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CONDITION MONITORING OF SHIP PROPULSION SYSTEMS: STATE-OF-THE-ART, DEVELOPMENT TREND AND ROLE OF DIGITAL TWIN

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ABSTRACT

This paper describes the current implementations and development trends of condition monitoring as it pertains to ship propulsion systems. In terms of total incidents in the shipping industry in the last five years, failures relating to the propulsion system represent the majority. Condition monitoring offers effective early detection of failure which translates to increased reliability and decreased maintenance costs. Current industrial practices are often limited to performance monitoring rather than condition monitoring. Special focus is afforded to how condition monitoring is implemented on board ships, which regulatory codes are relevant and the summary of state-of-the-art research in marine machinery. Moreover, operation and monitoring in extreme environmental conditions, such as the Arctic and Antarctic with ice impact on the propulsion has been discussed. The new developments, in particular, digital twin approaches in health and condition monitoring have been highlighted, considering its pros and cons and potential challenges.

1 INTRODUCTION

Maritime transportation plays a key role in globalization, as it now accounts for over 80 % of world-wide trade in terms of volume [1]. In its annual report Safety and Shipping Review of 2020, Allianz (AGCS) even claims that the global shipping industry is responsible for transporting 90 % of the world trade [2]. Thus, the value of a ship in the value chain is strongly dependent on its ability to transport the goods, which in turn depends on its propulsion system. Therefore, the probability of damage to a ship's propulsion system or the probability of a complete failure needs to be reduced or at least known in order to be able to assess possible risks for the value chain and minimize them.

The Lloyd's List Intelligence Casualty Statistics [2] reported 26,071 shipping incidents between 2010-2019. More than a third (35 %) of these incidents were caused by damage or failure of the propulsion system, which is over twice as many as the next highest cause, collision. According to the report of 2019 by AGCS, the number of propulsion-system-damage incidents have increased by a third over the past decade [3]. This ratio increases

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further, when looking at the incidents in Arctic Circle waters. The same report outlines that there have been 522 shipping incidents reported in Arctic Circle waters over the past decade [3]. Here, driven by the harsh operating environment, damage or failure of the propulsion system is the most frequent cause of incidents, accounting for almost half of all cases (47 %). The number of incidents in Arctic Circle waters may increase over the next decades, as research by Stephenson et al. [4] shows a link between climate change and the accessibility of new transit routes and areas for marine traffic in polar waters.

Thus, it becomes clear that the maintenance of a ship's propulsion system is relevant for the value chain and therefore it is stated that the improvement of the maintenance system leads to a reduction of incidents. The developing trend is increasingly progressing from reactive maintenance to scheduled maintenance and predictive maintenance. Predictive maintenance, enabled through condition monitoring, is an alternative to scheduled maintenance which offers effective early detection of failure. This translates to increased reliability and decreased maintenance costs and reduces unexpected shut-downs.

This paper reviews the current implementations and development trends of condition monitoring as it pertains to ship propulsion systems. Special emphasis is placed on the implementation of condition monitoring on ships, relevant regulatory codes and current research frontiers in condition monitoring and fault detection. The need for, and the trend towards the use of digital twins for condition monitoring is explicitly discussed. Finally, the use of a digital twin for condition monitoring of the propulsion system of a polar supply and research vessel is proposed as a valuable case-study that practically shows how condition monitoring, both diagnosis and prognosis, can be implemented. The discussion includes special considerations for this digital twin such as propeller ice impacts. For this, the state-of-the-art of ice material models is discussed and it is shown how ice material models are derived and validated experimentally and numerically.

2 FAILURE STATISTICS

The risks associated with failures serve as a strong motivation for the development of advanced predictive maintenance technologies. Furthermore, it may provide insight as to which sub-systems are the most vulnerable. Therefore, this section will focus on available statistics covering the frequency and financial impact of failures. The data is collected from *Lloyd's List Intelligence Casualty Statistics* as reported by [2, 3, 5–7].

Figure 1 provides a stacked plot of the total shipping losses world wide over the past decade and the causes thereof. The number of total losses has been declining over the past decade, with foundering accounting for the majority of losses (75 % in 2019). Factors contributing to the foundering included bad weather, flooding, engine problems, and capsizing [2].

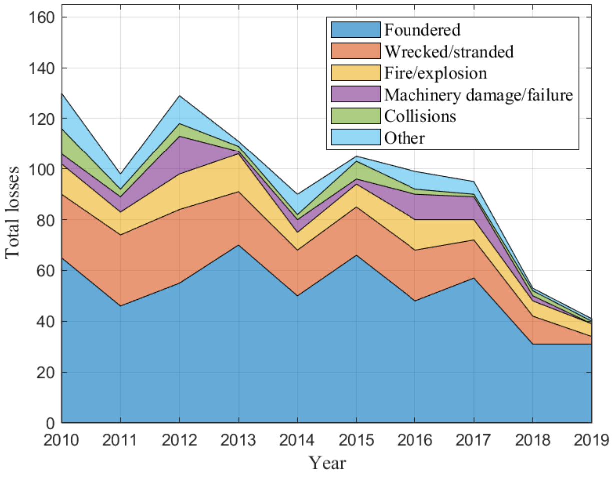

FIGURE 1. Total losses in shipping from 2010 to 2019 [2]

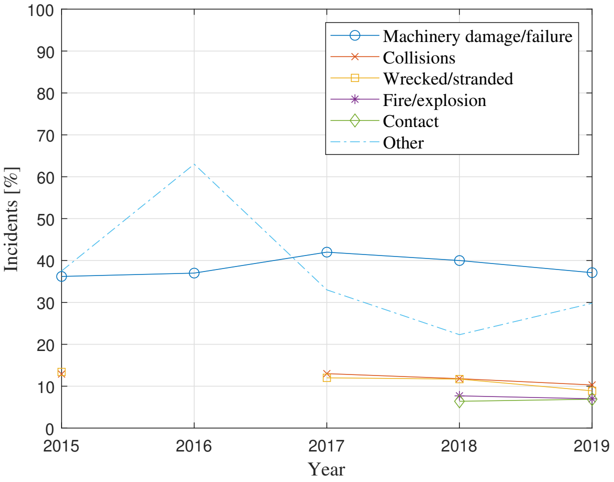

FIGURE 2. Incidents in shipping from 2015 to 2019 [2, 3, 5–7]

From the data shown in Figure 1 there is a general trend of decreasing total losses over the period, especially in the last few years. In addition, it can be seen that failures of the propulsion machinery result in fewer total losses than foundering, wrecking, stranding or fires.

