for in a rig move procedure. Gunnu et al. [15] analysed the behaviour of an AHV in the horizontal plane in a uniform current field. The drifting behaviour of the vessel under different control forces (failure modes) was illustrated. However, the current loads on the mooring line were not studied explicitly. Moreover, wind and wave effects were not included. In this paper, a detailed model including wind, wave and current loads on both vessel and mooring line was established. In this way, more realistic external forces acting on the vessel can be estimated.

The SIMO [16] and the Riflex [17] are used as tools to perform steady-state analysis. Environmental loads on the vessel are obtained through SIMO, while mooring line loads are calculated from Riflex and added as external loads to the vessel. In the following section, the theory background applied will be addressed. The adopted thrust allocation method will be addressed as well.

3.1 Coordination system

The plain view of the coordinate systems applied is illustrated in Fig. 5. Two coordinate systems are used. Vessel position, mooring line configuration and environmental load direction are defined in the global coordinate system, (X_G, Y_G, Z_G). The global coordinate system is earth-fixed and the origin is defined at the rig end of the mooring line on the water plane. The vessel has its own local coordinate system, (x_B, y_B, z_B), which is at the projection of the centre of gravity on the water plane. The loads on the AHV are referred to the local coordinate system. The mooring line orientation is in line with the AHV heading because zero angle of attack is assumed in a normal operation.The direction definitions of wind (φ), wave (ψ) and current (γ) are also shown in Fig. 5. A value of 0° means that the weather is coming along the mooring line orientation, from stern to bow of the AHV, while a value of 90° indicates that the weather is coming perpendicularly to the mooring line orientation, from starboard to port of the AHV. The rig is not numerically modelled so that it is illustrated with dashed lines.

3.2 Wave drift loads

Mean drift loads are of importance in certain contexts, for instance, in the design of mooring system. Although the mean drift loads are relatively small in magnitude compared with the first order components, the mean drift loads may still contribute significantly to the total static environmental loads on the AHV. Therefore, it is important to obtain reasonable wave drift loads in this study.

When estimating the mean drift loads on an offshore structure, the common practice is to solve the first-order problem in potential flow theory. The mean drift loads can then be obtained by applying the theory of conservation of momentum (the far-field theory). More details can be found in [18]. A benchmark study on the calculation of potential theory among seven leading commercial codes was carried out by Naciri and Sergent in 2009 [19]. It is shown that all the codes involved predict very consistent first order quantities, as well as the mean drift coefficients calculated by the conservation of momentum theory. The WADAM code [20], one of the tested codes in the benchmark study, was used to obtain the mean wave drift coefficients for the Bourbon Dolphin vessel in this paper.

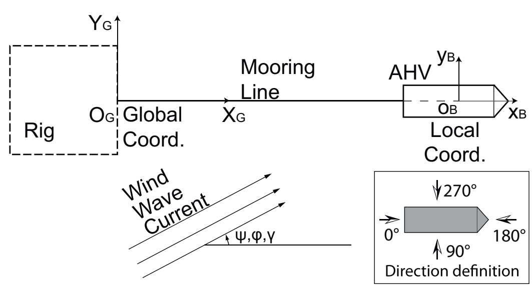


Fig. 5 Coordinate systems for an anchor handling operation and definition of direction

Table 1 Principal particulars of the Bourbon Dolphin

Properties	Notations	Values	Units
Length overall	L_{oa}	75.20	m
Length between perpendiculars	L_{pp}	64.91	m
Breadth	B	17.00	m
Depth	D_{p}	8.00	m
Draught at midships	D_{m}	5.80	m
Transverse projected area	A_{t}	314.34	m^2
Lateral projected area	A_{l}	653.28	m^2
Displacement	Δ	4,500	Tonne

The centre of gravity is located 6.90 m from keel and 32.03 m from aft perpendicular

The main particulars of the Bourbon Dolphin AHV are listed in Table 1. The 5.80 m draft is the draft when the Bourbon Dolphin accident happened. A convergence test on the meshing density of the panel model has been carried out. Good convergences of the required coefficients are observed when the element length is smaller than 0.6 m. In this paper, the results are based on a panel model with an element length of 0.5 m (see Fig. 6). The mean wave drift coefficients of the Bourbon Dolphin vessel in surge, sway and yaw are illustrated in Fig. 7a–c, respectively. These coefficients are imported into SIMO. The mean wave drift force can then be estimated for a given wave spectrum.

3.3 Wind drag force

The wind drag force is calculated based on the mean wind velocity on the vessel as follows:

$$F_{wx} = \frac{1}{2}\rho_{\mathrm{a}} C_{wx}(\varphi) V^2 A_{\mathrm{t}} \tag{1}$$

$$F_{wy} = \frac{1}{2}\rho_{\mathrm{a}} C_{wy}(\varphi) V^2 A_{\mathrm{l}} \tag{2}$$

$$M_{wn} = \frac{1}{2}\rho_{\mathrm{a}} C_{wn}(\varphi) V^2 A_{\mathrm{l}} L_{\mathrm{oa}}, \tag{3}$$

where F_{wx}, F_{wy} and M_{wn} are the wind force in surge, in sway and wind moment in yaw, respectively; ρ_{a} is the density of air; C_{wx}, C_{wy} and C_{wn} are the wind drag coefficient in surge, sway and yaw, respectively; φ is the wind direction relative to the vessel heading (see Fig. 5); V is the wind velocity; A_{t} and A_{l} are the transverse and lateral projected area of the vessel superstructure, respectively; and L_{oa} is the length overall.

Information about the wind drag coefficient for specific vessels is quite limited in the public literature. To obtain the best approximation of the Bourbon Dolphin in the study, data of similar vessels were used. The wind drag coefficients were obtained in [21] for an offshore supply vessel (see Fig. 8).

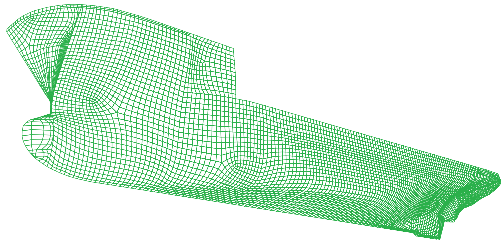


Fig. 6 Panel model of the Bourbon Dolphin, the port half

3.4 Current loads

The static current drag forces and moments are estimated using the following equations:

$$F_{cx} = \frac{1}{2}\rho C_{cx}(\gamma) U^2 B D_{\mathrm{m}} \tag{4}$$

$$F_{cy} = \frac{1}{2}\rho C_{cy}(\gamma) U^2 L_{\mathrm{pp}} D_{\mathrm{m}} \tag{5}$$

$$M_{cn} = \frac{1}{2}\rho C_{cn}(\gamma) U^2 L_{\mathrm{pp}}^2 D_{\mathrm{m}}, \tag{6}$$

where F_{cx}, F_{cy} and M_{cn} are the current force in surge, in sway and current moment in yaw, respectively; ρ is the density of water; C_{cx}, C_{cy} and C_{cn} are the current drag coefficient in surge, sway and yaw, respectively; γ is the current direction relative to the vessel heading (see Fig. 5); U is the current velocity; B is the beam at midships; D_{m} is the draught at midships; and L_{pp} is the length between perpendiculars.

The current drag coefficients could be obtained both from model testing and from CFD calculation. In this paper, the current drag coefficients are obtained in the ShipX station keeping plug-in [22] (see Fig. 9). These coefficients were gathered from the MARINTEK model test for an offshore supply vessel similar to the Bourbon Dolphin.

3.5 Morison's equation

The modified Morison's equation was used to calculate current loads on the mooring line through the Riflex code. The drag force acting normal to the mooring line section with a length of dx is shown in Eq. 7:

$$\begin{aligned} \mathrm{d}F_n = \rho \frac{\pi D_{\mathrm{h}}{}^2}{4}\mathrm{d}x\dot{w} + \rho C_{\mathrm{a}} \frac{\pi D_{\mathrm{h}}{}^2}{4}\mathrm{d}x(\dot{w} - \dot{s}) \\ + \frac{1}{2}\rho C_{\mathrm{D}} D_{\mathrm{h}} \mathrm{d}x(w - s)|w - s| \end{aligned} \tag{7}$$

where $\mathrm{d}F_n$ is the hydrodynamic force on an element with length of dx; ρ is the water density; D_{h} is the hydrodynamic diameter; w is the water particle velocity; C_{a} is the added

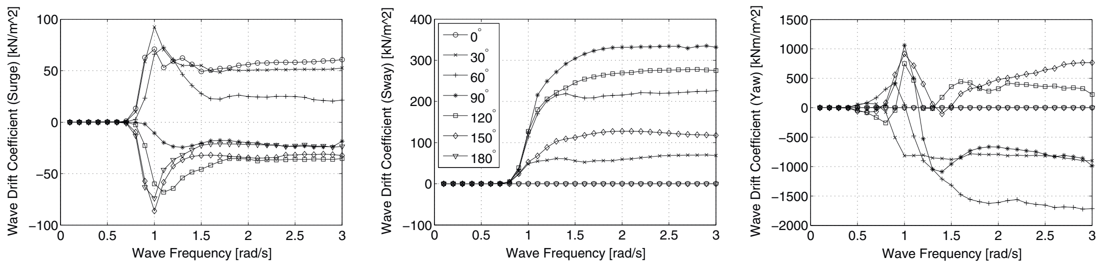


Fig. 7 Wave drift coefficients of the Bourbon Dolphin. **a** Surge, **b** sway and **c** yaw

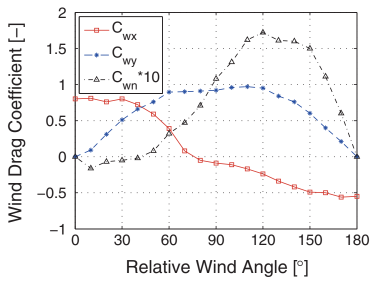


Fig. 8 Wind drag coefficients

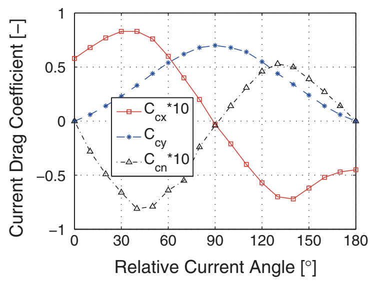


Fig. 9 Current drag coefficients

mass coefficient; s is the element velocity normal to cross section; and C_D is the quadratic normal drag coefficient. The first and second terms on the right represent the Froude–Krylov force and hydrodynamic mass force, respectively. The third term is the drag force. In a static calculation, the first two terms are zero, and only the drag force term remains.

3.6 Thrust allocation and thrust utilisation plot

The basic idea of the thrust utilisation plot, is to assess how much thrust capacity of the AHV is consumed to keep the vessel in a desired position and heading for a given weather condition. Therefore, the required thrust should be estimated first. The static external forces acting on the vessel, including mean wave drift load, mean wind load, mean current loads and mooring load can be determined by the theory mentioned above. Then, a thrust allocation method can be applied to obtain the demanded thrust for each position unit. The allocation method is usually formulated into an optimisation problem so that minimised power consumption can be achieved. In this study, the thrust allocation method follows the approach of Zhou et al. [23].

The general relationship between the control demand and the individual actuator demand thrusts is given by Eq. 8:

$$\boldsymbol{\tau}_{\mathbf{c}} = \boldsymbol{T}_{\mathbf{a}}\boldsymbol{T}_{\mathbf{th}}, \tag{8}$$

where $\boldsymbol{\tau}_{\mathbf{c}}$ is the vector of thrust and moment demand from the controller, $\boldsymbol{T}_{\mathbf{th}}$ is a vector of thruster demands in Cartesian coordinates, and $\boldsymbol{T}_{\mathbf{a}}$ is the thruster allocation matrix, defined as follows:

$$\boldsymbol{T}_{\mathbf{th}} = [T_{1x}\ T_{1y}\ \cdots\ T_{nx}\ T_{ny}] \tag{9}$$

and

$$\boldsymbol{T}_{\mathbf{a}} = [\boldsymbol{t}_1\ \cdots\ \boldsymbol{t}_n], \tag{10}$$

where n is the number of thrusters. In our case, only horizontal plane motions, i.e. surge, sway and yaw are to be balanced, the matrices $\boldsymbol{t}_i$ in Eq. 10 are given by Eq. 11:

$$\boldsymbol{t}_i = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -l_{iy} & l_{ix} \end{bmatrix}}_{\text{azimuth thruster}},\ \boldsymbol{t}_i = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 0 \\ -l_{iy} & 0 \end{bmatrix}}_{\text{main propeller}},\ \boldsymbol{t}_i = \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 0 & l_{ix} \end{bmatrix}}_{\text{tunnel thruster}} \tag{11}$$

where l_{ix} and l_{iy} are the longitudinal and transverse positions of the ith thruster, respectively.

In general, there will be more variables describing the thruster settings than available equations to solve (see Eq. 8) so that $\boldsymbol{T}_{\mathbf{th}}$ is not unique. This problem is usually formulated as an optimisation problem by introducing a power minimisation condition. According to Fossen [24], the least-norm solution of $\boldsymbol{T}_{\mathbf{th}}$ could be achieved by finding the Moore–Penrose generalised inverse of $\boldsymbol{T}_{\mathbf{a}}$. The solution can be expressed in the following form:

$$\boldsymbol{T}_{\mathbf{th}} = \boldsymbol{T}_{\mathbf{a}}^{\dagger}\boldsymbol{\tau}_{\mathbf{c}} \tag{12}$$

$$\boldsymbol{T}_{\mathbf{a}}^{\dagger} = \boldsymbol{W}^{-1}\boldsymbol{T}_{\mathbf{a}}^{T}(\boldsymbol{T}_{\mathbf{a}}\boldsymbol{W}^{-1}\boldsymbol{T}_{\mathbf{a}}^{T})^{-1} \tag{13}$$

and

$$\boldsymbol{W} = \begin{bmatrix} w_{1x} & & & & 0 \\ & w_{1y} & & & \\ & & \ddots & & \\ & & & w_{nx} & \\ 0 & & & & w_{ny} \end{bmatrix} \tag{14}$$

where $\boldsymbol{T}_{\mathbf{a}}^{\dagger}$ is the generalised inverse of $\boldsymbol{T}_{\mathbf{a}}$, $\boldsymbol{W}$ is the weighting matrix in which the element w_{ix} is the cost to use the ith thruster in the surge axis, and w_{iy} is the cost to use them in the sway axis. The higher the cost in a DP system, the less thrust will be assigned to that thruster.

When the required thrust, i.e. $\boldsymbol{T}_{\mathbf{th}}$, is obtained by Eq. 12, the ratio between the required thrust and the available thrust of each thrust unit can then be calculated. Here, the available thrust is based on the thrust setup. Thrust loss is beyond the scope of this study and therefore is not considered. The maximum consumption ratio among all thrust units is used to represent the thrust utilisation for a specific weather direction. The results are usually presented in a rosette format, which shows the ratio as a function of weather direction.

