NTNU – Trondheim
Norwegian University of
Science and Technology

Analysis and correction of sea trials

Katharina Haakenstad

Marine Technology
Submission date: June 2012
Supervisor: Sverre Steen, IMT
Co-supervisor: Willy Reinertsen, KGJS

Norwegian University of Science and Technology
Department of Marine Technology

Scope of work

MASTER THESIS IN MARINE TECHNOLOGY
SPRING 2012
for
Katharina Haakenstad

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

Analysis and correction of sea trials

All new merchant ships above a certain size will do sea trials as part of the delivery from the yard to the ship owner. Many types of equipment and performances are tested during this delivery sea trial, which might take several days. An important part of the delivery sea trial is to determine the speed capability of the ship in the contractual condition, which is traditionally deep, calm water and no wind, at some specified loading condition. However, it is seldom possible to perform this particular test under such conditions, and when the test is done in other conditions, the result is corrected back to the contractual condition. The correction can be of a significant magnitude. There are ISO standards for both how to perform the trial and for how the correction of the result shall be done, but still there is a significant variation in how the corrections (and trials) are performed in practice. The issue is important, since economic penalties of significant magnitude are given if the speed is lower than the contracted value. In addition comes the new IMO Ship Energy Efficiency Index, which is used to classify the energy efficiency of ships. The value of this index is typically to be determined based on the results of the delivery sea trial. The scope of the project thesis is to:

- Describe briefly the role of the speed tests in the delivery sea trial in a contractual context the parties involved, who are responsible for what, and its economic significance.
- Summarize the standardized procedures for correcting sea trials according to the relevant standards. Discuss difference between accepted standards. Discuss what corrections that are likely to be most important for the end results.
- Compare the different methods to correct sea trials results for the effect of waves that are used in the different standards. Discuss the results. Compare with measurements or other benchmark data if possible.

- Compare the results of corrections performed by ship yards with the results of corrections performed according to the standards. Discuss how the different corrections contribute, and the overall level of corrections obtained by the yards compared to the standards. It is recommended to perform this part as a case study. It is strongly beneficial if more than one case can be included.

In the thesis the candidate shall present his personal contribution to the resolution of problem within the scope of the thesis work.

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The plan should include a budget for the use of computer and laboratory resources that will be charged to the department. Overruns shall be reported to the supervisor.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The thesis shall be submitted in two copies:

- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervisor : Professor Sverre Steen Advisor : Willy Arne Reinertsen (Kristian Gerhard Jebsen Skipsrederi) Start : 16.01.2012 Deadline : 15.06.2012

Trondheim, 13.01.2012

Sverre Steen Supervisor

Preface

This master thesis is written at the department of Marine Technology at the Norwegian University of Science and Technology, NTNU, in Trondheim, the spring 2012. The work presented is a continuation of my project thesis.

Working on this subject has been of great academic value. During the semester, I have developed an improved understanding of hydrodynamics, Matlab and resistance calculations in relation to speed trials.

It has been challenging to present the data in a clear way, without requiring the reader to have profound knowledge of the topics discussed. As data provided by Hyundai has been somewhat sparse and cryptic, it has generally been demanding to perform calculations. In return it has been truly interesting to immerse myself into this issue.

I am grateful for the invaluable help and guidance, provided by my supervisor Sverre Steen. He has given me very rapid and concise support, which has steered me in the right direction. I would also like to extend my thanks to Willy Reinertsen at Kristian Gerhard Jebsen Skipsrederi. He gave me the opportunity to visit the Hyundai shipyard in Mokpo in South Korea, which was extremely rewarding both academically and socially. He has provided me with relevant material and been very helpful throughout the process.

I am thankful for the warm welcome and enthusiasm shown by Leif Harsem and Nasos Pavlidis during my stay in South Korea.

I would like to thank Renato Skejic for professional guidance regarding added wave resistance calculations in oblique waves. He has been patient and willingly shared of his time.

Further, I want to express gratitude to Oystein Johannessen for constructive assistance in Matlab. I also want to show appreciation to Torstein Ingebrigtsen Bo and Pal Levold who eagerly have shared of their knowledge in Latex.