However, in terms of total incidents, failures of the propulsion system represent the majority. Figure 2 provides a breakdown of the incidents that occurred world wide in shipping from 2015 to 2019. The main cause of reported incidents has consistently been damage to, or failure of, the propulsion machinery. Furthermore, although the total losses in shipping has been decreasing the total incident occurrence has not. The total incidents that occurred world wide from 2015 to 2019 is presented

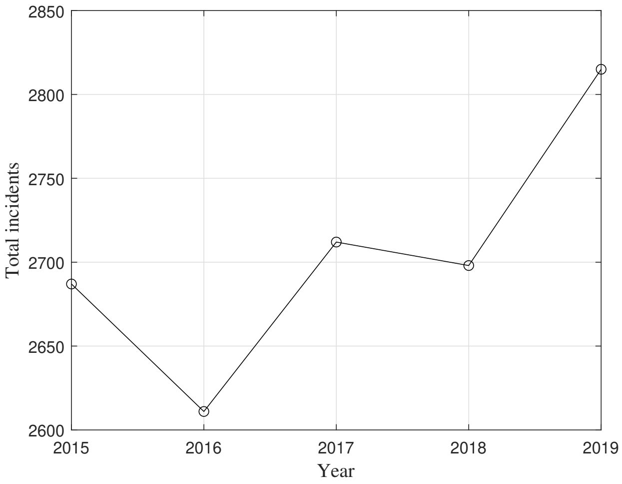

FIGURE 3. Total incidents in shipping from 2015 to 2019 [2, 3, 5–7]

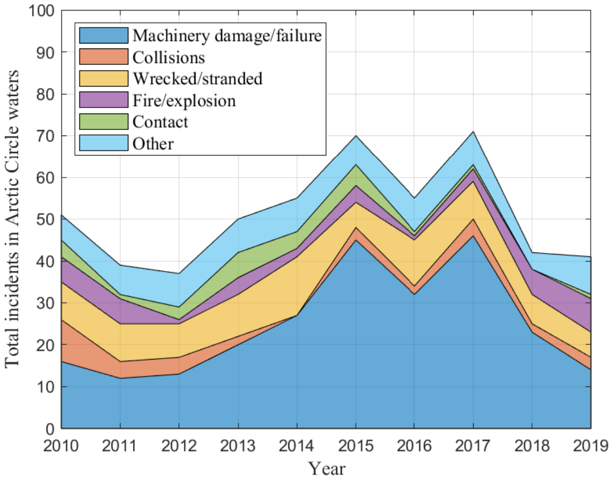

FIGURE 4. Total incidents in Arctic Circle waters from 2010 to 2019 [2]

in Figure 3 which shows an overall increasing trend to the number of incidents that have occurred during this period. As shown in Figure 2, the largest contributing cause of incidents is consistently attributed to the damage or failure of propulsion machinery. Combined consideration of Figures 2 and 3 leads to the conclusion that there is an increasing trend in propulsion-related failures.

Figure 4 provides a breakdown of the incidents that have occurred in Arctic Circle waters from 2010 to 2019. Again, the majority of reported incidents are related to the failure of or damage to propulsion machinery, especially due to the harsh operating conditions in these regions.

According to AGCS [8], machinery breakdowns continue to be one of the largest causes of loss in terms of both value and consistency. In 2018, machinery breakdowns accounted for 12 % of the total value of claims made, tied with claims related to damaged goods, and following ship sinking and collision claims (at 16 %), and fire and explosion claims (at 13 %). This despite machinery breakdowns only accounting for 3 % of the total number of claims. Based on this data, the propulsion system emerges as a crucial system to benefit from the advantages of monitoring for failure.

3 PROPULSION MAINTENANCE

3.1 Codes and standards

The shipping industry is heavily regulated and consideration should be given to codes and standards that inform maintenance strategies on vessels. The International Maritime Organization (IMO) is a body created to ensure that the relevant conventions and standards concerned with shipping are up to date and relevant [9]. The principle technical advisor of IMO is the International Association of Classification Societies (IACS) which establishes minimum requirements aimed at increasing maritime safety and decreasing pollution [10]. The IACS combined these rules into Unified Requirements (UR) which serve as minimum requirements for all member societies [11]. Classification societies are independent bodies which confer classification to vessels which are built and operated according to the requirements set out by the individual classification society. This section will be focused on the classification rules and selected international standards with relevance to predictive maintenance of propulsion systems.

The maintenance of critical systems on board ships can increase system reliability and reduce the risks associated with propulsion losses [12]. Maintenance strategies comprise routine- or planned preventative maintenance, condition based maintenance, unplanned maintenance or a combination of these methods [12]. Condition-based maintenance uses condition monitoring to determine the maintenance strategy [13]. Condition monitoring uses data as a means to quantify the condition of components as a function of time [13].

As a basic requirement, DNV GL classified ships must have all equipment "properly maintained" according to recognised standards or manufacturer recommendations [14]. Maintenance is defined to be carried out at defined intervals as part of a maintenance plan. Periodic surveys are mandated in order to confirm satisfactory condition of the hull, machinery, equipment and systems [15]. Vessels are to have a design life of 25 years with design checks necessary for the serviceability limit state, accidental limit state, ultimate limit state and fatigue limit state of the hull [16]. With regards to machinery, failure is defined as a sudden event or gradual deterioration leading to loss of function [17]. Concepts such as Mean Time to Failure (MTTF) and

Mean Time to Repair (MTTR) are introduced to quantify the availability of components. Calculation of reliability and availability as well as a Failure Mode and Effect Analysis (FMEA) is required to describe the reliability of components. For machinery drivers, requirements for maintenance is based mainly on manufacturer requirements which are to be listed in a maintenance manual [18]. These manuals must cover methods, intervals and acceptance criteria related to maintenance. Requirements for annual, periodic and complete surveys of machinery are listed with reference to necessary examination methods and components which have to be surveyed [15]. For the propeller shaft, surveys should consider bearing areas, bearings, sealing and lubrication systems with special consideration given to the propeller to shaft connection [15]. The society however allows for alternative arrangements in lieu of regular surveys including allowance for condition monitoring of selected components while also adhering to surveys specified in a planned maintenance system [15]. The older GL rules for classification contains specific guidelines for condition monitoring of machinery which describe the process as calculating trends of parameters which indicate condition of machinery in order to implement changes to a planned maintenance system. Separate to the general class notations, DNV GL allow for additional class notations of ships which have additional requirements. Some additional classes including *TMON* (Tailshaft monitoring) provide specific requirements for condition monitoring of the propeller shaft and bearings. Requirements are supplied with stipulations for which parameters to measure and limits for these parameters [19]. The *Smart* additional class notation provides a framework for digital solutions on vessels including reference to condition based maintenance of machinery as one of multiple requirements [20].