4 Case study

The Bourbon Dolphin accident has been selected as the basic case for application of the suggested method. The static loads on the vessel during the accident are first investigated and discussed, including the mooring line loads in different current profiles. Then, a comparison between normal condition and accident condition (definition will be given in Sect. 4.1.2) is presented. Finally, the results of several sensitivity studies are shown. Some simplifications are made so that more general information can be obtained.

A short reminder of the Bourbon Dolphin accident [2]: the accident happened on the Rosebank oilfield in the western part of Shetland where the water depth was 1,100 m. The distance between the rig and the mooring position was approximately 3,000 m. The mooring line was approximately 3,500 m, of which 900 m was 84 mm chain and 920 m was 76 mm chain, plus 1,725 m of 96 mm wire. During the lowering of anchor, approximately 1,220 m of 83 mm wire was used by the Bourbon Dolphin. The Bourbon Dolphin ran out all the chain (approximately 1,820 m) for the last anchor (no. 2). Then the vessel drifted considerably off the mooring line and asked the rig for assistance. However, the attempt at chain grappling by another vessel failed. At that moment, the vertical angle α (the angle between the mooring line and the vertical plane, see Fig. 3) was 38°. Then the vessel capsized during a turn. See Fig. 1 for the track plot of the Bourbon Dolphin before the accident happened.

4.1 Load analysis

In this section, the external forces on the AHV during operation are analysed. First, the current loads on a free-spanning mooring line are investigated. Then, the total forces acting on the vessel under different environmental conditions are presented.

4.1.1 Mooring line loads

While mooring line analysis is commonly conducted for moored floating structures, study of the effect of a mooring line during an AHO is not common. As the water depth increases, the weight of the mooring line increases, which demands a higher capacity for the AHV. A higher winch capacity on board is needed due to the mooring line weight. Meanwhile, the drag force induced by the current increases as the length of the mooring line increases. The current-induced mooring load will consume a part of the lateral thrust forces, which is usually neglected in shallow waters. Although the shape and tension of a mooring line in calm water can be predicted well by the traditional catenary equation, the situation becomes complicated if the current load is applied. For instance, the shape of the mooring line will depend on the weight and buoyancy as well as the current field and thus the loads applied on the vessel could vary. Therefore, the effect on the loads coming from the mooring line is of interest.

This subsection describes a parametric study to assess the effect of current on the mooring line. A two-end-fixed free-spanning mooring line with uniform cross-section is placed into different current profiles. A sketch of this study is illustrated in Fig. 10. The mooring line is assumed to be aligned with the AHV centre line. The aim is to analyse the force on the AHV end. The parameters involved are shown as follows: length of mooring line L, vertical angle α, types of mooring line, diameter of mooring D, surface current velocity U, current direction γ and current profile. With a different end distance and a different vertical angle, the mooring line will have different initial shape (in still water). Then the current force is applied (with varied

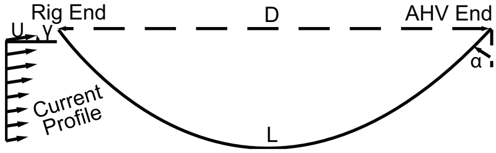


Fig. 10 Sketch of two-end-fixed mooring line in current

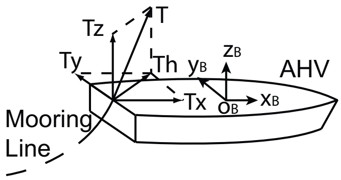


Fig. 11 Force components of mooring line tension

direction and velocity) and the mooring line will have a modified shape based on the current condition. As a result, the distribution of tension along the mooring line will be changed as well. Iterations should be performed to obtain the final static shape of the mooring line. Once the static shape is found, the tension along the mooring line is also determined. Finally, the force components acting on the vessel can be obtained.

The significant force components in the total tension T are the longitudinal force component T_x and the lateral force component T_y (see Fig. 11). The total tension T is related to the capacity of the main winch on board. The winch capacity should be greater than the total tension coming from the mooring line, or the winch might be unable to handle the mooring line. The longitudinal force component T_x is directly linked to the bollard pull. If the bollard pull of the vessel is smaller than this component, the vessel will be pulled backward by the mooring line. The lateral component, T_y, could consume part or even all of the lateral positioning capability of the vessel. If the amount is large, T_y could hamper the vessel bollard pull as well. In practice, T and T_x are quite high compared with the current loads and not affected much . Emphasis is placed on the current effect on T_y.

The selected length of the mooring line in this study is 1,800 m, which is almost the same as what Bourbon Dolphin had paid out (1,817 m) before the accident happened. Based on the rig move plan that was carried out during the Bourbon Dolphin accident, two types of mooring line were used, including the stud chain and the wire with wire core. Within each type of mooring line, two diameters were selected to study the effect of diameter. So in total, there were four mooring lines that were studied, and the properties of these mooring lines are summarised in Table 2. In fact, the type of mooring line used is normally selected according to the mooring performance analysis of the mooring system rather than the AHO analysis. The comparison between these mooring lines, however, can show the influence of mooring line properties on the force components within the same practical project.

In the actual practice, the vertical angle between the mooring line and the vertical axis (α) is usually between 20° and 60°. This angle describes the relative importance of the horizontal and the vertical components of the total tension. A different angle α can be achieved by altering the distance (D) between the two ends of a mooring line. For the purposes of convenience, the same distance is applied on all four types of mooring line for a nominal α value. Due to the difference in axial stiffness between chains and wires, there are small differences in the actual angle α of

Table 2 Mooring line properties

Properties	Units	Mooring line type			
		Stud chain		Wire	
Geometry					
Diameter (nominal diameter)	m	0.084	0.076	0.096	0.083
Equivalent diameter	m	0.159	0.144	0.077	0.066
Weight and buoyancy					
Mass per unit length	kg/m	154.50	126.50	37.77	27.49
Weight per unit length	kN/m	1.516	1.241	0.361	0.270
Buoyancy per unit length	kN/m	0.199	0.164	0.047	0.035
Weight per unit length in water	kN/m	1.317	1.077	0.314	0.235
Structure					
Axial stiffness	kN	7.13×10^5	5.83×10^5	3.72×10^5	2.78×10^5
Hydrodynamics					
Normal drag coefficient	–	2.6	2.6	1.2	1.2
Tangential drag coefficient	–	1.4	1.4	0.0	0.0

The nominal diameter of chains represents the bar diameter. The equivalent diameter is for a line with constant volume along its length. The drag coefficient is defined on the nominal diameter. The drag coefficients are obtained from DNV recommended practice [28]

Table 3 Relationship between D and α for a 1,800-m-long mooring line

D (m)	Actual α(°)		Nominal α (°)
	Stud chain	Wire	
773	10.00	10.01	10
1,137	19.95	19.99	20
1,370	29.99	30.05	30
1,501	37.95	38.06	38
1,589	44.96	45.12	45
1,716	59.73	60.18	60
1,787	74.09	75.92	75

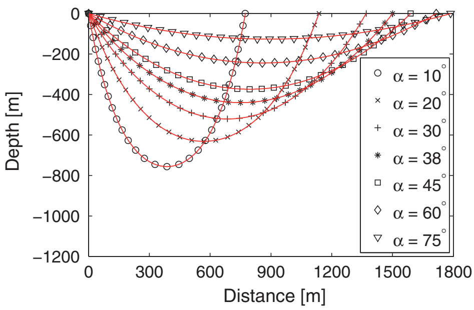


Fig. 12 Static shape of a 84-mm K4 studded chain mooring line for different angle α, $L = 1,800$ m. Analytical solutions are presented with *red solid lines*. Riflex results are presented with *different markers* (colour figure online)

the mooring lines. However, the difference between the actual and nominal value is small. The selected distance and the corresponding α (both actual and nominal) are tabulated in Table 3. The nominal α varies from 10° to 75°. Hereafter, angle α in this paper refers to the nominal value. The static shapes of 1,800-m-long mooring line with 84 mm chain properties (with different α) in still water, calculated by Riflex, are illustrated in Fig. 12 with markers. The analytical solutions of the elastic cable line equations, see [18], are also presented in Fig. 12 (as red solid lines). As shown, the Riflex results are in very good agreement with the analytical solution.

The current profile, velocity and direction have an influence on the mooring line shape, thus they have an effect on the force components as well. Six current profiles in total have been chosen to evaluate the effect. The six current profiles are uniform, linear sheared, uniform with 50-m slab, linear sheared with 50 m, Ormen Lange field (representing the profile in the North Sea) and Loop eddies current field (representing the profile in the Gulf of Mexico). The first two profiles are theoretical current profiles for deep water. The middle two profiles are the design profiles proposed by DNV recommended practice [25] for

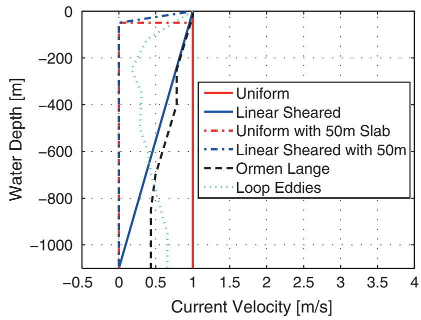


Fig. 13 Current profiles

wind generated current, in which the current velocity is zero below 50 m. More detail about the last two current profiles can be found in Rustad et al. [26]. According to ISO 19901-1 [27], the indicative value for 1-year-return surface current speed in the west of Shetland is 1.64 m/s. This value coincides with the maximum estimation of current speed (3 knots) during the accident in terms of order. The normalised current velocity profile, with a surface velocity equals to 1 m/s, are illustrated in Fig. 13.

The influence of the current profiles as well as the angle α on the lateral force component T_y is shown in Fig. 14. The length of the mooring line is 1,800 m and the current direction is normal to the mooring direction($\gamma = 90°$) with a surface velocity of 1.0 m/s. In this case, T_y represents half of the total lateral current loads on the mooring line. In general, the difference between stud chain and wire are quite significant. The T_y of chains is more or less twice the magnitude of the T_y of wires in most cases. Therefore, deploying mooring line with chain sections is usually more demanding than using wire sections (of the same length) because the weight will be heavier and possible current drag loads will be higher. The diameters have less importance for the current loads within the same type of mooring line. The maximum difference due to diameter occurs in the uniform current field in stud chains. However, the difference is less than 10 kN (1 tonne).

The T_y has a strong angle α dependence in all profiles except the uniform profile mainly because a different angle α means a different spanning depth of the mooring line. In a uniform current field (see Fig. 14a), T_y is almost the same among all angles α for the same property. This equality is easy to understand because the profile is uniform and therefore the mooring lines are subjected to almost the same current loads. A 1,800-m 84 mm mooring chain can lead to approximately 100 kN (10 tonnes) in T_y in 1 m/s uniform current. In a linear sheared current profile (see Fig. 14b), T_y increases from 40 kN to almost 90 kN as the angle α varies from 10° to 75°. Within the practical range

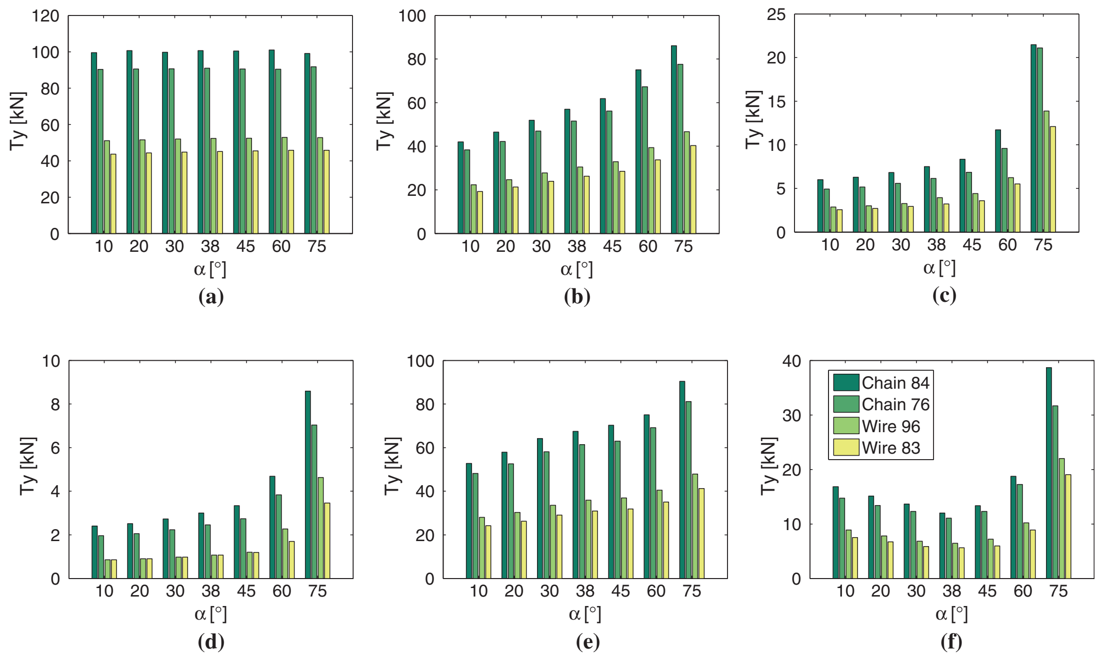


Fig. 14 Lateral force component (T_y, see Fig. 11) comparisons for different current profiles and different angle α (see Fig. 10), $\gamma = 90°$, $U = 1.0$ m/s, $L = 1,800$ m. **a** Uniform current profile, **b** linear sheared current profile, **c** slab uniform current profile (50 m depth), **d** linear sheared current profile (50 m depth), **e** Ormen Lange field current profile and **f** loop eddies current profile

of α, for example, 38°, the current-induced lateral force is more than 55 kN.

In the two design profiles of wind generated current, T_y are smaller compared with other cases because current only affects the very upper part of the mooring line (within 50 m water depth). Figure 14c shows that there is a jump in the magnitude for all mooring lines when α is 75° because the spanning depth of the mooring lines is small in this case (see Fig. 12) and a much greater portion of the lines is exposed to the slab current. Therefore, the total current loads on the lines are much higher. In the linear sheared profile with 50 m depth, the phenomenon is similar (see Fig. 14d). Within the practical range of α, however, T_y is very small for wind generated current profiles.

In regard to the actual current profile, the results are more interesting. In the current profile at the Ormen Lange field, the current remains quite strong over the water depth resulting in a relatively high drag load on the mooring line (see Fig. 14e). In the Norwegian sector, AHV might have a higher demand on the thrust capacity due to possibly higher current load on the mooring line. In the current profile at the Gulf of Mexico (GOM), the minimum T_y occurs when the angle α is equal to 38° (see Fig. 14f), due to the uniqueness of this current profile. There is a drop of the current strength in approximately 350 m of water depth. However, the current gradually becomes stronger as the water depth increases. To keep the main part of the mooring line in the low current strength region might be an advantage to take in the GOM.