Finally, I extent my thanks to Hermod Liland for proofreading my report and providing constructive feedback.

Katharina Haakenstad
Trondheim, 10.06.2012

Summary

When a ship-owner orders a vessel from a shipyard, a contract is written to confirm and guarantee the agreement for both parts. An important requirement of the contract is the vessel's speed at a given engine power, RPM[1] and draught, in "ideal" conditions (i.e. calm, infinitely deep and current free water, with smooth hull and propeller surfaces at with no wind and *zero* drift and rudder angle). The speed capacity of the recently built ship is measured carrying out a speed trial. It is rarely possible to perform the trial under ideal, contractual conditions, and the speed will normally be reduced by environmental factors. Whenever the test is carried out in conditions deviating from those contractually specified, the speed must be corrected for, to best coincide with the contractual stipulations. These corrections can be of significant magnitude and are of great economic importance. Penalties of considerable size are given to shipyards that fail to deliver in accordance with the contract.

There are various standards published providing guidelines regarding the execution of speed trials, the measurements that are to be performed during the trials and corrections for environmental factors that are to be made in retrospect. ISO (2002), Perdon (2002), Bose (2005) and B. Henk (2006) were chosen for evaluation and comparison in this thesis. The recommendations of the standards are occasionally disagreeing.

The main resistance contribution is claimed to be wind and wave (Bose (2005) and B. Henk (2006)). B. Henk (2006) states; "these corrections (small displacement deviations, shallow water, and salinity deviations) are relatively small compared to wind and wave directions". Reinertsen (2011) suspects that the added wave resistances calculated by the Hyundai shipyard are too large. This assumption is based on Haugan (2011)'s (employee of KGJS[2]) mean wave load calculations that generally gave results 30 % lower than those found by Hyundai. An unrealistically large correction factor for wave resistance is most definitely advantageous for the shipyard. This will give a higher calculated contractual speed, and the shipyard is consequently more likely to meet the contractual requirements.

The Hyundai shipyard's correction procedures were evaluated based on the relevant standards. The shipyard neglects all resistance components, but the added resistance due to wind and waves (they also correct for large discrepancies between the trim/draught obtained at speed trial and that contractually stipulated. This is however not relevant for tankers, as these generally are capable of achieving design draught at the sea trial). This is consistent with the

[1] Revolutions per minute (RPM) is a measure of the frequency of a rotation.

[2] Kristian Gerhard Jebsen Skipsrederi AS (KGJS) is an international ship-owning and management company, with its head office located in Bergen. It is part of the Kristian Gerhard Jebsen Group and is a key international ship owning company. Their Ship Management division has expanded consistently over the years, and they are now managing about 50 vessels (KGJS; 2012).

recommendations of Perdon (2002) and B. Henk (2006).

The shipyard does not have the speed trials conducted in head - or following waves, nor head - or following wind. B. Henk (2006) and Bose (2005) underline the importance of executing the speed trials in head - or following waves. Perdon (2002) argues; "in the case when the waves do not come from the bow or the stern the correction methods are not sufficiently reliable and the effects of steering and drift on the ship's performance may be underestimated". ISO (2002) recommends performing the trials in head and following wind (note that there usually is a correlation between true wind - and wave direction).

The Hyundai shipyard assumes that the wave direction with respect to the ship's centerline equals the relative wind angle. This conflicts with the recommendations of the standards. They advise to obtain the wave direction by visual observations or instruments such as buoys or sea wave analysis radars. Furthermore, Hyundai's assumption is highly illogical from a scientific standpoint.

In this thesis, the added wave resistance (due to diffraction) was computed by a handful of methods proposed in the literature. The computed values obtained in this report were all substantially larger than those found by Hyundai. This denies Reinertsen (2011) suspicion of Hyundai's correction factors for wave resistance being unrealistically high.

B. Henk (2006) emphasizes the importance of accounting for the location of the anemometer in the computations of added resistance due to wind. This is not done by the shipyard. B. Henk (2006) proposes a formula for correction of improper placements of the anemometer. In this thesis, the added wind resistance was calculated, including this correction. The added resistance found was 28 % smaller than the value obtained by Hyundai. This is relevant as the wind tends to be a key resistance contribution.