In addition to maintenance requirements, DNV GL guidelines enforce the need for continuous monitoring of temperature, pressure, speed and other parameters of propulsion components such as bearings, gearboxes, clutches and propellers [21, 22]. These measurements are intended to indicate faulty operation requiring immediate intervention. Some additional class notations require additional parameters to be monitored DNVGL-6-2 while others have specific load cases and requirements to be considered during design. Standardized methods exist to label data captured as part of these monitoring programs [23].

DNV GL accounts condition monitoring in its rules as follows. Condition monitoring of a ship propulsion system is a survey arrangement based on audits of an approved and implemented condition based maintenance program on ship's board, allowing the maintenance intervals of various components to be adjusted based on the monitored data [15]. Nonetheless, the audits shall be part of the main class annual survey [15]. In order to offer an alternative to planned based renewal surveys, companies providing condition monitoring services of ship propulsion systems shall be approved by the society [24]. The class program of DNV GL is limited to the following standardised methods [24]: (i) Vibration condition and diagnostics, and (ii) Lubricant analysis (oil).

In their Preventative Maintenance Program (PMP) the classification society American Bureau of Shipping (ABS) provides requirements for ship owners to achieve alternative survey crediting of machinery by applying preventative maintenance practices [25]. PMP is a program which consists of planned maintenance and/or condition based maintenance [25]. The following data is recommended by ABS to be recorded at least monthly, unless indicated otherwise, for condition monitoring arrangements of reciprocating internal combustion engines [25]:

i) Operating time (running hours)
ii) Power output (MCR)
iii) RPM
iv) Lubricating oil and cylinder oil consumption
v) Bearing temperatures (main, crank pin, crosshead and internal thrust, as fitted)
vi) Vibration of engine structure and components
vii) Lubricating oil analysis (monthly minimum), and more ...

Lloyd's Register (LR) defines condition monitoring as the use of instrumentation to make regular or continuous measurements of certain parameters, in order to indicate the physical state of the machine, without disturbing its normal operation [26]. According to Lloyd's Register, the following techniques are most commonly used to determine the condition of a machine [26,27]:

i) Vibration Monitoring
ii) Lubricating Oil and Water Monitoring
iii) Thermography

Whereas the general requirements for condition monitoring systems are declared in LR's Rules and Regulations for the Classification of Ships Part 5, Chapter 21 [28].

The International Organization for Standardization (ISO) offers a framework for condition monitoring of machinery which considers aspects such as criticality of components and measurement approaches [29]. The method of prognostics predicts a remaining useful life (RUL) of components with a suitable accuracy in order to inform maintenance intervals with sufficient time to enact maintenance [30]. For this method to give valuable insights, detailed information is required concerning causes of faults and the confidence level of all methods used [30].

3.2 Condition monitoring practices

Ship operators are required by the component manufacturers and the classification society to maintain their systems on a regular basis. For this purpose, the ship operators work out a maintenance plan with the component manufacturers and the classification societies taking into account the risk of failure, minimization of maintenance costs and time spent in dry docking, among other things. In industry, the trend is moving towards condition monitoring services, where the monitored condition of the component is accounted for in the maintenance plan and maintenance intervals can be adjusted in a cost- and risk-efficient manner.

Wärtsilä is a company known for manufacturing power plants and marine engines. The Wärtsilä Propulsion condition monitoring service (PCMS) is recognised by the classification societies ABS, LR and DNV GL and eliminates the need to enter a dry dock for visual inspections. In addition, these classification societies have acknowledged that Wärtsilä PCMS can determine the condition of propulsion equipment without visual internal inspections and detect potential failures. This is achieved by measuring vibration and oil condition in order to effectively monitor gears, bearings, the propeller and other propulsion equipment components. Additionally, the service gathers operational parameters from the propulsion control system. At the same time, the data is processed onboard and sent to Wärtsilä. The transmitted data to Wärtsilä is continuously processed by the PCMS central server and alerts the personnel at Wärtsilä when issues arise. If these issues require immediate attention the operator will be informed. Each month a PCMS report is sent that outlines the latest findings and recommendations. It also describes the condition of the propulsion equipment, the recommended maintenance interval and how the equipment can be kept in optimal condition [31].

PCMS is applicable to steerable thrusters, transverse thrusters, electric pods, controllable pitch propellers including reduction gears and water jets. Typical measurements include:

i) Vibration
ii) Lubrication oil contamination
iii) Lubrication oil-water saturation
iv) Drive shaft RPM
v) E-motor load (for E-driven applications)
vi) Control system parameters

Vibration is measured with industrial grade accelerometers. These sensors are mounted on the propulsion machinery, in an x-, y- and z- direction and are sampled continuously and simultaneously at a rate of up to 50,000 Hz. The system is configured to collect four types of data from the acceleration measurements. RMS vibration level are sampled at a rate 10 - 1000 Hz, low frequency spectra at a rate 0 - 1000 Hz, high frequency spectrum at a rate 1000 - 10,000Hz and envelope spectrum at a rate 0 - 1000 Hz. Frequency spectra are stored periodically per operating condition, or in the event of irregularities. The PCMS system stores frequency spectra for each operating condition (based on pitch, load and RPM) on a periodic- and a triggered basis. The drive shaft RPM is measured on a flange with an inductive proximity sensor. An accurate RPM measurement makes it possible to correlate frequency spectra to the shaft rotation speed. With PCMS lubrication is monitored by measuring the oil water saturation and the oil contamination levels according to ISO 4406 [32]. In a measurement cycle of a minute the ISO contamination class is measured by an optical transmitter for particle sizes of $> 4\ \mu$m, $> 6\ \mu$m, $> 14\ \mu$m [33].

Condition monitoring services for marine propulsion systems are offered by ABB Ltd, Kongsberg Gruppen ASA, Rolls-Royce Holdings plc, SCHOTTEL GmbH, Siemens AG and ZF Friedrichshafen AG among others. Information about what the systems measure, what is done with the data and how these systems are implemented on board is difficult to access. The description of Wärtsilä's condition monitoring service is freely available and recognized by the major classification societies and therefore it reflects the industry's expertise in condition monitoring of marine propulsion systems sufficiently.

4 MAINTENANCE STRATEGIES FOR MARINE PROPULSION SYSTEMS

Over time, the shipping industry has moved away from time-based maintenance, and begun employing preventative and condition based maintenance [2]. Preventative maintenance schedules usually follow from recommended maintenance plans provided by the manufacturers of propulsion system components. As an example, the maintenance of the propulsion system of a polar supply and research vessel, S.A. Agulhas II (SAAII), is discussed in this article. The majority of the maintenance on this ship focuses on preventing failure through the scheduled maintenance of components. Limited condition monitoring is employed during operation, specifically the monitoring of oil, bearing, and motor temperatures.