The uniform current profile is used to investigate the effect of current direction and velocity on T_y. The current velocity varies from 0.5 to 2.0 m/s. A value of 2.0 m/s is too high for an operation weather window and is just for illustration. However, 1.0 m/s is usually chosen as the design criterion (the same as the Bourbon Dolphin rig move procedure), therefore the value is quite reasonable. Because the α has no influence on T_y in a uniform current field, there is no need to vary α. The T_y induced current on an 1,800-m 84 mm mooring chain with angle α equal to 38° is presented in Fig. 15. The figure shows that T_y is generally proportional to velocity squared. In the 1.5 m/s current speed, current load on an 1,800-m 84 mm stud chain can be more than 220 kN, which is approximately 22 tonnes. If this happened in the real world, the AHV would be in a very challenging situation to maintain position. The maximum values occur at 90° in a low current speed profile and shift to 80° when in a high current speed profile.

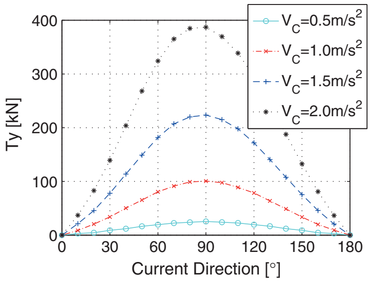


Fig. 15 Lateral force component (T_y) comparisons for different current directions and velocities, uniform current profile, $L = 1,800$ m, $\beta = 38°$, 84 mm chain

Due to the considerable differences in lateral mooring loads among different current profiles, it is very important to take the mooring line effect into account and apply the current profile in practice as closely as possible. Further discussion will be provided in the following subsections.

4.1.2 External loads on the vessel

The external forces acting on an AHV depend on the vessel dimensions and environmental conditions as well as the mooring line configuration. The main particulars of the Bourbon Dolphin anchor handling vessel are listed in Table 1. The 5.80 m draft is the draft when the Bourbon Dolphin accident happened.

According to the accident report [2], the weather conditions referred to in the rig move procedure mooring analysis for the Bourbon Dolphin are listed as follows:

- Maximum waves of 4.0 m, significant wave height (H_s) is approximately 2.2 m, with a wave period (T_p) of 8.5 s
- Wind speed (V_W) 10 m/s (19.4 knots)
- Current speed (V_C) 1.0 m/s (1.94 knots).

The weather conditions during the day of the accident were different from the rig move procedure. Based on several assessments from weather forecasts and testimony of masters, the weather observations were relatively consistent on wave and wind, while there were strong disagreements on the current. The actual weather situation is listed as follows:

- Significant wave height was approximately 3.5 m (max wave approximately 7 m) with a wave period of 7–8 s.
- Mean wind strength was approximately 18 m/s (30–35 knots).
- Estimated current speed varied from 0.3 to 1.5 m/s (0.6–3 knots).

Table 4 Environmental conditions

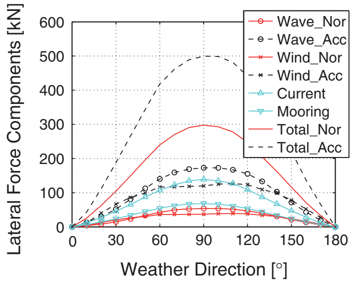
		Normal	Accident	Units
Wave	H_s	2.2	3.5	m
	T_p	8.5	7.0	s
Wind	V_W	10	18	m/s
Current	V_C	1.0	1.0	m/s

Based on the above information, two environmental conditions are defined in this study. The condition used in the rig move procedure is denoted as the "Normal" condition, while the actual weather condition is denoted as the "Accident" condition. The details of these two weather conditions are tabulated in Table 4. The selected wave spectrum is the Jonswap spectrum and the wind field is considered as constant with uniform profile. The current profile used here is the Ormen Lange profile, which is supposed to be the most suitable one among the six studied profiles. Due to the inconsistency on the surface current speed estimation in the accident condition, the current speed in the accident condition is set the same as the current speed in the rig move procedure, i.e. 1 m/s. In this way, the influence from deterioration of the wind and the waves can be investigated.

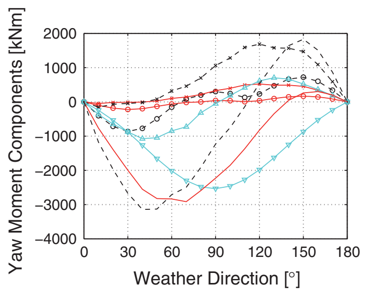
Static analyses were performed to obtained static loads on the Bourbon Dolphin under these two sets of conditions. No weather misalignment was considered. The mooring line was attached at the stern of the AHV at the centre line. The distance between the attach point to the centre of gravity is 37.23 m. The mooring line was set as 1,800 m of 84 mm chain with the angle α equal to 38°. The configuration is similar to that in the accident. The lateral force and yaw moment with respect to the centre of gravity of the Bourbon Dolphin as a function of weather direction is shown in Fig. 16. The current load acting on the vessel is denoted as "current", while the mooring load acting on the vessel due to current is denoted as "mooring". Because the current conditions are the same in both normal and accident conditions, the "current" and "mooring" loads in both case remain the same.

For lateral force components, the highest total force occurs around the beam sea condition, i.e. 90°. The maximum total force in the accident condition is approximately 67 % higher than that in the normal condition. In the normal condition, the current load on the vessel is predominant, while the other three are quite similar in magnitude. In the accident condition, the wave drift force becomes stronger and contributes the most to the total load. The mean wind load also increases significantly.

For the yaw moment components, the trend is not as clear as the lateral force because the peak value of each component does not occur in the same weather direction. In general, high total yaw moment appears at a stern



(a)



(b)

Fig. 16 Force components for a variable weather direction, " Nor" and " Acc" indicate normal and accident conditions, respectively. **a** Lateral force components and **b** yaw moment component

quartering sea under normal conditions. Because the wave drift moment increases significantly in the accident condition, especially in a bow quartering sea, high yaw moment occurs at both stern and bow quartering sea in the accident condition.

As the total external yaw moment does not reach the maximum value as the lateral force does in beam sea conditions, the most severe case might not occur in beam sea conditions. This situation will be illustrated in the following subsection.

4.2 Vessel positioning capability

The propulsion and thrust setup for the Bourbon Dolphin are sketched in Fig. 17. The vessel has one bow tunnel thruster

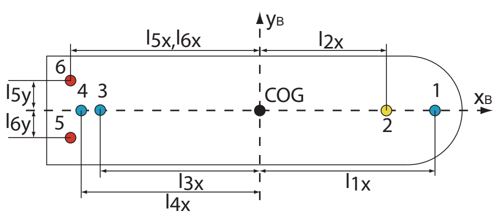


Fig. 17 The thruster arrangement schematic of the Bourbon Dolphin

Table 5 Propulsion and thrust setup for the Bourbon Dolphin

Propulsion unit	Thrust no.	Power (kW)	Force (kN)	l_{ix} (m)	l_{iy} (m)
Bow tunnel thruster	#1	883	149	27.37	0.00
Bow azimuth	#2	883	158	19.80	0.00
Stern tunnel thruster 1	#3	590	100	−24.83	0.00
Stern tunnel thruster 2	#4	590	100	−27.93	0.00
Main propeller 1	#5	6,000	967	−29.60	−4.65
Main propeller 2	#6	6,000	967	−29.60	4.65

(#1), one bow azimuth thruster (#2), two stern tunnel thrusters (#3 and #4) and two main propellers (#5 and #6). The numbering and position information for these units is listed in Table 5. The main propellers are normally used to provide bollard pull for the AHV to balance the mooring weight and water resistance. The tunnel thrusters are normally used to withdraw later loads and external yaw moment. The azimuth thruster can produce force in different directions depending on need. The capability of the vessel to withstand drift and maintain heading is of primary concern in this study. The tunnel thrusters and azimuth are assumed to be used to balance all the lateral forces and yaw moments. The two main propellers provide only longitudinal forces. Therefore, the thrust allocation scheme only involve the three tunnel thrusters and the bow azimuth thruster. The cost for these thrusters is assumed to be the same and set as 1 in Eq. 14. The lateral thrust utilisation plot is first applied to the Bourbon Dolphin accident. Then the propeller thrust utilisation and total thrust utilisation plots will be looked into.

Due to symmetries of the vessel about the longitudinal axis, in this study the thrust utilisation plots are also symmetrical about the same axis. In the case of other vessels, the plots could be asymmetric.

4.2.1 *Bourbon Dolphin accident*

First of all, the proposed lateral thrust utilisation plot is applied in the Bourbon Dolphin accident, in both normal and accident conditions (see Table 4). The current profile here is from Ormen Lange. The mooring line configuration also remains the same as a 1,800 m 84 mm mooring chain, with α as 38°. The result is illustrated in Fig. 18. The black solid line in the figure is used to highlight the 100 % circle, which is not supposed to be exceeded.

In general, the plots for both conditions show a similar trend. The thrust utilisation becomes low when the weather direction is toward 0° or 180°, because of low lateral force and moment. As the weather is coming more from the beam sea, the utilisation level increases significantly. However, the highest consumption occurs at approximately 70° and 290° instead of exactly at the beam sea condition. The figure shows clearly that the Bourbon Dolphin is

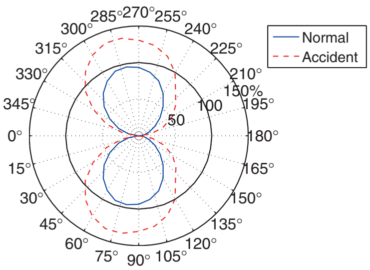


Fig. 18 Lateral thrust utilisation plot for normal conditions and accident conditions, $L = 1,800$ m, $\alpha = 38°$, Ormen Lange current profile

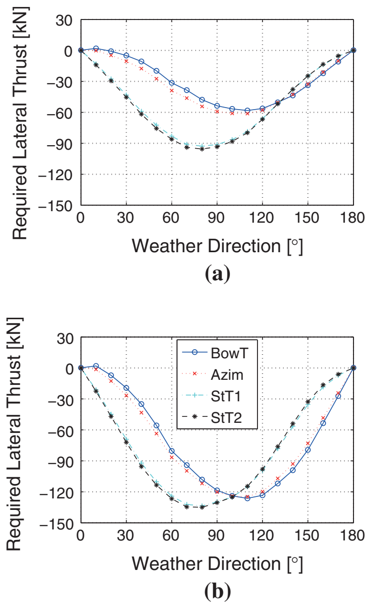


Fig. 19 Required lateral thrust force of different unit as a function of weather direction, " BowT", " Azim", " StT1" and " StT2" represent bow tunnel thruster (#1), azimuth thruster (#2), stern tunnel thruster 1 (#3) and stern tunnel thruster 2 (#4), respectively. **a** Normal conditions and **b** accident conditions

capable of handling the situation under normal conditions. Under the accident conditions, however, there is such a wide range of weather directions that the vessel is not capable of maintaining position. Moreover, according to the accident report, the prevailing weather direction in the accident event was from the southwest. Taking the mooring line 2 orientation (north by northwest) into account, a weather direction of approximately 290° is found in our coordinate system (see the actual direction from Fig. 1 and the definition of direction from Fig. 5). Figure 18 shows that at a direction of 290°, the thrust utilisation ratio almost reaches the maximum, which is approximately 135 %. The Bourbon Dolphin might have been in the most unfavourable weather situation during the accident condition when it began to drift, in terms of lateral positioning capability.

The variation of the required thrust force of the three tunnel thrusters and the azimuth are presented in Fig. 19. Only results from 0° to 180° weather directions are shown due to symmetries. The results are consistent with the force and yaw moment components plot (Fig. 16b). Other than balancing the lateral forces on the vessel, an unequal thrust distribution is required between the bow and stern to counteract the external yaw moment. When the yaw moment tends to make the bow of the vessel turn to the starboard side, i.e. a negative yaw moment exists, more thrust induced moment from the stern rather than the bow is demanded to maintain the heading of the vessel, resulting in a higher required thrust on the stern units than on the bow units (for example, in the 60° case in normal conditions). When a positive yaw moment acts on the vessel, more thrust is needed from the two bow units (for example, in the 150° case under accident conditions). As the available thrust of the stern tunnel thrusters is approximately 30 % lower than the available thrust of the bow units (see Table 5), the stern units are much easier to overload. In all cases of exceeding capacity under accident conditions, the stern thrusters (#3 and #4) have the highest usage.

The most critical weather directions under normal and accident conditions are 80° and 70°, respectively. The detailed force and moment components in these situations are tabulated in Tables 6 and 7. The current load acting on the vessel is denoted as "current", while the mooring load acting on the vessel is denoted as "mooring". At 80° under normal conditions, the total lateral force is 290.70 kN. Current load on the vessel contributes 46 % to the total loads. Together with the lateral loads from the mooring line due to the current, the total lateral loads induced by current is 69 %. For the yaw moment, contribution from mooring line is predominant. All these data emphasise the importance of the current effect in anchor handling operation.

Under accident conditions at 70°, the lateral force is as high as 461.30 kN, which will consume most of the lateral thrust that is available (507 kN). The lateral force together with the yaw moment lead to insufficient thrust. The wave drift force becomes the most important with a 35 % contribution in the lateral force as a single source. But the total lateral loads contribution induced by current (including the lateral mooring load) is 40 %. For the yaw moment, the mooring line loads contribute most as 92 % and current load on the vessel is 29 %. But wave drift and mean wind loads have a negative effect, which results in lower total yaw moment.

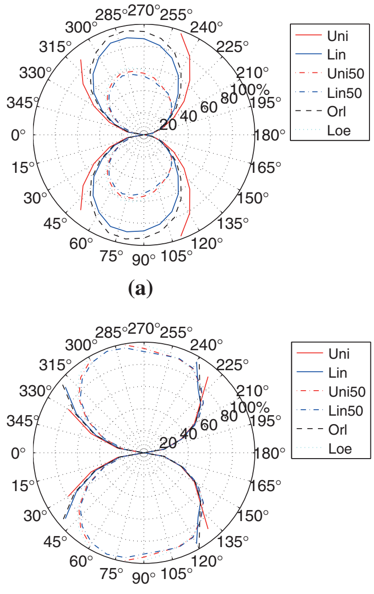
Forces in surge in both cases are dominated mainly by the mooring loads.