Finally, the Energy Efficiency Design Index (EEDI) has been described. The EEDI estimates a ship's CO_2 emission per ton-mile of goods transported; put differently, the vessel's impact on the environment in relation to its benefit for society. The EEDI is to be implemented for all new ships, 1^{st} of January 2013. The value of this index will be determined based on results from speed trials.

Contents

List of Figures

List of Tables

Abbrevations

KGJS	Kristian Gerhard Jebsen Skipsrederi AS
ITTC	International Towing Tank Conference
STA-JIP	The Joint Industry Project regarding Sea Trial Analysis
ISO	The International Organization for Standardization
DGPS	Differential Global Positioning System
Hyundai	Hyundai Heavy Industries Co
MCR	Max Continuous Rating
m	meter
NCR	Normal Continuous Rating
s	seconds
IMO	International Maritime Organization
EEDI	Energy Efficiency Design Index
gt	Gross tons
DNV	Det Norske Veritas
g	grams
kg	kilograms
W	Watts
kW	kilowatt
CO_2	Carbon dioxide
$const.$	constant
$var.$	variable
kN	kilo Newton
PP	Percentage point
rad	radians
SFC	Specific fuel consumption
deg	degrees
$^\circ$	degrees
RPM	Revolutions per minute

List of symbols

ω	[rad/s]	Circular frequency
ω_e	[1/s]	Circular frequency of encounter
U	[m/s]	Ship speed over ground
g	[m/s^2]	Acceleration due to gravity
W_{rw}	[N]	Wind resistance due to relative speed between the ship and the wind
ρ_{ar}	[kg/m^3]	Density of air in actual conditions
$C_{rw}(\psi_{rw})$	[-]	Relative wind resistance coefficient
ψ_{rw}	[rad]	Relative wind direction
A	[m^2]	Area of the maximum transverse section exposed to the wind
U_{rw}	[m/s]	Relative wind velocity
U_{aw}	[m/s]	Actual wind velocity
h	[m]	Water depth
B	[m]	Ship beam
L_{pp}	[m]	Length between perpendiculars
H	[m]	Wave height
$H_{1/3}$ [m]	[m]	Significant wave height
$H_{s1/3}$	[m]	Significant wave height for swell
R_T	[N]	Total resistance
P	[Watts]	Power
Δ	[kg]	Displacement
ρ	[kg/m^3]	Mass density of sea water (1025 kg/m^3 was used)
$\overline{F}_d$	[N]	Mean wave load component due to diffraction for a regular wave
β	[rad]	Angle of the wave propagation direction with respect to the centerline of the vessel
θ	[rad]	Angle between waterline tangent of the hull and the x-axis
k	[1/m]	Wave number
d	[m]	Ship draught (mainly design draught in this report)
I_1,	[-]	Modified Bessel function of the first kind
K_1	[-]	Modified Bessel function of the second kind
l	[-]	Coordinate along the waterline
$S(f)$	[m^2/s]	Frequency distribution of the incident waves (energy spectrum)
$S(\omega)$	[m^2/s]	Circular frequency distribution of the incident waves (energy spectrum)
f	[1/s]	Frequency
$G(\alpha - \beta)$	[-]	Direction distribution of the incident waves