Preventative maintenance occurs at regular intervals based on maintenance plans set forth by component manufacturers [34–37]. Table 1 provides a summary of the maintenance plans for the SAAII propulsion system. The various components or systems include the shafting, hydraulics, oil-distribution box, bearings, propeller, motor (and attached generators), and control system.

5 CONDITION MONITORING METHODS AND DEVELOPMENT TREND

The research and development trend relating to condition monitoring techniques and methods for marine propulsion systems is discussed. It is important to note that most of the techniques and methods are generic in their nature and have also been used in other industries.

5.1 Component monitoring methods

Electric components

Condition monitoring and fault diagnosis of electrical machines has always been a topic of interest and importance in industry and academia. In recent years, there has been extensive research activity in this field towards the development of predictive maintenance systems. This is because electrical machines

TABLE 1. Maintenance of the S.A. Agulhas II propulsion system [34–37]

	Component / System						
Frequency	Shafting	Hydraulics	OD-box	Bearings	Propeller	Motor	Control
Daily	✓	✓					
Weekly	✓	✓	✓				✓
Monthly	✓		✓				✓
Every 3 months		✓		✓			
Every 6 months	✓	✓	✓		✓	✓	✓
Annually	✓	✓	✓	✓	✓	✓	✓
Every 5 years (dry dock service)	✓	✓	✓	✓	✓	✓	✓
During operation		✓		✓		✓	

(either as motors or generators) are increasingly used in new applications and are often a critical part of the system. As an example, transportation electrification has significantly increased the use of electrical machines in automotive, aerospace, and maritime sectors. Electric motors and generators are now utilized in marine propulsion systems, increasing the energy efficiency and reducing the emissions. Ship propulsion motors are normally induction motors (as in S.A. Agulhas II) or wound-field synchronous motors [38]. Permanent magnet (PM) synchronous machines have also been developed for ship propulsion and are now available in the market [39]. Faults in electrical machines can be classified into three main categories: stator winding faults (e.g. short-circuited turns), rotor faults (e.g. broken bars in induction machines, short-circuited turns in synchronous machine, and demagnetization in PM machines), and mechanical faults (e.g. eccentricity and bearing damage). According to the surveys conducted by different organizations [40], most common faults in electrical machines are related to stator windings and bearings. Most common signals measured for fault diagnosis in electrical machines are vibration and stator current. Vibration analysis is typically used for condition monitoring and fault detection in rotating machinery. Frequency analysis of vibration signals can reveal valuable information about the health of the machine and detect different types of faults, including eccentricities, bearing damage, and short circuit faults. Using the stator current signal for fault diagnosis has attracted a lot of research efforts in the past two decades. This method, commonly referred to as motor current signature analysis (MCSA), can detect a variety of electrical and mechanical faults, including short-circuits and eccentricity faults, as well as bearing damage. In addition to vibration and stator current, other methods such as installation of magnetic field sensors and search coils, partial discharge measurement, and temperature monitoring can also be employed for detection of failures. Signal processing techniques and development of AI-based algorithms have featured in recent research works dealing with fault detection and classification in electrical machines. A desired fault diagnosis system should be able to detect different types of faults, discriminate between them, and prove functional in non-steady states of operation. Lifetime of electrical machines are normally limited by aging of winding insulation. One way to monitor the condition of insulation is partial discharge measurement, which can reveal information about the aging and remaining lifespan. This method is usually only applied in large critical machines. The aging process is closely linked with operating temperature. Hence, lifetime of electrical machines can be predicted if hotspot temperature data is available. Since measurement of hotspot temperature in the windings is not straight-forward, a thermal model is required to estimate the hotspot temperature, either using available temperature sensor data or stator current. This can be realized with implementation of digital twins, highlighting the potentials of this technology for enabling predictive maintenance of electrical machines.

Propulsion shaft

Again, vibration based condition monitoring is commonly associated with shafts. This is usually to detect defects such as misalignment, unbalance, or bent shafts. Frequency domain methods are often employed, with different defects resulting in specific responses in the vibration profile of the shaft. These defects are usually detected through measurements conducted at the bearings supporting the shaft, but measurements can also be conducted directly on the shaft [41], for instance crack detection [42]. The method makes use of order analysis to monitor the vibration frequencies caused by cracks and misalignments based on the rotational speed of the shaft.

Plain bearing monitoring

Using condition monitoring of plain bearings, critical operating conditions and incipient damage can ideally be detected without delay. This allows needs-based maintenance and cost savings. In the following, common monitoring systems are presented in accordance with [43].

Thermal monitoring: Temperature measurement is the most frequently used method for monitoring plain bearings. Here, the temperature is recorded, which changes as a function of the internal friction and, therefore, lubricating condition in the bearing. In hydrodynamic operation, fluid friction creates a temperature gradient with respect to the ambient temperature. In critical operating conditions, the proportion of mixed or solid friction increases due to insufficient separation of the surfaces, resulting in an increase in the temperature in the load zone [44]. The measurement of the temperature takes place close to the sliding surface to achieve the earliest possible response. A possible positioning of the temperature sensors is shown in DIN 31692-2 [45]. In industrial applications, it is not always possible to position the temperature sensors directly in the load zone. This reduces the sensitivity of the temperature sensors regarding friction progress. As a result, damage cannot always be detected reliably or only at an advanced stage. Thus, temperature measurement alone is not well suited for condition monitoring and early-stage damage detection.

Monitoring of the lubricant: Another way of damage detection is monitoring the lubricant quality. In this method, the lubricant is evaluated by analysing the entrained particles. During critical operating conditions, particles are detached from the component surface and carried away with lubricant. The quantity, size and type of particles provide information about the contamination of the lubricant and the current wear of the component. Based on the size and quantity of the particles, an estimation can be made for the operation condition of the plain bearing regarding the probability of abrasive wear. However, this method has two major limitations: In the case of multiple bearing locations, no clear conclusion can be made about the condition of individual plain bearings due to the common lubricant circuit. In addition, most commercially available systems are connected in a bypass, which does not allow for a holistic approach of the lubricant [46].

Monitoring of the frictional torque: The change of the operating condition in plain bearings during the transition to mixed friction can be detected by the change of the frictional torque. This results in an increase in the applied torque, which can be detected immediately. In contrast to laboratory applications, in the field usually only the total torque of the shaft can be detected with relatively little effort. Accordingly, the frictional torque generated in the plain bearing cannot be measured directly [44].

Orbital analysis: In orbital analysis, the displacement of the shaft during operation is measured without contact. Three inductive distance sensors are used. Based on the measurement signals, the movement of the shaft can be determined by triangulation. This makes it possible, on the one hand, to record the changes in the shaft orbit over the system runtime and thus to determine the wear. On the other hand, it is possible to make an indirect statement about the current lubrication condition based on the geometry, the current position and the surface roughness values [47, 48]. An implementation in industrial applications is mostly not feasible due to the high sensor costs.