Table 6 Detailed load components under normal conditions, 80°

Item	Actual value			Percentage (%)		
	Surge (kN)	Sway (kN)	Yaw (kNm)	Surge (–)	Sway (–)	Yaw (–)
Wave drift	0.33	52.54	−2.17	0	18	0
Wind	−0.97	36.56	214.50	0	13	−8
Current	1.01	134.80	−318.90	0	46	12
Mooring	−933.90	66.74	−2,485.00	102	23	96
Total	−919.60	290.70	−2,591.00	100	100	100

Table 7 Detailed load components under accident conditions, 70°

Item	Actual value			Percentage (%)		
	Surge (kN)	Sway (kN)	Yaw (kNm)	Surge (–)	Sway (–)	Yaw (–)
Wave drift	−26.09	159.20	81.57	−3	35	−3
Wind	5.01	117.20	460.10	−1	25	−18
Current	2.01	122.90	−730.70	0	27	29
Mooring	−928.70	61.94	−2,306.00	105	13	92
Total	−881.60	461.30	−2,495.00	100	100	100



(a)

(b)

Fig. 20 Lateral thrust utilisation plot with different current profiles, $L = 1,800$ m, $\alpha = 38°$, "Uni", "Lin", "Uni50", "Lin50", "Orl" and "Loe" represent the six current profiles in the same order as shown in Fig. 13. **a** Normal condition and **b** accident condition

4.2.2 *Effect of current profile*

Based on the findings in the previous subsection, current loads are of significant importance in the AHO. The current profile has a high influence on the mooring load, which has already been shown. Therefore, a parametric study was carried out to investigate the influence on the lateral thrust utilisation plot from current profiles. All profiles shown in Fig. 13 were used. The mooring line configuration also remains the same as an 1,800 m 84 mm mooring chain, with α is 38°. Both normal and accident conditions were tested and the results are presented in Fig. 20.

Figure 20 shows that the results can be classified into three groups. Group one includes the two wind generated-current profiles and the loop eddies profile. Under both sets of conditions, the vessel can maintain sway and heading in these current profiles, except that there is a small exceeding for the loop eddies profile under accident conditions. Because the current load on the mooring line in these three profiles is quite low (see Fig. 14), the results can be considered as no current effect applied on the mooring line. The second group includes the uniform profile. The positioning capability of the vessel is not sufficient even under normal conditions for certain directions, let alone in accident conditions. The remaining profiles form the third group, including the linear sheared profile and the Ormen Lange profile. A vessel in this profile group is capable of withstanding the external lateral force under normal conditions but will drift-off under accident conditions at certain weather directions.

Clearly using the uniform current profile overestimates the current loads on the mooring line and thus leads to conservative results. Profiles in group one are reasonable, provided that the wind induced current are dominant in the region where the operation is taking place. The current profile effect in this group can be neglected because the lateral mooring load is small (see Fig. 14). The linear sheared profile and the Ormen Lange profile are the most suitable profiles to use in the Bourbon Dolphin case. Applying these profiles gives a much more realistic external forces description for the vessel. Therefore, more reliable thrust utilisation plots can be obtained.

4.2.3 *Effect of mooring line configuration*

During the deployment of the anchor, the mooring line is paying out based on the rig move procedure and the judgment of the tow master. As the length of mooring line in water increases, the loads acting on the vessel vary as well. If the angle α remains the same, the longer the mooring line is, the more loads the vessel needs to carry in the longitudinal direction. The current loads on the mooring line also vary, depending on the current profile (but it usually increases). As previously mentioned, the bollard pull was materially reduced due to the use of thrusters during the Bourbon Dolphin accident. From the accident report, the total bollard pull of the Bourbon Dolphin reduced from 180 to 125 tonnes at maximum side thruster loading. How the propeller usage is influenced by the mooring line is of interest. Therefore, the propeller utilisation plot is introduced in the same way as the tunnel thrusters and azimuth, taking the reduction effect into account in a simple manner. Due to the lack of information, the two propellers are assumed to provide 180 tonnes of thrust forward in total when the lateral thrust usage is zero. As the lateral thrust utilisation increases, the thrust from the propellers decreases linearly to 125 tonnes when the lateral thrust utilisation reaches 100 %. In practice, the real reduction relationship can be applied.

First, the demanded thrust of the tunnel thruster and azimuth is estimated, summed and compared with the total available side thrust. Applying the ratio in the relationship of the propeller deduction, the "available" thrust of the propellers can then be obtained. Thus, the thrust utilisation plot for the propeller can then be generated. The maximum value between the thruster and propeller is used to establish the total thrust utilisation plot.

A parametric study has been carried out to examine the influence on the total thrust utilisation plot, with respect to different mooring line pay-out lengths. Different lengths of mooring line can represent different stages of the anchor handling process. Both normal and accident conditions were tested. The results are presented in Fig. 21. With a longer pay-out mooring line, the side thrust utilisation gradually increases when the weather is coming from the side, and remains low in a head sea and following sea conditions (see Fig. 21a, d). Under normal conditions, the vessel can handle the lateral external loads for all weather directions with a mooring line up to a length of 1,800 m. With longer pay-out length, the vessel is lack of position capability at approximately 80° and 280°. However, under accident conditions, the vessel is vulnerable in stern quartering sea weather conditions. Even with a 600 m length of mooring line the thrust usage is over 100 %.

The propeller utilisation is dominated mainly by the length of the mooring line (see Fig. 21b, e). As the length of the mooring line increases, increasing tension is applied on the AHV due to the increasing total weight of the line. The propeller utilisation increases quite evenly. However,

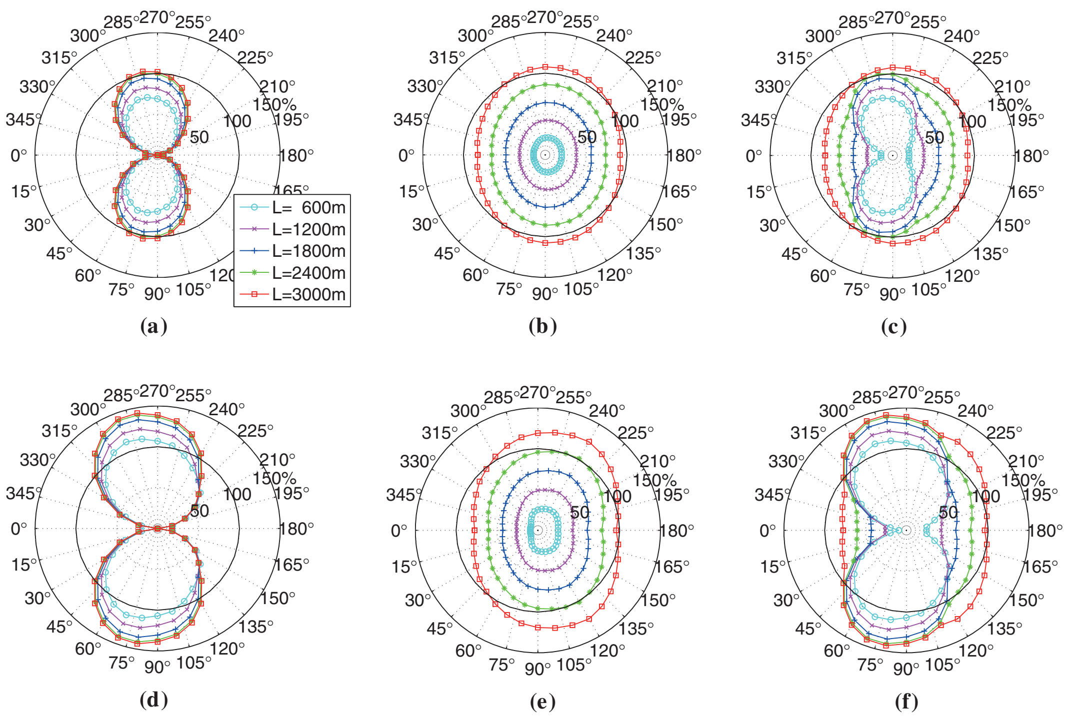


Fig. 21 Thrust utilisation plots with varying mooring line pay out length, $\alpha = 38°$, Ormen Lange current profile. **a** Thruster and azimuth, normal conditions, **b** propeller, normal conditions, **c** total, normal conditions, **d** thruster and azimuth, accident conditions, **e** propeller, accident conditions and **f** total, accident conditions

the propeller utilisation is also influenced by the side thrust usage because the available propeller thrust is lower in side weather conditions comparing to other weather directions. As a result, higher propeller utilisation is observed in about beam sea conditions, especially under accident conditions. The propeller utilisation is higher in head sea (180°) than in following sea condition (0°) because in head sea condition, the direction of current-induced loads on the mooring line is opposite to the thrust of the propellers, so the required bollard pull is higher, and vice versa.

The total thrust utilisation plots for normal and accident conditions are shown in Fig. 21c and f. Under normal conditions, the vessel can fulfil the task in all weather directions. However, if the length of mooring line reaches 3,000 m, the propellers will be overloaded in side weather conditions due to the increased mooring weight and bollard pull deduction. Under the accident conditions, the weather directions in which the vessel can maintain position are limited to a small spread around the following sea. As a result, if this information were provided before the operation commenced, the tragedy might have been averted.

5 Conclusion

Anchor handling operations, like all human activities, are potentially hazardous. The mooring line represents a significant risk factor for the anchor handling vessel due to its heavy weight as well as possible current loads, especially in deep water. Considerable drift is considered an initial event in the notable Bourbon Dolphin accident and should be prevented. Therefore, there is a need to establish a method to quantify the positioning capability for anchor handling vessel during anchor deployment.

In this paper, the thrust utilisation plot is proposed to present the positioning capability of the anchor handling vessel in a basic anchor deployment operation. Emphasis has been placed on obtaining realistic static loads on the vessel, including mean wind loads, mean wave drift load, mean current loads and mooring line loads.

A case study was carried out based on the Bourbon Dolphin case. The main conclusions can be summarised as follows:

- Lateral mooring loads vary significantly in different current profiles, therefore it is important to apply a reasonable current profile and take the mooring line effect into account.
- The thrust utilisation plot is useful to demonstrate the most critical weather direction. When the Bourbon Dolphin began to drift during the accident event, it might have been in the most unfavourable weather direction, which is 290°, in terms of lateral positioning capability.
- Current loads represent the most important loads in the Bourbon Dolphin case (with the Ormen Lange field current profile). Current loads on the vessel together with current-induced mooring loads contributed up to 69 % (in normal condition) and 40 % (in accident condition) to the total lateral loads.
- In regions where wind driven current is dominant, current loads on the mooring line can be neglected. In regions where a characteristic current profile exists, current-induced mooring line load should be considered in the thrust utilisation plot, for instance, in the Ormen Lange field in Norwegian waters.
- When the vessel deploys a very long mooring line, the limitation might come from the available propeller thrust due to heavy mooring weight and bollard pull deduction.

In general, the proposed method (see Fig. 4) is easy to implement and is useful for presenting the limitations of the anchor handling vessel before the operation commences. The proposed method is a good tool for defining vessel specific limitations, selecting a proper anchor handling vessel in terms of positioning capability during the planning stage and can also serve as the basis for establishing critical scenarios that are valuable for crew training in a simulator.

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A.8. Visit report

Visit report of rig move Songa Delta from Far Sapphire vessel

Authors: Giri Rajasekhar Gunnu

Published in Norwegian University of Science and Technology, Trondheim, Norway, p. 48.

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Appendix B

Anchor handling equipment

B.1. Anchor handling, towing and mooring equipment

Vessels with the notation “anchor handling” are fitted with, for example, an anchor handling winch, a shark jaw, towing pins, tow-wire, spare tow-wire, a towing gog, a stretcher, pennants, shackles, hinge links, a grapnel, a J-chaser or a J-lock chaser, chains, a pelican hook, any chain stopper (Karm fork or triplex stopper), and a stern roller. To conduct AHOs, along with this equipment, other equipment is provided by the rig including anchors, buoys, pennants, shackles and chains.

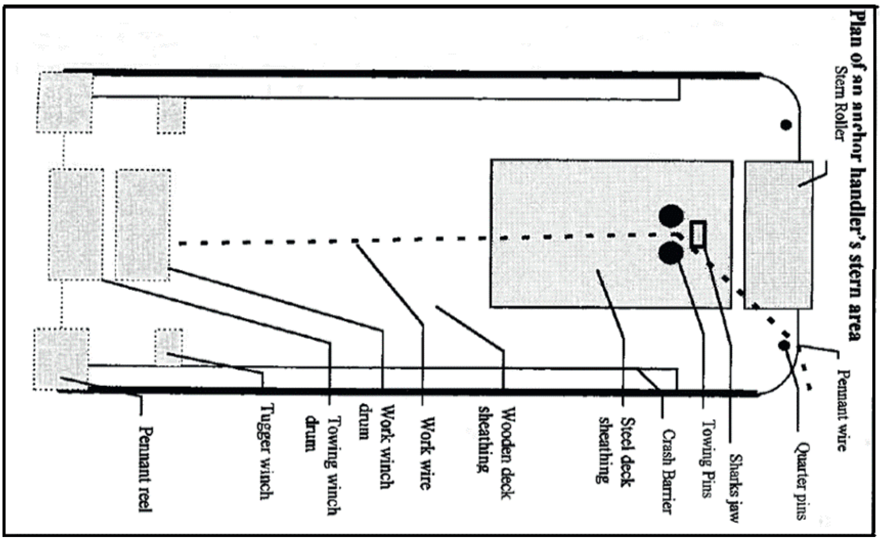


Figure B. 1: Deck layout of an AHV (Gibson, 1999)

B.1.1. Anchor handling winch

In general, the anchor handling winches are large and heavy construction equipment (see Figure B. 2) in the range of 150 to 900 tons. These winch positions are designed by considering the safety of the operation and work in connection with them. In accordance with the rules and regulations (DNV GL, 2017), the control system of these winches should be capable of conducting a controlled operation, that is, lowering and hoisting the anchor when the anchor is submerged and over the stern roller. Moreover, these winches should be fitted with an emergency brake system. This braking system should be able to work independently of the ship’s main power source. These winches should be fitted with an instrument to monitor the load on the wire continuously (during not only traction but also lowering and breaking operations). Adjustment of braking, tensile and lowering forces should normally be able to be performed from the control panels. It should be possible to monitor the winch, along with its movable parts, including the winding devices, drums and cable fittings, from all control points. Typically, TV monitoring systems are used for this purpose. These control point locations should be designed by considering the protection of the operator in the event of wire breakage.

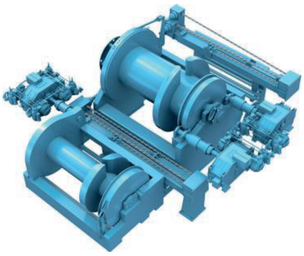


Figure B. 2: Anchor handling winch ("Rolls-Royce deck machinery for Edison Chouest anchor handlers," n.d.)

B.1.2. Tugger winch

Traditionally, a Tugger winch (see Figure B. 3) is considered a part of the deck handling equipment. These winches are widely used for deck handling applications such as pipeline handling and dragging items along the tracks. However, with respect to anchor handling vessels, these winches are specifically designed to help the crew to handle heavy towing gear during anchor-handling operations. These winches are positioned on the cargo deck between the stern roller and the superstructure. These winches are powered electrically or hydraulically.

Figure B. 3: Tugger winch ("Tugger Winch, Hydraulic Tugger Winch, Electric Tugger Winch," n.d.)

B.1.3. Karm forks

A Karm fork is a wire and chain-handling device. Fitted forward of the stern roller, it secures the chain or wire, allowing the crew to perform work safely on the deck. Karm forks (see Figure B. 4) consist of a pair of slotted tubes that are positioned in line with each towing pin. Before the chain or wire is brought on deck, it is stowed under the deck and raised hydraulically. Another design with the same function is known as the shark jaws (see Section B.1.4.)