Electrical contact voltage measurement: An additional possibility for condition monitoring is the observation of the electrical contact voltage between shaft and plain bearing. For this purpose, an electrical potential is built up between the plain bearing and the shaft. In the case of hydrodynamic operation, there is an infinitely high resistance between the contact surfaces since the lubricants used are usually non-conductive. As soon as the operating condition changes and metallic contact occurs, the resistance drops rapidly, resulting in current flow. The current flow can be used to indicate mixed or solid state friction conditions as well as their duration. Despite the simple design, an industrial application is not always possible since insulation is required between the shaft and the plain bearing and other attachments of the system [49].

Acceleration monitoring: Acceleration monitoring is one of the most used vibration monitoring methods for condition monitoring of rotating machinery [50–52]. Monitoring is performed by using piezoelectric accelerometers, which are used to record the vibration behaviour of the machine. Individual components such as gears or rolling bearings have a characteristic frequency and amplitude. If the respective component is damaged, frequency and amplitude change. Vibration monitoring is usually used for rolling bearings, as these functionally emit a characteristic frequency as a result of over rolling. In the case of the plain bearing, no excitation takes place in hydrodynamic operation, which means that up to now only advanced plain bearing damage could be detected based on the acceleration signal [53–55].

Acoustic Emission: Systems based on Acoustic Emission (AE) represent one possibility for early damage detection. Such systems are based on the detection of sound waves that occur as a result of an abrupt release of energy during structural changes, e.g. crack formation. Characteristic for these sound waves are frequencies in the range of 100-100,000 kHz. In the past, such systems have been successfully used for damage detection and condition monitoring of seals, rolling bearings and gears [56–60]. Investigations with AE systems on plain bearings [53–55, 61, 62] have shown that a successful assignment of the signal characteristics to the present lubrication condition is possible [43]. However, the implementation of AE systems in practice faces significant challenges. An area-wide application of AE Condition Monitoring Systems is prevented at the present time due to the required investments, lack of methods for signal assignment, pattern recognition and data reduction.

To summarize the monitoring methods for plain bearing, temperature measurement is seen as the most widely used in the monitoring of plain bearings, as it is low-cost and easy to implement. However, damage can only be detected at a late stage. In contrast, Acoustic Emission is a comparatively young technology that stands out from the others in that it allows damage to be detected at an early stage. Initial investigations have shown that AE is suitable for detailed condition monitoring of plain bearings as well as for allocation of the lubrication condition. Therefore, this technology is considered to be particularly promising for research purposes, despite high investment costs and the high effort required for signal processing.

5.2 Digital twin condition monitoring approach

Recent developments have shown the shift of technological advancement towards virtual representations of assets named digital twins [63]. Even though some ambiguity exists in the use of the term, recent systematic reviews have attempted to provide a consistent framework by identifying common characteristics of digital twins [64–66]. At the core, digital twins are virtual entities connected to physical assets so that the virtual entity replicates the behaviour of the physical asset in a way from which value can be extracted [64, 67]. In other words, three pillars of measurements, models and decision making tools are seen essential steps of a digital twin [68, 69]

Digital twins can be described as physics-based, data-driven or hybrid. Physics-based digital twins use high fidelity simulations and/or physics to model the behaviour of the system while data-driven digital twins use machine learning models as the foundation to predict behaviour [70]. Hybrid models combine physics and data in order to create a digital twin that ideally leverages the advantages while negating the shortcomings of both methods [70, 71].

5.3 Digital twin value proposition

Michael Grieves and John Vickers can be considered as the originators of the digital twin concept even though similar technologies have existed under different names [63, 64]. Grieves described digital twins in 2003 as having the possibility of influencing assets throughout the lifecycle [72]. Grieves presents the concept in the context of manufacturing technology and it has been implemented in this sphere for production planning, maintenance and layout planning [65] while the usefulness of the technology to provide a framework for predictive maintenance has also been identified [73].

The usefulness of digital twins extend to a wide variety of fields such as health, aerospace, automotive and construction [74]. Of interest is the applications of digital twins to the marine environment as a whole [75] and to propulsion systems in particular [68].

A significant advantage to the use of digital twins for condition monitoring rather than conventional methods include the possibility of creating virtual sensors that predict values of parameters that cannot be measured directly [73]. Digital twins created with high enough fidelity create the opportunity for the analysis of conditions for which no historical data is available [69, 76, 77].

From a classification standpoint, DNV GL acknowledges the use of digital twins as a way to verify systems once the society is satisfied that the utilised method is trustworthy and of sufficient quality [78]. In addition, DNV GL has developed a recommended practice that informs the development of digital twins in the oil and gas industry which has not been published yet [79].

5.4 Digital twin challenges

Data-driven digital twins are mainly applicable to cases where a large amount of similar or identical physical assets exist in order to increase the amount of captured data. Physics-based digital twins however are limited by the detail included in the model. These twins should be sufficiently accurate to capture all relevant behaviour of the system [64], but increased complexity of the twin can result in excessive computational cost [70].

Careful consideration should be given to the ownership of the digital twin [67]. Further research is required to fully understand the challenges related to ownership of data and digital twins [64]. This problem is magnified in cases where multiple stakeholders are concerned [74]. This is shown in the case of a ship where parties with ownership claims to the digital twin would be the developer of the digital twin, the ship manufacturer, the component manufacturers and the ship owner.

The implementation of digital twins to the maritime industry poses some unique challenges. These challenges include slow or unreliable connectivity as well as complex interactions between systems created by unaffiliated designers [67]. The risk associated with digital twin implementation has also been indicated [69].

A hybrid digital twin can be a reasonable solution for propulsion system as it will enable a solution that accurately mirrors the behaviour of the physical asset for known and unknown environmental and operating conditions. Data-driven and physics-based methods can be used in parallel to predict parameters such as RUL which can be used to increase certainty in the outputs of the digital twin [71].

In order to implement this digital twin some requirements include:

1. Dynamic models of components
2. Degradation models of components
3. System model utilizing component models
4. Models to calculate RUL of components
5. Measurement infrastructure
6. Models to correlate environmental conditions and measurements with loads

7. Predictive model of future operating conditions
8. Feedback to engineer of change in RUL of components

5.5 Operation and monitoring in extreme environmental conditions

Ships operating in ice-covered waters require special consideration in the design phase and operation in order to ensure safety for the ship, personnel and environment. Sea ice affects the hull as well as the ship propulsion system causing more statistically significant incidents compared to ships operation in ice-free waters [3]. Thus an appropriate economical design requires a good assessment of occurring loads in order to maximize the payload and minimize cost in acquisition and operation [80]. The most reliable method to assess ice loads consists of full-scale measurements on board ships [81]. Riska shows in 2014 a significant discrepancy between the required scantlings based on ice load measurements and those based on the Finnish-Swedish Ice Class Rules (FISCR) or the Polar Code [82].

Commonly in full-scale measurements the direct load is derived from the measurement of the response of the loaded structure. This eases the instrumentation setup and consequently reduces the cost of instrumentation. The downside of indirect ice load measurements is the additional uncertainty through the applied methodology which derives the loads out of the measured structural response. Böhm et al. [83] investigated the measurement accuracy of instrumented ship structures under local ice loads using indirect ice load measurements. With an idealized FEM model it was shown that the measurement accuracy decreases with an increasing ice load length [83]. The investigated example showed a relative error of 16.5 % within the instrumented area with a chosen line load with an height of 0.3 m, a length of 0.8 m and a magnitude of 100 kN [83]. In addition it could be shown that the common methodology overestimates the load inside the instrumented area and underestimates the load outside the instrumented area [83].

The compressive strength is a fundamental property of sea ice among other properties. Observation of both large and small-scale sea ice failures show that ice often fails in compression [84]. In ice-structure interactions it occurs by crushing against an offshore structure or a ship's hull [84]. Milling of ice pieces by a ship's propellers are another type of compressive failure of ice [84].

In terms of propeller-ice interaction two potential failure modes can be observed: milling and impact loads:

1. Soininen [85] designed a model for milling-type contact, where the leading edge of the propeller is in contact with an extensive ice block. This model does not account for dynamic effects but approximates contact loads based on quasi-static contact between the propeller and ice.
2. The second type of contact refers to impact loads where the back side or the face of ice debris impacts the propeller. There exists several variations in this class of ice contact loads where e.g. the first blade cuts through ice.

The most prominent models for loads on propellers are of Kotras et al. [86], Veitch [87], and Soininen [85]. In Veitch's works a numerical simulation was developed which includes the equation of motion for submerged ice. Simplified hydrodynamic loads were also added. Veitch emphasized the influence of ice failure during propeller-ice interaction. Although Veitch assumed an appropriate propeller-ice interaction scenario, blade dynamics including the effect of interaction between propeller blades, was ignored. It is important to highlight that all models account for the compressive strength of ice without specifying it in depth.

Kellner et al. [88] developed a unique database to compile all available compressive strength measurements including all available experimental parameters. This establishes a global understanding of strain rate sensitivity of compressive strength. This especially helps for high impact velocities (as in propeller-ice interaction) where little experimental data is available and extrapolation might be required. The actual failure mechanisms and detailed description of the ice failure process when a sharp edge such as a propeller blade cuts through ice is not yet available. Consequently, it is unclear to what extent the uni-axial compressive strength relates to governing failure processes.

While there are several studies and experiments on ice-propeller interaction, less attention has been given to the propulsion machinery's response due to ice. Among one of the few works on ice impact and machinery interaction Dahler et al. [89] presented a full scale test investigating the response in the propeller shaft line on the ice going bulk carrier MV UMIAK I, which was mainly limited to torsional vibration investigations and shaft shear failure.

The ice pressure in all models depends on the uniaxial compressive strength or crushing strength of ice, which is an ambiguous parameter as the loading scenario of compressively tested ice samples and the interaction of the propeller blade with ice has a limited common ground. The compressive strength and the failure process depends on temperature and the strain rate. Compressive tests [88] are generally conducted at lower strain rates than those occurring in propeller-ice interaction. Therefore, the database of knowledge has to be increased for tests with higher strain rates.

The impact of the ice blocks on the shaft line might be described best with a lumped mass model, similar to the one of Kotras et al. [86]. The latter does not account for inertial effects and only incorporates the ice crushing strength as an ice property, without further specification. In order to determine the load spectrum on the propeller the ship speed and cusp size is of high significance. The Hamburg University of Technology (TUHH) is developing a model based on physical parameters only for the ice breaking resistance of ships, but this model can also be employed to determine the size of broken ice cusps [90], which will serve as input for the load model. It should also be noted that there are other ship ice interaction scenarios besides level ice breaking that might be relevant to propeller-ice impacts.

6 CONCLUDING REMARKS

In this article the state-of-the-art and development trend of condition monitoring and maintenance in marine propulsion system were discussed. Machinery failure is often on top of the list of incidents in shipping industry and condition monitoring is seen as an important tool to reduce the unexpected shutdowns and improve the system reliability. The current industrial practices found to be limited to temperature and oil monitoring, often focused on the performance monitoring rather than prognosis approach. The development trend toward digital twin based condition monitoring is seen as an innovative approach to implement condition monitoring in the marine industry. However, more research are needed to address the challenges specially with regards to associated risk, modelling uncertainty assessment and decision making support tools.

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REFERENCES

[1] United Nations Council on Trade and Development (UNCTAD), 2009. Review of maritime transport, 2009.

[2] Allianz Global Corporate & Specialty (AGCS), 2020. Safety and shipping review 2020.

[3] Allianz Global Corporate & Specialty (AGCS), 2019. Safety and shipping review 2019.

[4] Stephenson, S. R., Smith, L. C., and Agnew, J. A., 2011. “Divergent long-term trajectories of human access to the arctic”. *Nature Climate Change,* ***1***(3), pp. 156–160.

[5] Allianz Global Corporate & Specialty (AGCS), 2018. Safety and shipping review 2018.

[6] Allianz Global Corporate & Specialty (AGCS), 2017. Safety and shipping review 2017.

[7] Allianz Global Corporate & Specialty (AGCS), 2016. Safety and shipping review 2016.

[8] Allianz Global Corporate & Specialty (AGCS), 2018. Global claims review 2018.

[9] International Maritime Organization, n.d.. Conventions.

[10] International Association of Classification Societies. About IACS.

[11] International Association of Classification Societies, n.d.. Unified requirements.

[12] ISO 13613, 2011. Ships and marine technology – maintenance and testing to reduce losses in critical systems for propulsion.

[13] ISO 13372, 2012. Condition monitoring and diagnostics of machines - vocabulary.

[14] DNV GL, 2020. Rules for classification: Part 1 General regulations, Chapter 1 General regulations.

[15] DNV GL, 2020. Rules for classification: Part 7 Fleet in service, Chapter 1 Survey requirements for fleet in service.

[16] DNV GL, 2020. Rules for classification: Part 3 Hull, Chapter 1 General principles.

[17] DNV GL, 2020. Rules for classification: Part 4 Systems and components, Chapter 1 Machinery systems, general.

[18] DNV GL, 2020. Rules for classification: Part 4 Systems and components, Chapter 3 Rotating machinery - drivers.