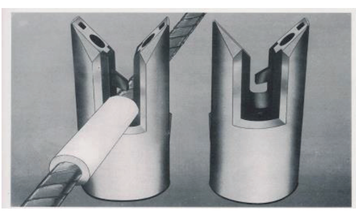


Figure B. 4: Karm forks (Hancox, 1994)

B.1.4. Shark jaw

This equipment has been installed with the objective of safe and secure handling of the wire and chain and to make it possible to connect/ disconnect an anchor system safely. In general, most AHVs are provided with two shark jaws (see Figure B. 5), one on the starboard side and one on the port side of the aft deck. The control plants for these devices are installed in the aft part of the bridge console close to the winch operator panels. The panels are located on the port side and starboard side, referring to the respective plant. The characteristics of a shark jaw are defined by considering the SWL (safe working load) in tonnes and the maximum chain or wire diameter that it can handle. During the operation, the deck crew makes a final call concerning whether the shark jaw is locked. Once they convince themselves, they will inform the bridge in charge. This system has two levels of redundancy. Even when a blackout occurs, it remains possible to operate by taking the power supply from the vessel's emergency generator. If the emergency power supply fails, it can be released by activating the emergency release system.

Figure B. 5: Shark jaw

B.1.5. Guide pins

In general, AHVs are installed with two sets of guide pins (see Figure B. 6) to ensure guidance when handling wire or chains. Most of these vessels have a common power pack to control the shark jaw and tow pins. The rollers on the guide pins can be manufactured as a single roller or divided into two rolls. The control plants for these pins are installed in the aft part of the bridge console close to the winch operator panels. If the guide pins are Karm pins, which have a flap for horizontal locking. When a pin moves upward, it turns the flaps towards one another. Thus, this system traps the wire / chain inside a "square" that avoids the wire / chain jumping off the towing pins.

Figure B. 6: Guide pins

B.1.6. Stop pins / quarter pins

The stop pins are located on the "whale back", which helps to prevent a wire or chain sliding over the side of the cargo rail.

B.1.7. Stern roller

Ships used for anchor handling operations are equipped with stern rollers (see Figure B. 7) with a sufficient diameter or an equivalent arrangement.

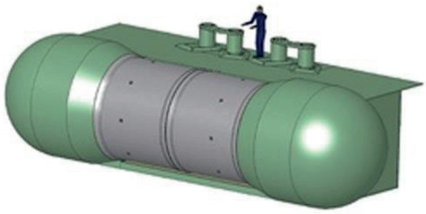


Figure B. 7: Stern roller ("Maersk Supply Service Orders Large Stern Rollers from HATLAPA (Germany) | World Maritime News," n.d.)

B.1.8. Pelican hook

The pelican hook (see Figure B. 8) fits over a chain and can be securely closed or opened when needed. This equipment is used to secure chain and wire on the deck of AHVs; it is connected to a short wire pennant, which in turn is connected to a deck-mounted pad eye situated by the deck side barriers.

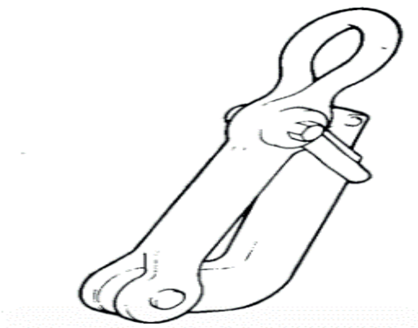


Figure B. 8: Pelican hook (Hancox, 1994)

B.1.9. Swivel

The swivel (see Figure B. 9) is inserted between the dead man wire and the permanent chasing pennant (PCP). This equipment ensures no stress, turns and/or torsion in the wire, enabling the deck crew to disconnect the mooring system components safely.

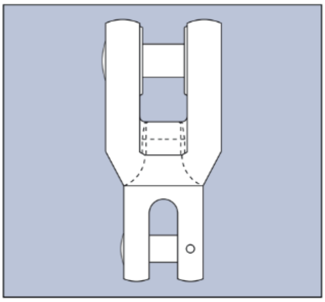


Figure B. 9: Swivel

B.1.10. Shackles

The travel of the wire or hawser shall be limited to the extent necessary by bollards, shackles (see Figure B. 10), supports or the like that are rounded to ensure at all times good manoeuvring with the tow line and to prevent the wire/hawser from jamming or being damaged in some other way.

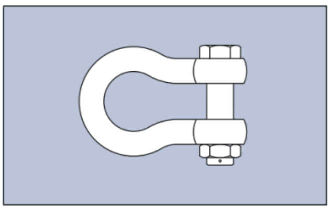


Figure B. 10: Shackle

B.1.11. Grapnel

The grapnel (see Figure B. 11) was designed as a "fishing" tool primarily to recover an anchor and a chain that have become detached and fallen to the seabed. The operational sequence is shown in Figure B. 12.

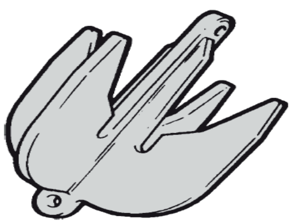


Figure B. 11: Grapnel

B.1.12. Anchor pendant

An anchor pendant is a wire that is attached to the crown of an anchor, enabling it to be pulled out of the seabed. The pendant wire is used by the anchor-handling tug to set and retrieve anchors using the cable eye on the free end of the wire.

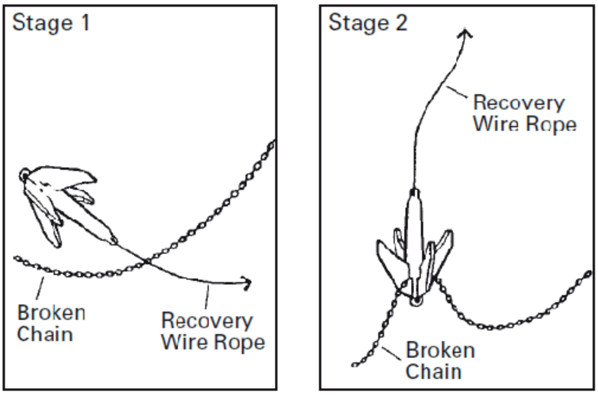


Figure B. 12: Picking up a chain or an anchor with the help of a grapnel

B.1.13. J-Chaser

Chain chasers are used in recovering rig anchors when the PCP fails in service. The chaser is designed to fit over the shank of the anchor so that the anchor cable and joining shackles will pass easily through it. The operational sequence of chasing is shown in Figure B. 13:

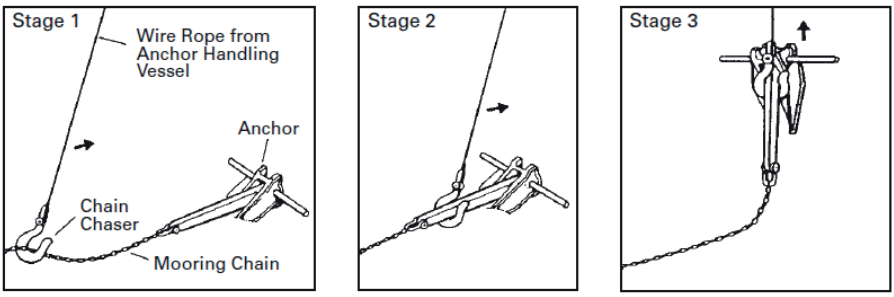


Figure B. 13: Sequence of steps in picking up an anchor with a chaser

B.2. Bollard pull

Vessel owners and masters should ensure that the vessel's bollard pull is adequate for the proposed operations. In considering this value, masters should be aware that bollard pull, as measured for vessel certificates, in some cases does not allow for the power used by the deck machinery, thrusters and other consumers to be diverted from the main propulsion. Allowance for any reduction should be made when considering bollard pull available during any operation. Maximum bollard pull is achieved with the cable right astern with rudders amidships. A reduction in bollard pull must be accounted for when the cable deviates from the right astern direction. The mooring line (or towline) dynamic factor in waves is approximately 1.4. Therefore, the maximum tension in a line should not exceed 50% of the minimum breaking load (MBL) of the weakest link in the assembly. Aiming for tension utilization of 30% of the MBL to allow room for peak loads is recommended. Winch tension controls, when available, can be set with the above recommendations in mind. For anchor breakout operations, the above values might require evaluation. This situation must be risk assessed and agreed upon by all stakeholders.

B.3. Thrusters

In AHOs, the AHVs are required to maintain their position and/or heading to a high degree of accuracy. For this reason, these vessels are fitted with very powerful thrusters. The thruster configuration for the Bourbon Dolphin was shown in Article JP4 (see Appendix A).

B.4. Anchor types

Anchors used in offshore structures can be divided into four categories: drag anchors, deadweight anchors (see Figure B. 14), pile anchors and embedded plate anchors. Drag anchors generate their holding power by embedding in the seafloor when pulled horizontally, mobilizing the shear strength of the soil to resist the pulling force. Deadweight anchors depend primarily on their own mass to provide holding capacity, whereas pile anchors generate their holding power by mobilizing lateral earth pressure and skin friction in the surrounding soil. Like drag anchors, embedded plate anchors gain their holding capacity from mobilizing the shear strength of the soil but are distinguished from drag anchors by not being self-embedding. The number and type of anchors used for positioning the structure depend on the size and type of the structure and on the seabed conditions.

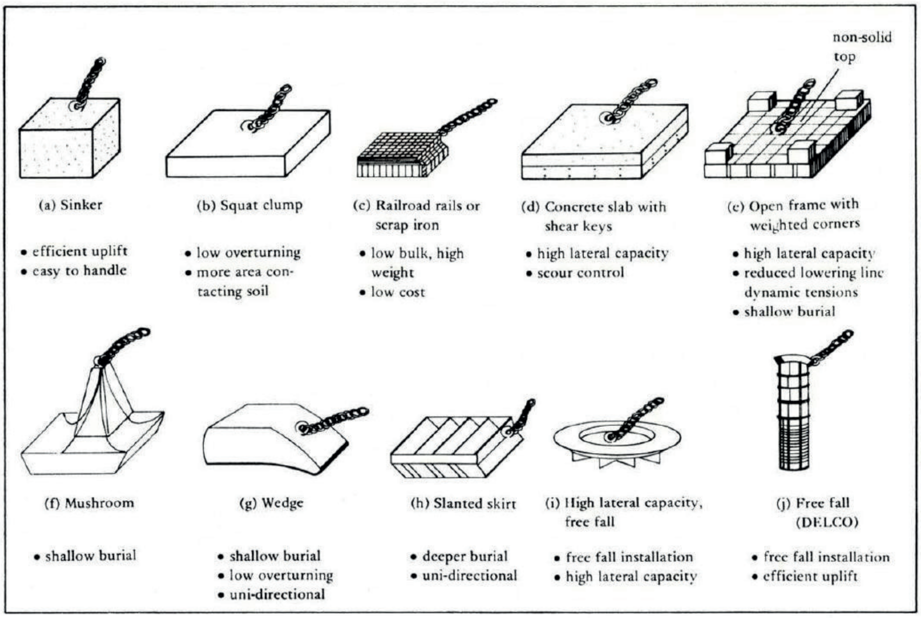


Figure B. 14: Types of deadweight anchors (OWET, 2009)

B.4.1. Drag embedded anchors

In conventional mooring systems for positioning MODUs, floating production systems, single buoy moorings, storage buoys, crane barges, flotels and pipe-lay barges almost invariably use drag anchors. Drag anchors (see Figure B. 15) are chosen for these applications in preference to other types of anchor because of their mobility (ease of deployment/recovery). In North Sea applications, drag embedded anchors are widely used.

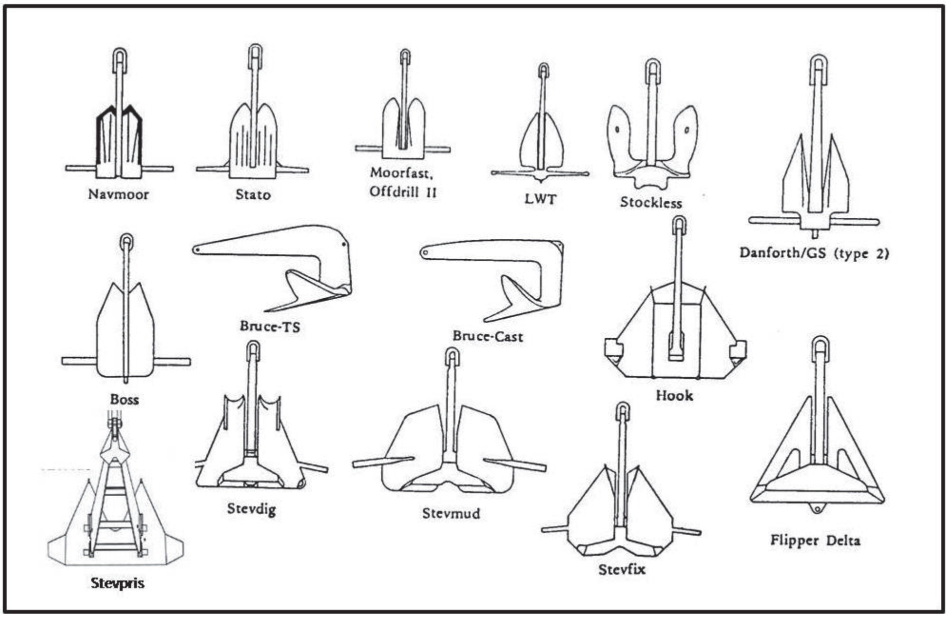


Figure B. 15: Types of drag anchors (OWET, 2009)

B.4.2. Suction anchor

Suction anchors (see Figure B. 16) are used in ultra-deep water for systems requiring taut or semi-taut pre-lay mooring systems. The anchor is embedded using an ROV (remotely operated vehicle) to pump water out of the top of the caisson until the anchor is fully penetrated into the seabed. The process is simply reversed to recover the anchor. Delmar has installed and retrieved more suction anchors than has any other offshore contractor. This system uses a suction caisson as the anchor. The caisson is cylindrical in shape with the bottom end open. A rig- and location-specific mooring analysis can determine the desired configuration for each system. Before the rig arrives, the suction anchor system is installed using Delmar's proprietary single vessel/single line installation method, which uses one vessel with ROV capability. The anchor is over boarded, lowered, and pumped into the seabed. The pre-lay mooring line is attached and suspended with a surface or submersible buoy, awaiting rig arrival. Once the rig is on location, it is connected to the mooring lines by one or two AHVs in a short amount of time. The recovery of the system is a simple process, with the suction anchor being pumped out of the seabed and recovered over the stern of the vessel. Delmar's suction anchor system incorporates the patented

Delmar Subsea Connector (DSC), which allows the anchor to be deployed with a single line and the mooring line to be connected or disconnected at any time by an ROV. This capability adds significantly to the flexibility of the system and reduces the cost of installation and recovery. The advantage of the suction anchor mooring system is the anchor's ability to hold at higher uplift angles, thereby reducing the circumference of the mooring pattern and watch circle maintained by the rig. The suction anchor system provides excellent performance in ultra-deep water and allows a rig to significantly extend its water depth capability. Another significant advantage of the suction anchor is the ability to target an exact location, its soil-holding properties, and alignment to the rig, allowing confidence in the anchor's ultimate holding capacity. Submersible syntactic buoys in the mooring system reduce the weight of the mooring lines on the rig. The suction anchor system is a safe and cost-effective alternative to dynamic positioning for ultra-deep-water drilling and development. The use of the Delmar Subsea Connector makes the system ideal for permanent installations in which a single AHV can install and maintain the entire mooring system at a fraction of the cost required for a conventional permanent mooring.