[19] DNV GL, 2020. Rules for classification: Part 6 Additional class notations, Chapter 9 Survey arrangements.

[20] DNV GL, 2020. Rules for classification: Part 6 Additional class notations, Chapter 5 Equipment and design features.

[21] DNV GL, 2020. Rules for classification: Part 4 Systems and components, Chapter 4 Rotating machinery – power transmission.

[22] DNV GL, 2020. Rules for classification: Part 4 Systems and components, Chapter 5 Rotating machinery – driven units.

[23] ISO 19848, 2015. Ships and marine technology – standard data for shipboard machinery and equipment.

[24] DNV GL, 2016. Class programme: DNV GL approval of service supplier scheme.

[25] American Bureau of Shipping, 2020. Rules for: Survey after construction, Part 7.

[26] Lloyd’s Register, 2017. Shipright: Annexes to machinery planned maintenance and condition monitoring.

[27] Lloyd’s Register, 2019. Shipright: Machinery planned maintenance and condition monitoring.

[28] Lloyd’s Register, 2020. Rules and regulations for the classification of ships.

[29] ISO 17359, 2018. Condition monitoring and diagnostics of machines – general guidelines.

[30] ISO 13381-1, 2015. Condition monitoring and diagnostics of machines – prognostics – part 1: General guidelines.

[31] Wärtsilä, 2018. Wärtsilä propulsion condition monitoring service brochure.

[32] ISO 4406, 2017. Hydraulic fluid power - fluids - method for coding the level of contamination by solid particles.

[33] Wärtsilä, 2018. Wärtsilä propulsion condition monitoring service product specification; doc id: Dbaf140282.

[34] Converteam, 2012. Final report: Part 1 Manual of safety,

installation and maintenance for asynchronous motors.

[35] Converteam, 2012. Final report: Part 4 Annexes: General instructions for the commissioning, maintenance, repair and troubleshooting of hydraulic systems.

[36] Converteam, 2012. Final report: Part 4 Annexes: Bearing maintenance.

[37] Rolls-Royce, 2011. User manual Kamewa$^{\text{TM}}$ CP-A D.

[38] McCoy, T. J., and Amy, J. V., 2009. "The state-of-the-art of integrated electric power and propulsion systems and technologies on ships". In 2009 IEEE Electric Ship Technologies Symposium, IEEE, pp. 340–344.

[39] Kongsberg, 2020. Azimuthing permanent magnet thruster. `https://www.kongsberg.com/maritime/products/propulsors-and-propulsion-systems/thrusters/azimuth-thrusters/azimuthing-permanent-magnet-thruster-az-pm/`, January. [Online; accessed 22-Dec.-2020].

[40] Zhang, P., Du, Y., Habetler, T. G., and Lu, B., 2010. "A survey of condition monitoring and protection methods for medium-voltage induction motors". *IEEE Transactions on Industry Applications,* ***47***(1), pp. 34–46.

[41] Elnady, M., Sinha, J., and Oyadiji, S. O., 2012. "Condition monitoring of rotating machines using on-shaft vibration measurement". In Proceedings of the 10th International Conference on Vibrations in Rotating Machinery.

[42] Azeem, N., Yuan, X., Raza, H., and Urooj, I., 2019. "Experimental condition monitoring for the detection of misaligned and cracked shafts by order analysis". *Advances in Mechanical Engineering,* ***11(5)***, pp. 1–11.

[43] Mokhtari Molk Abadi, N., 2020. *Überwachung hydrodynamischer Gleitlager basierend auf der Körperschallanalyse*, Vol. 7. Universitätsverlag der TU Berlin.

[44] Deckers, J., 2001. *Entwicklung einer Low-Cost Körperschallsenorik zur Überwachung des Verschleißverhaltens von wälz- oder gleitgelagerten Kreiselpumpen*. VDI-Verlag.

[45] DIN 31692-2, 1996. Gleitlager – teil 2: Temperaturüberwachung.

[46] Dickerhof, M., 2011. "Potentiale der schallemissionsanalyse zur überwachung und diagnose tribologischer systeme". PhD thesis, IPEK Institut für Produktentwicklung.

[47] Sturm, A., and Förster, R., 2013. *Maschinen-und Anlagendiagnostik: Für die zustandsbezogene Instandhaltung*. Springer-Verlag.

[48] Bueren, C., and Humer, M., 2018. *Lagerschädigungen bei Dampf- und Gasturbinen*. VDI Schadensmechanismen an Lagern.

[49] Nguyen, H. T., 2013. "Optimierung des schmiermittelangebots zur steigerung der energieeffizienz von hydrodynamischen gleitlagern mittels körperschallanalyse". PhD thesis, IPEK Institut für Produktentwicklung.

[50] Márquez, F. P. G., Tobias, A. M., Pérez, J. M. P., and Papaelias, M., 2012. "Condition monitoring of wind turbines: Techniques and methods". *Renewable Energy,* ***46***, pp. 169–178.

[51] Koulocheris, D., Gyparakis, G., Stathis, A., Costopoulos, T., et al., 2013. "Vibration signals and condition monitoring for wind turbines". *Engineering,* ***5***(12), p. 948.

[52] Shakya, P., Darpe, A., and Kulkarni, M., 2013. "Vibration-based fault diagnosis in rolling element bearings: ranking of various time, frequency and time-frequency domain data-based damage identification parameters". *International journal of condition monitoring,* ***3***(2), pp. 53–62.

[53] Fritz, M., Burger, W., and Albers, A., 2001. "Schadensfrüherkennung an geschmierten gleitkontakten mittels schallemissionsanalyse". *Tribologie Fachtagung,* ***1***, pp. 30–1.

[54] Mirhadizadeh, S. A., 2012. "Monitoring hydrodynamic bearings with acoustic emission and vibration analysis".

[55] Raharjo, P., 2013. "An investigation of surface vibration, airbourne sound and acoustic emission characteristics of a journal bearing for early fault detection and diagnosis". PhD thesis, University of Huddersfield.

[56] Al-Dossary, S., Hamzah, R. R., and Mba, D., 2009. "Observations of changes in acoustic emission waveform for varying seeded defect sizes in a rolling element bearing". *Applied acoustics,* ***70***(1), pp. 58–81.

[57] Eftekharnejad, B., and Mba, D., 2009. "Seeded fault detection on helical gears with acoustic emission". *Applied acoustics,* ***70***(4), pp. 547–555.

[58] Al-Ghamd, A. M., and Mba, D., 2006. "A comparative experimental study on the use of acoustic emission and vibration analysis for bearing defect identification and estimation of defect size". *Mechanical systems and signal processing,* ***20***(7), pp. 1537–1571.