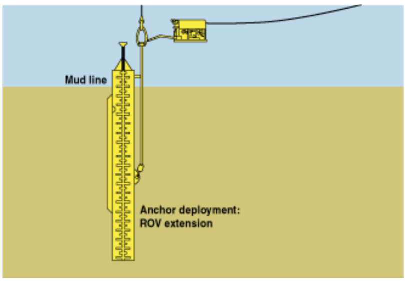


Figure B. 16: Suction anchor

B.4.3. OMNI-Max

The OMNI-Max (see Figure B. 17) is a multi-directional, self-inserting, gravity installed anchor. Of relatively small size, the anchor offers high capacity, high uplift and genuine out-of-plane loading capabilities not found in other traditional anchor foundations. The anchor can maintain sufficient capacity at high uplift angles with any pull direction—360° around the axis of the anchor. This unique feature increases station-keeping reliability during storm events.

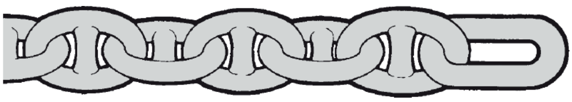
Figure B. 17: OMNI-Max anchor (Shelton, 2007)

B.5. Types of mooring lines

Widely used mooring line types for rig station keeping include chains, steel wire ropes and polyesters.

B.5.1. Chains

There are currently two types of chains in common use in the offshore industry. The stud link chain (see Figure B. 18) is the chain type most commonly used by the shipping and oil industry. Open link or stud-less (see Figure B. 19), which has no studs, is generally used in special mooring applications such as permanent moorings for FPSOs for the larger diameter chains and buoy and marine moorings for smaller diameters. Two chains are connected with joining links. These links are the weakest points in the chain. To avoid this weakness, longer chain lengths are used in the offshore industry. However, longer lengths are difficult to ship and handle. Hence, a balance between these two is considered. Chain sizes are expressed as the diameter of the steel bedding area. Chains can be fitted with open-end links to enable shackle connections. These connections can be used to connect two different types of chain diameters, or they can be connected with wire.



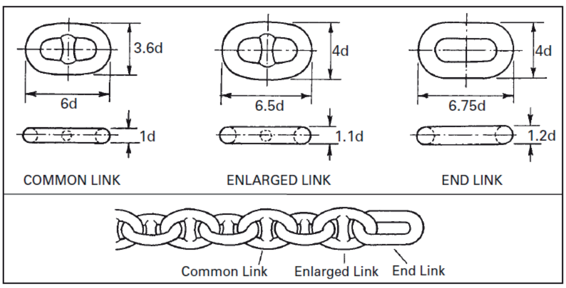


Figure B. 18: Stud link mooring chain

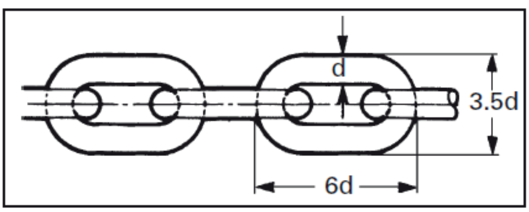


Figure B. 19: Open link mooring chain

B.5.2. Steel wire ropes

Steel wire ropes normally consist of four components (Figure B. 20):

- Steel wire that forms a strand;
- Strands that are wrapped around a core;
- The core;
- Lubrication of the core and the stands.

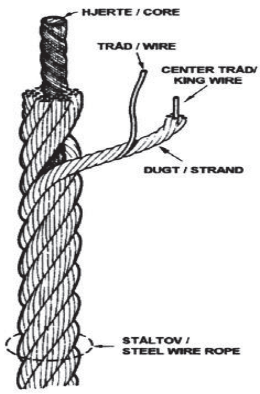


Figure B. 20: Steel wire ropes

Steel wire ropes are defined by how individual wires are laid together to create a strand and how the strands are laid around the core. The tensile strength of the steel wire ropes depends on the rope's dimensions, the tensile strength of the wires and construction. During spooling, the winches might not spool perfectly; if the wire is dragged over or in the seabed, the geometry of the wire could lead to inadequate torque. When disconnecting the tensioned wire from the spool, the torque can cause a kink in the rope, which can cause severe damage to personnel and equipment. As a safety precaution, a swivel is inserted in the system to release stress, turns and torsion in steel wires.

B.5.3. Polyester

Synthetic mooring components are used in ultra-deep-water applications in which a rig is constrained by the weight of a traditional steel/wire/chain mooring system. Used in combination with traditional mooring components, synthetics extend the water depth capabilities of existing rigs for an efficient and effective mooring solution. Delmar was the first to use synthetics in the Gulf of Mexico, resulting from a 1999 JIP test. Thus, Delmar designed, procured, and installed the world's first semi-taut steel-polyester-steel MODU system of this type, which the only one ever to experience repetitive use. This unique system incorporated the patented Delmar Subsea Connector and Installation Method to deploy ultra-deep-water moorings efficiently using a single AHV with the ability to deploy the anchor separately from the mooring lines.

Delmar developed the methodology for the installation of suction anchors in ultra-deep water. Because water depth limitations prevented the use of traditional steel wire/chain systems, synthetic moorings were used as the next generation of ultra-deep-water mooring components. Delmar's proprietary installation methodology and the Delmar Subsea Connector (DSC) provide for installation and retrieval of synthetic mooring lines with lightly loaded conditions. By reducing loads on the synthetic line during handling on AHV winch drums, the most sensitive area of concern for synthetic line damage is virtually eliminated.

Synthetic mooring components (polyester) can be used repeatedly with minimal wear. Careful planning of deployment and recovery operations ensures maximized life. The increased cost of synthetic rope can be offset by increased service life beyond what traditional steel wire rope systems can offer.

Delmar has been able to introduce synthetic moorings as a means of problem solving in what is considered more shallow water – conventional mooring projects. Crowded seafloor conditions, pipeline avoidance, and mooring pattern interference with adjacent rigs present challenges in which synthetics have played a major role. These applications have been used to reduce the risk of steel mooring components suspended over pipelines or subsea equipment and to reduce the scope of mooring lines to facilitate proximity mooring to other structures. Delmar maintains a rental inventory of polyester mooring components complete with connection hardware for use in these challenging mooring assignments.

B.6. Emergency release system

A manually operated emergency shutdown device for towing and anchor-handling winches is required that cuts off the power supply and rapidly actuates the brake. Emergency release shall be able to be performed from all the control panels of the winch, from the control point and from suitable locations on deck. Following emergency release, the winch brakes shall immediately be capable of being used normally again. Control buttons or the like for emergency release shall be secured against accidental operation. Emergency release shall be able to be performed even when the ship's main power source fails and under any conditions arising with respect to heeling and trim for the ship and for any possible tensile direction of the wire. Ships used for anchor handling shall be fitted with remote controlled wire/cable stoppers that must be capable of being emergency released from the wheelhouse or from a control point from which there is communication with the bridge. Emergency release shall also be able to be performed in the event of a black out.

AHTS vessels are equipped with two main winches – towing and anchor handling – and several small winches and auxiliary capstans. These vessels are built with multi-engine conventional diesel and diesel electric propulsion plants. In conventional diesel propulsion, the main engine power is delivered to the propeller and often also to shaft generators and firefighting pumps (Górski and Giernalczyk, 2012; Reljić *et al*., 2014).

Appendix C

The Bourbon Dolphin Accident

The Bourbon Dolphin capsized west of Shetland with the loss of the lives of eight of 15 crew on board, while performing anchor work at the Transocean Rather on 12 April 2007 (Gibson, 2008; Lyng et al., 2008).

C.1. Vessel background

The Bourbon Dolphin was an anchor-handling tug supply vessel (AHTS) of Bourbon Offshore Norway. It was delivered to Bourbon Offshore Norway at the beginning of October 2006 by the shipyard Ulstein Group in Ulsteinvik, Møre og Romsdal County, Norway. The vessel was built with an Ulstein A102 design that was unique at the time of the future accident; it is like the Rolls-Royce UT722. In addition, due to the request of the Bourbon Offshore managers, it was built with a larger winch, more wire storage and greater pull. Thus, with respect to the handling, it was able to work in deep waters. Furthermore, it was equipped with a DP2 system for performing anchor handling, towing and supply operations in deep water. At that time, the vessel was marketed as being capable of handling 194 tons bollard pull from its 16,000 odd BHP. The vessel had a continuous bollard pull of 180 tons and a tension on the main winch of 400 tons. The vessel had a gross tonnage of 2,974 tons and was 75.2 m long and 17 m wide. The vessel was put into operation immediately; up to the accident, the vessel had completed 16 assignments.

C.2. Operation background

Since the end of March 2007, the "Bourbon Dolphin" had been on contract with Chevron. The contract concerned anchor handling in connection with the move of the rig in the Rosebank oil field, west of Shetland. The rig was provided with a chain and wire combination to allow it to work in deep water. However, to satisfy the POSMOOR requirements, modifications to this system were required to prevent an anchor uplift in the worst weather conditions. Consequently, 916 m of chain was added to the rig's own 900 m, which was deployed from the chain lockers of the attendant AHVs.

The ocean depth in the area concerned is 1,100 m. The distance between the rig and the mooring positions was approximately 3,000 m. At the beginning of the job, the Transocean Rather was moored with eight anchors at the "Rosebank G" field. The lengths of the mooring lines were approximately 3,500 m, of which approximately 900 m was 84 mm chain and approximately 920 m was 76 mm chain, plus 1,725 m of 96 mm wire. At the end of the insert chain was an 18 tonne Stevpris anchor.

C.3. Operational procedure

C.3.1. Rig de-positioning

Four of the eight anchors were 'primary anchors', which were Nos. 1, 4, 5 and 8 (the numbering starts from the starboard bow). The remaining four anchors were secondary anchors – Nos. 2, 3, 6 and 7 (see Figure C. 1). Typically, the mobile units are generally considered safe when moored with the primary anchors and able to drill when all anchors (primary and secondary) are deployed. Deployment of anchors was done by means of the vessel running out the rig's chain and connecting it to the chain that the vessel had on board. Then, the rig ran out wire and the anchor that was fastened to the vessel's chain. Thereafter, the anchor was lowered to the seabed with the help of the AHV's winch and wire. During the last part of the deployment, the secondary AHV participated in grappling the chain. Thus, the weight of the mooring system is distributed to the secondary vessel, which helps to relieve the strain on the rig.

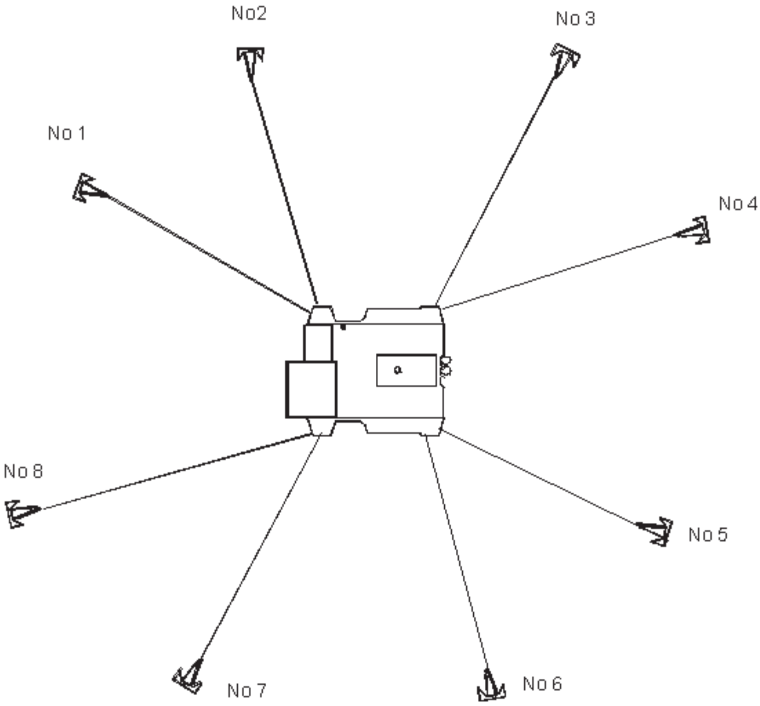


Figure C. 1: Mooring system configuration

The rig was fitted with a permanent chain chaser (PCC) system (see Figure C. 2), which consists of a collar that is installed round the mooring line and attached to a wire pennant. Normally, the AHV attaches its own work wire to the permanent chasing pennant (PCP) and then sets out the anchor. Thereafter, the AHV lowers its own work wire. This process works for any water depth. Here, the variant was the length of the ship's work wire. For deep-water AHOs, the rig uses a combination of chain and wire. The chain close to the anchor is used to prevent anchor uplift, and wire allows the rig to work in deep water due to its lower weight per unit length. At the point at which the chain is changed over to the wire, the rig crew disconnect the chain and connect to the wire. This step is known as the transition. Moreover, for the chasers to run down the wires without damaging them, they are typically fitted with rollers in the lowest part. These rollers had been damaged during the mooring of the rig at Rosebank G. Therefore, an alternative technique was used to recover these mooring lines. In this alternative technique, the main AHV activity is to J-hook (see Figure C. 3) the wire close to the rig and run it out to the secondary anchors. Thereafter, the anchors are recovered to the stern roller. Once the main AHVs have reached the anchors and recovered them to the roller, the assisting (secondary) AHVs are required to grapple for the chain astern of the main AHVs. Then, the main AHVs are to recover the anchors to their decks, remove them and stow the 900 m of chain in their chain lockers. The reason for the use of the assisting AHV was to reduce the weight on the chain and thus minimize the possibility of damage to the anchor. This technique was done in accordance with the requirements of the anchor-manufacturer's manual. The abovementioned procedure was to be used for recovering all the secondary anchors. Then, all four AHVs were used to lift the main anchors. Here, the tasks are the same, whether the ships were designated "main" or "assisting". Once all four vessels are on the primary anchors, their task is to lift them until they are at the rollers. Thereafter, the rig recovers its wire up to the transition.

Figure C. 2: Permanent Chain Chaser (PCC)

Figure C. 3: J hook chaser

C.3.2. Rig move

Once the rig de-positioning is done, the fifth vessel with less wire is connected to the towing bridle. In this configuration, the rig with all five vessels transits to the new location, which is 2 nautical miles from the existing location.