[59] Van Hecke, B., He, D., and Qu, Y., 2014. "On the use of spectral averaging of acoustic emission signals for bearing fault diagnostics". *Journal of Vibration and Acoustics,* ***136***(6).

[60] Zhang, Y., Lu, W., and Chu, F., 2017. "Planet gear fault localization for wind turbine gearbox using acoustic emission signals". *Renewable Energy,* ***109***, pp. 449–460.

[61] Albers, A., Burger, W., Scovino, R., and Dickerhof, M., 2006. "Monitoring lubrication regimes in sliding bearings using acoustic emission analysis". *Practicing Oil Analysis,* ***9***(3), pp. 8–12.

[62] He, Y., Yin, X., and Chu, F., 2008. "Modal analysis of rubbing acoustic emission for rotor-bearing system based on reassigned wavelet scalogram". *Journal of Vibration and Acoustics,* ***130***(6).

[63] Smogeli, Ø., 2017. Digital twins at work in maritime and energy. DNV GL Feature: February 2017.

[64] Jones, D., Snider, C., Nassehi, A., Yon, J., and Hicks, B., 2020. "Characterising the Digital Twin: A Systematic literature review". *CIRP Journal of Manufacturing Science and Technology,* ***29***, pp. 36–52.

[65] Kritzinger, W., Karner, M., Traar, G., Henjes, J., and Sihn, W., 2018. "Digital twin in manufacturing: A categorical literature review and classification". In 16th IFAC Symposium on Information Control Problems in Manufacturing INCOM, Vol. 51, pp. 1016 – 1022.

[66] Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., and Zimmermann, M., 2020. "What is a Digital Twin? – Definitions and insights from an industrial case study in technical product development". *Proceedings of the Design Society: DESIGN Conference,* ***1***, p. 757–766.

[67] Rødseth, O. J., and Berre, A. J., 2018. "From digital twin to maritime data space: Transparent ownership and use of ship information". In Proceedings of the 2018 13th International Symposium on Integrated Ship's Information Systems & Marine Traffic Engineering Conference.

[68] Johansen, S. S., and Nejad, A. R., 2019. "On digital twin condition monitoring approach for drivetrains in marine applications". In Proceedings of the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering.

[69] Ibrion, M., Paltrinieri, N., and Nejad, A. R., 2019. "On Risk of Digital Twin Implementation in Marine Industry: Learning from Aviation Industry". *Journal of Physics: Conference Series,* ***1357***, oct, p. 012009.

[70] Erikstad, S. O., 2017. "Merging Physics, Big Data Analytics and Simulation for the Next-Generation Digital Twins". In Proceedings of the 2017 Symposium on High-Performance Marine Vehicles.

[71] Liu, Z., Meyendorf, N., and Mrad, N., 2018. "The role of data fusion in predictive maintenance using digital twin". In AIP Conference Proceedings, Vol. 1949, AIP Publishing LLC, p. 020023.

[72] Grieves, M., 2017. Digital Twin: Manufacturing Excellence through Virtual Factory Replication. White paper.

[73] Aivaliotis, P., Georgoulias, K., Arkouli, Z., and Makris, S., 2019. "Methodology for enabling Digital Twin using advanced physics-based modelling in predictive maintenance". In 52nd CIRP Conference on Manufacturing Systems (CMS), Vol. 81, pp. 417 – 422.

[74] Rasheed, A., San, O., and Kvamsdal, T., 2020. "Digital twin: Values, challenges and enablers from a modelling perspective". *IEEE Access,* ***8***, pp. 21980–22012.

[75] Van Os, J., 2018. "The Digital Twin throughout the Lifecycle". In Proceedings of the SNAME Maritime Convention.

[76] Wang, J., Ye, L., Gao, R. X., Li, C., and Zhang, L., 2019. "Digital Twin for rotating machinery fault diagnosis in smart manufacturing". *International Journal of Production Research,* ***57***(12), pp. 3920–3934.

[77] Moghadam, F. K., Rebouças, G., and Nejad, A. R., 2021. "Digital twin modeling for predictive maintenance of floating offshore wind turbine drivetrains". *Forschung im Ingenieurwesen*.

[78] DNV GL, 2020. Class guidelines: Data-driven verification.

[79] DNV GL, 2020. DNVGL-RP-A204 Preview: Qualification and assurance of digital twins.

[80] von Bock und Polach, R., Ehlers, S., and Erikstad, S. O., 2015. "A Decision-based Design Approach for Ships Operating in Open Water and Ice". *Journal of Ship Production and Design,* ***31***(4), nov, pp. 209–219.

[81] Suominen, M., Kujala, P., Von Bock Und Polach, R., and Kiviranta, J., 2013. "Measured ice loads and design ice loads". In Analysis and Design of Marine Structures - Proceedings of the 4th International Conference on Marine Structures, MARSTRUCT 2013.

[82] Riska, K., 2014. *Design point in ice class rules*, Vol. 71 of *Research report/Winter Navigation Research Board, Finnish Board of Navigation*. Finnish Gov. Print Centre.

[83] Böhm, A. M., von Bock und Polach, R. U. F., Herrnring, H., and Ehlers, S., 2021. "The measurement accuracy of instrumented ship structures under local ice loads using strain gauges". *Marine Structures,* ***76***, p. 102919.

[84] Timco, G. W., and Weeks, W. F., 2010. "A review of the engineering properties of sea ice". *Cold Regions Science and Technology,* ***60***(2), pp. 107–129.

[85] Soininen, H., 1998. *A propeller-ice contact model*.

[86] Kotras, T., Humphreys, D., Baird, A., Morris, G., and Morley, G., 1987. "Determination of propeller-ice milling loads". *Journal of Offshore Mechanics and Arctic Engineering,* ***109***(2), pp. 193–199.

[87] Veitch, B., 1995. *Predictions of ice contact forces on a marine screw propeller during the propeller-ice cutting, Espoo, Helsinki University of Technology, Diss., 1995*, Vol. 118 of *Acta polytechnica Scandinavica : Me, Mechanical engineering series*. Finnish Academy of Technology, Helsinki.

[88] Kellner, L., Stender, M., von Bock und Polach, R. U. F., Herrnring, H., Ehlers, S., Hoffmann, N., and Høyland, K. V., 2019. "Establishing a common database of ice experiments and using machine learning to understand and predict ice behavior". *Cold Regions Science and Technology,* ***162***, pp. 56–73.

[89] Dahler, G., Stubbs, J. T., and Norhamo, L., 2010. "Propulsion in ice - big ships". *ICETECH 2010-133-R0*.

[90] Erceg, S., Ehlers, S., von Bock und Polach, R., and Leira, B., 2014. "A numerical model to initiate the icebreaking pattern in level ice". In Volume 10: Polar and Arctic Science and Technology, American Society of Mechanical Engineers.