C.3.3. Rig positioning

Once the rig has transited to the new location, the primary AHV's activity is to deploy all four primary anchors in opposite pairs. Initially, the tow vessel is released from the bridle. Then, two AHVs run out towards an anchor deployment location, with the rig paying out its wire until the anchor point is reached. Thereafter, the main vessel lowers the anchor to the bottom. Consequently, the secondary (grapple) vessel is free to move away. The same procedure is repeated for all the primary anchors. This process was an adjustment from the original procedures because the brakes on the rig's winches lack the restraining capacity of the wire against the weight of the chain and the pull of the vessels. As described earlier, the rig is safe once it is moored with all the primary anchors. Once the primary anchors were deployed, the main AHVs would move on to the secondary anchors. The assisting vessels could now be used to take the weight of the chain at the rig end. Once the wire was deployed, the secondary vessel could move to a position astern of the main vessels and take some of the weight when the anchors were launched. Again, this approach reduces the possibility of damage.

C.4. Sequence of events

On the 27th of March, the Olympic Hercules and the Bourbon Dolphin started to recover anchors, each acting as primary and assisting vessel until the 29th. Then, the Bourbon Dolphin was sent off to Scrabster for a crew change. The crew change for the Bourbon Dolphin occurred early on the 30th of March and took one and one-half hours. The AHV returned to the field on the 30th and continued to work with the Olympic Hercules. On the 2nd of April, the Highland Valour, the Vidar Viking and the Sea Lynx arrived, and the work continued.

The extremely powerful AHV winches can destroy anchors when retrieving them. Therefore, instead of a conventional chasing system, J-hooking is used for retrieving anchors, which is called a tandem operation. Two ships are often required to run out and then tension up the mooring lines in tandem operations. Although the anchors were all eventually recovered, there was some damage, and several J-hooks were broken. Additionally, due to winch failures and weather downtime, the anchors were not recovered until the 8th of April. The original plan was to lift the four primary anchors at the same time and move the whole setup to the new location without recovering (retrieving) the chains. However, this plan was abandoned. Instead, all the anchors were to be run from scratch.

It might be worth describing the running (deploying) of one of the anchors. Due to the winch problems, at the first location, it had been decided to use two ships in two parts of the operation. The primary vessel with the chain in its chain locker takes the chasing pennant from the rig and pulls the end of the rig chain aboard. It then starts out on the line towards the anchor position; at the same time, the rig deploys its chain until all 930 m of 84 mm chain runs out. At that moment, an assisting vessel grapples the rig chain close to the rig, and then, the transition occurs. Thereafter, the assisting vessel releases the grapnel, and the primary vessel connects the additional chain from the chain locker, running out all 915 m. It is necessary for the assisting vessel to grapple the chain astern of the primary vessel because doing so makes anchor launching easier. Furthermore, the rig and the ships were provided with a navigation system that shows vessels, rig positions and anchoring positions with respect to each other to assist the vessels' masters and rig in charge.

The mooring operation at the new location started in the morning of the 9th of April. Due to the bad weather forecast, the management decided to send the Bourbon Dolphin to exchange two 12 tonne Stevpris anchors for two 18 tons and the remaining three AHVs to re-arrange their equipment. All four AHVs arrived at Lerwick on the morning of the 10th of April. At 0745 hours on the 11th of April, the three ships were back on the location, and the job continued. It is important to examine the anchor No 6 installation because it is directly opposite to No 2.

At approximately 0242 hours on the 12th of April, anchor No 6 was run by the Olympic Hercules (AHV). Then, the rig started paying out its chain. Within the hour, the transition was performed, and the Hercules then paid out the insert chain. The master testified that his vessel was being constantly set to the east by the current. Thus, during the over boarding, the AHV ended up 700 m from the desired track despite using most of the vessel's available thruster power. Indeed, the master felt that the current was more than 2.5 knots. Finally, after some discussion with the rig, the mooring wire was paid out, allowing the vessel to gain headway and set course for the anchor drop position. This anchor was the second to last; therefore, at 1130 hours, the Vidar Viking (AHV), which had been assisting with No 6, was instructed to de-tension its work wire and leave the field. The No 6 anchor landed on the seabed at 1233 hours.

At approximately 0900 hours on Friday, 12 April 2007, the "Bourbon Dolphin" began to run out chain for the last anchor (No. 2). By this time, the weather was becoming somewhat worse. The wind velocity was approximately 30 knots, and the significant wave height was approximately 3.5 m. Later on, in late afternoon, the wave height increased slightly. In accordance with rig move procedure a wind speed of anything near 25 knots would pose a serious problem. Furthermore, if the wind speed were greater than 30 knots and the direction was the same as the current, then conditions would be "marginal" compared with operational allowable limits.

At 0920 hours, the PCP (Permanent Chasing Pennant) was passed to the Bourbon Dolphin. Once the PCP was secured, the vessel took off on a course of 340 deg., in the direction of the No 2 anchor position; simultaneously, the rig paid out its chain. At 1000 hours, all the rig chain had been paid out, and the transition occurred. According to the two-master's log, this process was completed at 1015 hours. However, the vessel did not resume its course in the direction of the anchor position until after 1200 hours. During the above-disputed two hours, i.e., between 1200 and 1400 hours, the vessel was most likely connecting the insert chain. Then, the insert chain was paid out. The vessel kept on track until approximately 1400 hours. At the same time, the vessel was approximately 1100 m from the rig and started to drift-off to the starboard side. Based on the witness information, between 1300 and 1400 hours, the thrusters were overheating. The engineers even tried to cool one with a pressure hose.

At approximately 1445 hours, all of the chain was out. The "Bourbon Dolphin" then drifted considerably off the mooring line direction and asked the rig for assistance. The "Highland Valour" was sent by the rig to assist the "Bourbon Dolphin" but failed in securing the chain. Thus, the "Bourbon Dolphin" drifted eastwards towards the mooring of anchor No. 3. The rig in-charge instructed the vessels to proceed westwards, away from anchor No. 3. During an attempt to manoeuvre the vessel towards the west, the chain's point of attack over the stern roller shifted from the inner starboard towing-pin to the outer port towing-pin. Thus, the vessel developed a serious list (static heeling angle) to the port side. At the time, the engines on the starboard side stopped. Subsequently, the vessel initially righted herself but soon listed again. At 1708, she rolled over on her port side. Then, the vessel capsized suddenly and with little warning.

A full alarm was immediately raised on the rig and the vessels to search for survivors. Other vessels in the vicinity also proceeded to the locality to performing search operations. Moreover, helicopters from the British coastguard were alerted and arrived at the location approximately one hour later. The 'Bourbon Dolphin' had a crew of 14 persons. Also on board was the master's 14-year-old son. Seven persons were saved. Of those on the bridge, only one of the first officers managed to escape. The crew on the deck managed to obtain life jackets, climb onto the vessel's side and jump into the sea before the vessel rolled right over. Two persons who had been in the mess reached the deck and jumped into the sea. The vessel remained afloat for several days, bottom-up, finally sinking on Sunday the 15th of April. Subsequently, the "Bourbon Dolphin" was located on the seabed lying in an almost upright position.

C.5. Description from survivors

Before the vessel left Aberdeen, the Trident Offshore Superintendent briefed the key personnel on the operation. According to the accident report, there was a disagreement between the Bourbon Dolphin master and the Superintendent. During the accident investigation, the master claimed that he had disputed the capability of the Bourbon Dolphin for the envisaged forces to run anchors in the depths of water (1,100 m) at which the job was to occur. In contrast, the Superintendent said that no such discussion had occurred and that it was going to be necessary for every vessel to run at least one anchor, which can be seen in the rig move procedures.

A survivor of the crew of the Bourbon Dolphin accident has described how a series of problems and misunderstandings in what should have been a routine AHO caused the AHV to capsize. First mate Geir Syversen said the ship's master, Oddne Arve Remoy, called a second vessel involved in the operation moments before the vessel capsized and asked whether they "knew the difference between north-west and south-east".

Mr Syversen told the inquiry commissions (at Aalesund in Norway) that he managed to climb towards the starboard side and observed other crewmen being thrown around as the vessel was capsizing. "The last thing I saw as I exited the bridge was the master and his son falling towards the other side". When he fell into the freezing water, he was not wearing a life vest. He managed to hold on to a crewman who drifted by wearing a life vest. Then, they entered a life raft, in which a third crewmember joined them. He also observed three other crewmen drifting on a chemical tank. The rescue crew from the standby vessel Viking Victory arrived. However, the men were left in the life raft while the searchers tried to locate any more survivors.

Questioned by Judge Knut Andreas Oskarsson and marine inspectors Nils Ivar Soerdal and Jon Ramsoey, Mr Syversen explained that the crew was involved in a routine operation in 10-ft waves and 32-knot winds. Because they were handling anchor chains in deep water, they requested help from a secondary AHV (defined as a special nomenclature), Highland Valour. The Highland Valour was asked to pull a relief wire to the north-west, but according to Mr Syversen, she headed in the opposite direction. At approximately the same time, the engine room reported that the engines were overheating and asked that thrust be reduced. The first mate said that would take them off course, but just then, the tension on the chain increased, indicating that the relief wire from the Highland Valour had slipped. By now, the Dolphin had started to list noticeably, and the rig suggested that one of the tow pins be released to allow the anchor slacker. When it was released, the anchor chain dragged towards the port side, turning the vessel over in that direction. Furthermore, Mr Syversen explained that ballast water was pumped into the starboard side to counteract the list, but it did not work. Therefore, an emergency release mechanism for the chain and wires ran too slowly.

The eight crew members confirmed dead are chief officer Bjarte Grimstad, 37; second officer Kjetil Rune Vage, 31; 44-year-old master Remoy and his son David Remoy, 14; chief engineer Frank Nygard, 42; second engineer Ronny Emblem, 25; electrician Soren Kroer, 27; and 54-year-old bosun Tor Karl Sando.

C.6. Key conclusions from the investigation report

The Bourbon Dolphin accident was investigated by the UK Health and Safety Executive, the Norwegian maritime authorities and a Norwegian Royal Commission, which reported on 28 March 2008. The Royal Commission report (*Lyng et al., 2008*) describes how a series of problems and misunderstandings caused the oil rig support AHV to capsize. All aspects of the operation up to and after capsizing were investigated in depth by the Commission, Transocean (the owners of the rig), and Chevron (the operator, who hired the ships). It is clear from the accident report that vessel stability is an issue, and it had been paramount in the minds of the crew of the ship. If the vessel master (or person in charge of a vessel during an AHO) had been aided with an appropriate information in time , there would not have been a vessel capsizing event.

Key conclusions of the accident report (Lyng *et al*., 2008) findings are listed below:

- The vessel was built and equipped as an all-round AHSV (Anchor Handling Supply Vessel). Uniting these functions poses special challenges. In addition to bollard pull, anchor handling demands thruster capacity, powerful winches, large drums and equipment for handling chains. Supply and cargo operations demand the largest possible, and flexible, cargo capacities both on deck and in tanks. The “Bourbon Dolphin” was a relatively small and compact vessel, in which these requirements were to be united.
- The company had no previous experience with the A 102 design and ought therefore to have undertaken more critical assessments of the vessel’s characteristics, equipment and, not least, operational limitations during both her construction and her subsequent operations under various conditions. The company did not notice that the vessel had experienced an unexpected stability-critical incident approximately two months after delivery.
- The vessel’s stability-related challenges were not clearly communicated from shipyard to the company and onwards to those who were to operate the vessel.
- Under given load conditions, the vessel did not have sufficient stability to handle lateral forces. The winch’s pulling power was over-dimensioned in relation to what the vessel could withstand concerning stability.
- The anchor-handling conditions prepared by the shipyard were not realistic, nor did the Norwegian Maritime Directorate’s regulatory system make any requirement that these conditions be approved.
- The ISM Code demands procedures for the key operations that the vessel is to perform. However, even though anchor handling was the vessel’s main function,

there was no vessel-specific anchor-handling procedure for the "Bourbon Dolphin".

- The company did not follow the ISM code's requirement that all risk be identified.
- The company did not make sufficient requirements for the crew's qualifications for demanding operations. The crew's lack of experience was not compensated for by the addition of experienced personnel.
- The master was given 1½ hours to familiarize himself with the crew and vessel and the ongoing operation. In its safety management system, the company has a requirement that new crews shall be familiarized with (inducted into) the vessel before they can take up their duties on board. In practice, the master familiarizes himself by overlapping with another master who knows the vessel before he himself is given the command.
- Neither the company nor the operator ensured that sufficient time was made available for hand-over in the crew change.
- The vessel was marketed with a continuous bollard pull of 180 tons. During an anchor-handling operation, thrusters are always used in practice for manoeuvring and dynamic positioning. The real bollard pull is then materially reduced. The company did not itself investigate whether the vessel was suited to the operation but left this decision to the master.
- The company did not see to the acquisition of information about the content and scope of the assignment the "Bourbon Dolphin" was set to perform. The company did not itself do any review of the Rig Move Procedure (RMP) with a view to risk exposure for crew and vessel. The company was thus not able to offer guidance.
- The Norwegian classification society Det Norske Veritas (DNV) and the Norwegian Maritime Directorate were unable to detect the failures in the company's systems through their audits.
- In specifying the vessel, the operator did not consider that the real bollard pull would be materially reduced by using thrusters. In practice, the "Bourbon Dolphin" was unsuited to addressing the great forces to which the vessel was exposed.
- The mooring system and the deployment method chosen were demanding to handle and vulnerable in relation to environmental forces.
- Planning of the RMP was incomplete. The procedure lacked fundamental and concrete risk assessments. Weather criteria were not defined, and the forces were calculated for better weather conditions than those operated in. Defined safety barriers were lacking. It was left to the discretion of the rig and the vessels whether operations should start or be suspended.
- In advance of the operation, no start-up meeting with all involved stakeholders was held. The vessels did not receive sufficient information about what could be expected of them, and the master misunderstood the vessel's role.
- The procedure demanded the use of two vessels that had to operate at close quarters in different phases during the recovery and deployment of anchors. The increased risk exposure of the vessels was not reflected in the procedure.
- The procedure lacked provisions for alternative measures (contingency planning), for example, in uncontrollable drifting from the run-out line, nor were there

guidelines for when and how such alternative measures should be implemented and what, if any, risk these measures would involve.

- The deployment of anchor No. 2 was commenced before the considerable drifting during the deployment of diagonal anchor No. 6 had been evaluated.
- Human error occurred on the part of the rig and the vessels during the performance of the operation.
- Communication and coordination between the rig and the vessel was defective during the last phase of the operation.
- Lack of involvement occurred on the part of the rig when the “Bourbon Dolphin” drifted.
- The roll reduction tank was most likely in use at the time of the accident.
- The inner starboard towing pin had been depressed, and the chain was lying against the outer starboard towing pin. The chain thereby acquired a changed angle of attack.

C.7. Statutory body recommendations after the accident

This accident generated a wakeup call for the authorities involved in AHOs. After the Bourbon Dolphin accident, the IMO and NMD issued stability guidance for anchor-handling vessels during AHOs for preventing similar accidents in future operations. Moreover, in the UK, the Marine Safety Forum set up committees to examine the following aspects:

- Means of auditing AHVs before hire;
- Means of improving rig move procedures;
- An approach for rig move risk assessment.

The above recommendations might be helpful for preventing similar types of accidents in future operations. However, none of these activities focusses on how to improve operational performance by considering safety and cost. Furthermore, the above activities do not address issues such as how to improve situational awareness (such as of the vessel’s stability margin and positioning capability) or decision-making in different phases of the operation.

C.8. Ålesund University and offshore simulator study

To identify a better approach to assessing the vessel stability margin in terms of safety during AHOs, the Ålesund University and Offshore Simulator Centre at Ålesund performed an expert survey. Their conclusion was to define a limiting angle; i.e., the vessel initial heeling angle (or static heeling angle) should be within 5 deg. to perform safe operations.

C.9. Further research questions left for enhancing AHV safety and efficiency

However, the one thing that shipmasters can realistically do today to keep their ships safe is to be aware of their stability condition; if it is not possible to determine the condition, then that is the time to stop the job. It is essential to develop a vessel stability monitoring system that can assist the personnel crewing the AHV. In addition, it is helpful to develop a decision-making system that will be helpful in applying suitable actions to perform the operation safely.

The Ph.D. candidate focussed on the development of better stability criteria, a methodology for identifying an operational and vessel-specific limit state criterion, and the identification of a margin of limit angle with respect to the limit state angle. Moreover, the research was focussed on awareness of vessel safety and implementation of appropriate actions in hazardous scenarios.

Appendix D

Human error taxonomies

D.1. Taxonomies for human error

Widely used human error classifications are listed below:

- Slip, lapse and mistake classification;
- Classification of error phenotypes;
- Performance level-based error classification;
- General failure types (GFT).

D.1.1. Slip, lapse and mistake classification

The first taxonomy is that human errors at a cognitive level are slips, mistakes and lapses (Hollnagel, 1993; Norman, 1981; Reason, 1990). The distinctive features between a slip and a mistake are the intention and the plan.

- Slip. Failure in the execution of a task in which the intention is correct;
- Lapse. Failure in the cognitive storage of task information in which the intention is correct;
- Mistake. Failure in the selection of plans conducted for an action in which the actions performed are correct.

D.1.2. Classification of error phenotypes

The second taxonomy classifies errors that occur based on observable task actions or phenotypes (Hollnagel, 1993), as shown in Figure D. 1.

D.1.3. Performance level-based error classification

The third taxonomy is the skill-, rule- and knowledge-based error taxonomy from Reason (1990). This taxonomy is based on Rasmussen's (1982) skill-rule-knowledge-based framework for human performance (see Figure D. 2). The corresponding error types are skill-based slips (and lapses), rule-based mistakes and knowledge-based mistakes (see Table D. 1).

Skill-based responses are highly routinized responses in familiar circumstances. These responses are mostly physical reactions that take little thought. Skill-based behaviour is most frequent in daily operations and less subject to error and accidents. Skill-based errors will occur only if the skills are not sufficient to handle the goal-oriented task – for example, failure to prioritize attention, the inadvertent use of system controls, an omitted step in the procedure, an omitted check list item, poor technique, and over-controlling a system.

The RB level is involved when an attentional check-up process detects a deviation from the planned conditions. For certain familiar situations, rule-based behaviour is applied. RB attempts to take actions based on the rules that govern actions and are largely automatic, like SB actions. The appropriate rules vary with respect to the situations in the RB performance. RB errors occur with misapplication of good rules or the application of bad rules to situations.

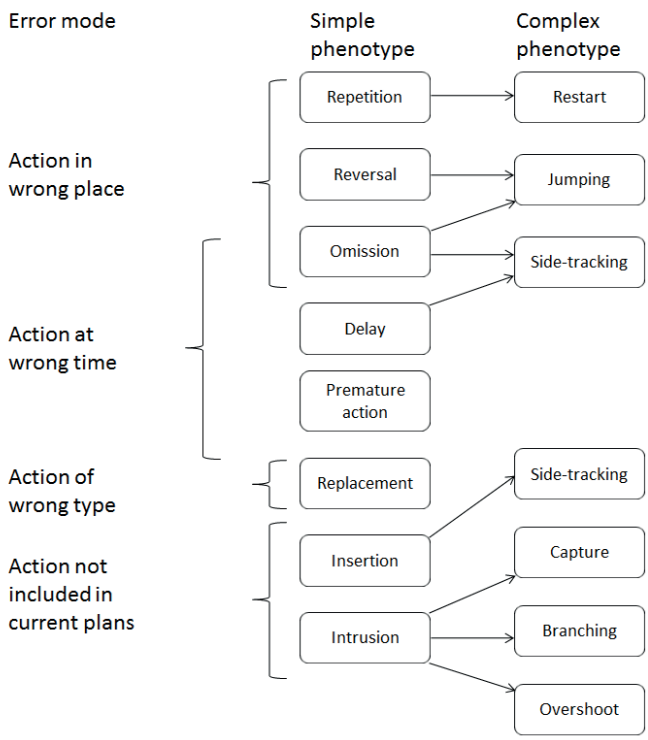


Figure D. 1: Taxonomy of phenotypes of erroneous actions (Hollnagel, 1993)

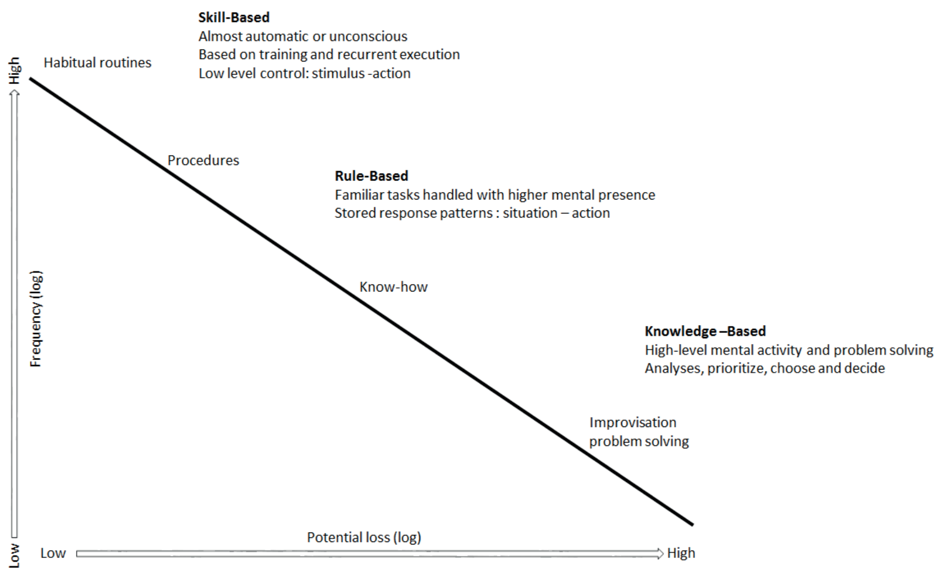


Figure D. 2: Alternative human performance levels (Rasmussen, 1982)

Table D. 1: Summarizing the main headings for the failure modes at each of the three performance levels (Reason, 1990)

Skill-based performance	
Inattention	*Over attention*
Double-capture slips	Omissions
Omissions following interruptions	Receptions
Reduced intentionality	Reversals
Perceptual confusions	
Interference errors	
Rule-based performance	
First exceptions	*Application of bad rules*
Countering and non-signs	Encoding deficiencies
Information overload	Action deficiencies
Rule strength	Wrong rules
General rules	Inelegant rules
Redundancy	Inadvisable rules
Rigidity	
Knowledge-based performance	
Selectivity	*Problem with causality*
Workspace limitations	*Problems with complexity*
Out of sight out of mind	Problem with delayed feed-back
Confirmation bias	Insufficient consideration of processes in time
Over confidence	Difficult with exceptional developments
Biased reviewing	Thinking in casual series not casual nets
Illusory correlation	Thematic vagabonding
Halo effect	Encysting

Complex situations require a type of problem-solving approach called knowledge-based behaviour. We apply knowledge-based behaviour to address unfamiliar and difficult tasks. Knowledge-based behaviour is event specific and is based on a functional understanding of what is occurring in the system (operation) when a demand is placed on the operator. This level of behaviour involves higher-level cognition processes – identification of system status and decisions based on the goal such as production, safety, and task planning. This behaviour might also have the largest consequence in the case of error. The planned task calls upon rule-based behaviour for stored procedure and skill-based behaviour for execution of the task (see Figure D. 3). Based on Reason (1997), the cognitive framework of human error classifies unsafe acts into two types of activities, as shown in Figure D. 4.

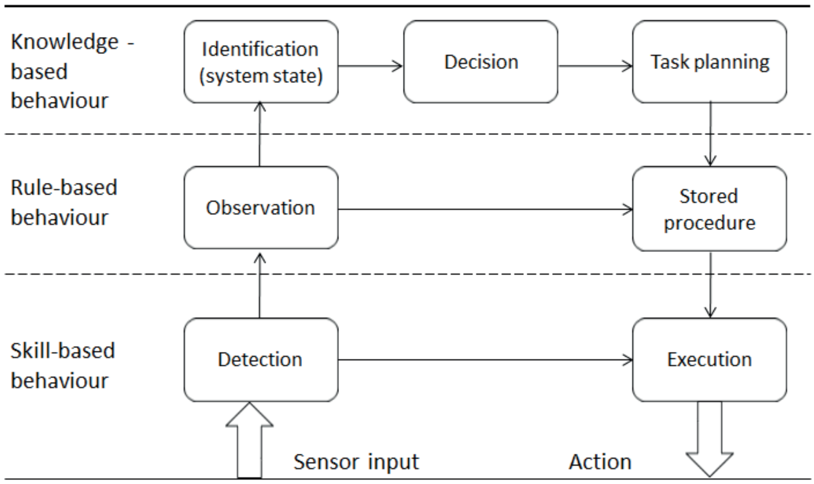


Figure D. 3: Skill-based, knowledge-based and rules-based behaviour (Rasmussen, 1981)

D.1.4. General failure types classification

The final taxonomy is GFTs. In this taxonomy, organizational human error can be examined. GFTs are used in the Tripod-Delta and MESH methods for analysing organizational accidents. Other similar taxonomies for organizational accidents include EPCs (Error Producing Conditions) used in the HEART (Human Error Assessment and Reduction Technique) and PIFs (Performance-Influencing Factors) used in the Influence Diagram Approach. Figure D. 5 shows the GFT taxonomy.

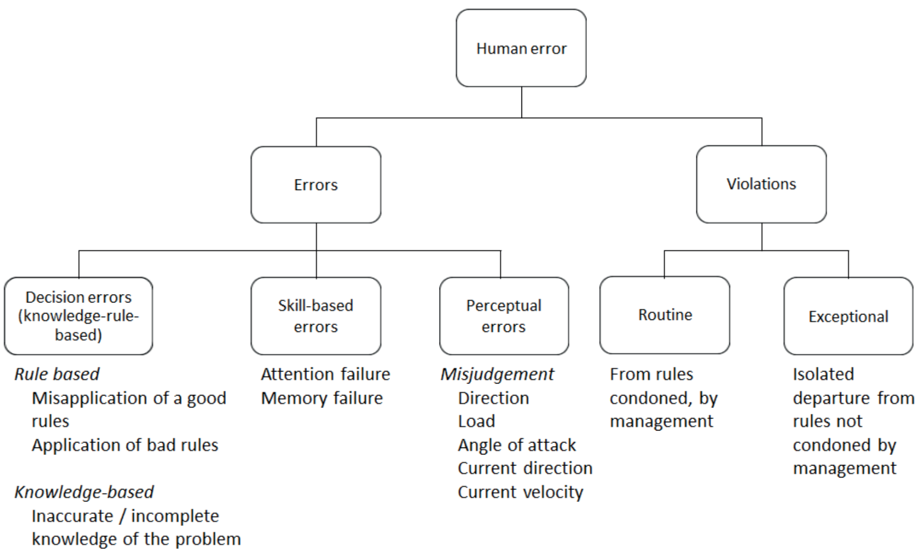


Figure D. 4: Human error classification (Reason, 1997)

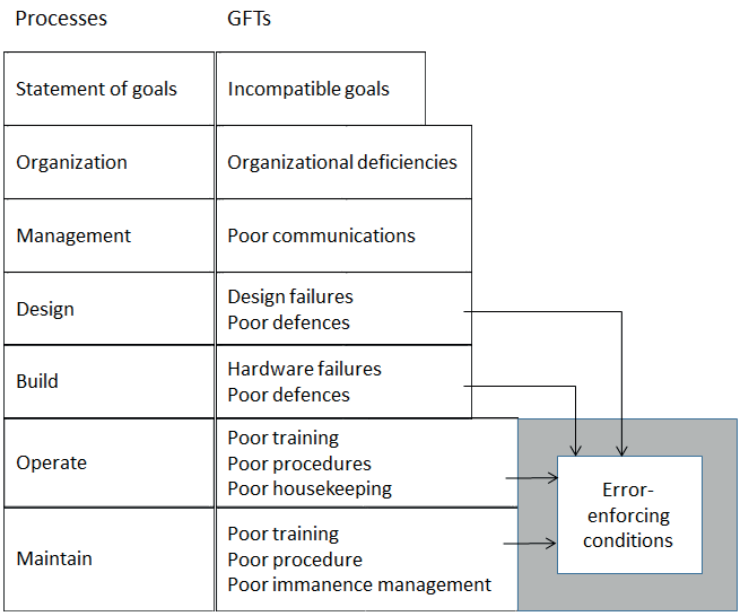


Figure D. 5: The relationship between the basic systemic processes and the general failure types, and the combined effect of the GFTs on the error-enforcing conditions (Reason, 1997)

Appendix E

List of previous PhD theses at Dept. of Marine Tech.

Previous PhD theses published at the Departement of Marine Technology (earlier: Faculty of Marine Technology) NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Report No.	Author	Title
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)
UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)
UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of

		Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
UR-86-49	Heinz-Joachim Wessel, MK	Fracture Mechanics Analysis of Crack Growth in Plate Girders. (Dr.Ing. Thesis)
UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)

UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis
MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)
MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
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		Thesis)
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MTA-99-127	Haugen, Elin M., MH	Hydroelastic Analysis of Slamming on Stiffened Plates with Application to Catamaran Wetdecks. (Dr.Ing. Thesis)
MTA-99-128	Langhelle, Nina K., MK	Experimental Validation and Calibration of Nonlinear Finite Element Models for Use in Design of Aluminium Structures Exposed to Fire. (Dr.Ing. Thesis)
MTA-99-	Berstad, Are J., MK	Calculation of Fatigue Damage in Ship Structures.

129		(Dr.Ing. Thesis)
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