α	[rad]	Direction of the elementary incident wave
n_1	$[-]$	The normal vector (n) decomposed in x-direction
γ	$[N/m^3]$	Specific weight
L	[m]	Ship length
$\triangle P_{Wr}$	[hp]	Added resistance due to radiation
$\triangle P_{Wd}$	[hp]	Added resistance due to diffraction
η_s	[-]	Shaft efficiency
η_d	[-]	Quasi propulsive efficiency (from model test report)
$\overline{F}_r$	[N]	Mean wave load component due to radiation for a regular wave
$C_{\bar{F}_r}$	[-]	Added resistance coefficient for radiation
$\overline{F_r^s}$	[N]	Mean wave load component due to radiation for irregular waves
ζ_A	[m]	Wave amplitude
$\triangle W$	[N]	Added resistance due to wind
T_1	$[s]$	Mean wave period
T_2	$[s]$	Zero-crossing period
T_p	$[s]$	Peak period
W_{iw}	[N]	Air resistance in ideal conditions
$C_{iw}(\psi_{iw})$	[-]	Wind resistance coefficient for ideal conditions
ρ_a	$[kg/m^3]$	Density of air in ideal conditions
L_{WL}	[m]	Length in the waterline at design draught
T	$[s]$	Period
B_N	[-]	Beaufort number
ψ_{iw}	[rad]	Actual wind direction with respect to the ship heading
C_B	[-]	Block coefficient
P_M	[hp]	Measured power during the speed trial
$\triangle P_W$	[hp]	Total added resistance due to waves (diffraction + radiation)
λ	[m]	Wavelength
$\overline{F_d^s}$	[N]	Mean wave load component due to diffraction for a irregular waves
F_n	[-]	Froude number
V	[m/s]	Steady fluid velocity
$\triangle\omega$	$[2\pi/s]$	Step of ω
β_s	[deg]	Angle of the wave propagation direction with respect to the centerline of the vessel (180° = following sea)
α_1	[-]	Correction coefficient for finite draught
α_2	[-]	Correction coefficient for advance speed
α_3	[-]	Correction coefficient for finite draught
α_4	[-]	Correction coefficient for advance speed
$\bar{F}_{d,dim}$	[-]	Dimensionless wave load component due to diffraction for a regular wave
F_M	[N]	Force corresponding to measured power P_M
C_T	$[-]$	Total resistance coefficient
C_{Fa}	[-]	Carbon emission factor
R	$[N]$	Total ship resistance
f_w	$[-]$	Weather factor
p	$[N/m^2]$	Pressure
C_F	[-]	Frictional resistance coefficient
$\triangle C_F$	[-]	Surface roughness coefficient
k_w	[-]	Form factor
ν	$[m^2/s\ ]$	Kinematic viscosity

R_e	[-]	Reynolds number
Q	[μm]	Roughness
m	[-]	Constant included in Prohaska's method
C_p	[-]	Constant included in Prohaska's method
S	[m^2]	Wetted surface
W	[- or tons]	Gross tons or deadweight
a	[$-$]	Coefficient based on regression analyses of attained EEDI values in the existing world fleet
c	[$-$]	Coefficient based on regression analyses of attained EEDI values in the existing world fleet
z_{ref}	[m]	Reference height for wind resistance tables
z	[m]	Altitude of the anemometer

Chapter 1

Introduction

Whenever a ship-owner orders a vessel from a shipyard, a contract is written to affirm and guarantee the agreement for both parts. An important specification of the contract is the vessel's speed at a given engine power, RPM[1] and draught, in "ideal" environmental conditions (i.e. calm water, no wind, no current, sufficiently deep water etc.). The speed capability of the newly built vessel is measured conducting a speed trial. It is rarely possible to perform the trial under ideal, contractual conditions, and the speed will normally be reduced by environmental factors. Whenever the test is carried out in conditions deviating from those contractually specified, the speed must be corrected for, to best coincide with the contractual stipulations. These corrections can be of significant magnitude and are of great economic importance, as penalties of considerable size are given to shipyards that fail to deliver in accordance with the contract. During operation of the vessel, the ship-owners will suffer economically from a reduction in service speed[2], and the fines are given as a compensation for this loss. However, according to Reinertsen (2011), Assistant Vice President in Kristian Gerhard Jebsen Skipsrederi AS (KGJS)[3] the fines are far from compensating fully for the extra expenses.

As a rough guideline, Reinertsen (2011) indicates that a speed deviation of *0.3 knots* between the trial speed (after correction) and that contractually stipulated, results in a fine of *100, 000 U.S. dollars*. Each additional *0.1 knots* exceeding this discrepancy, increases the penalty by *100, 000 USD*. If the measured trial speed (after correction) is *0.8 knots* or more below that contractually specified, the buyer has the right to cancel the contract.

There are various standards published providing guidelines concerning the execution of the speed trial, the measurements that are to be carried out during the trial and the corrections for environmental influences that are to be made in retrospect. The computed trial speed tends to suffer from imprecision due to inaccurate measurements and correction procedures lacking scientific credibility (Bose; 2005). The methodical uncertainties associated with resistance

[1] Revolutions per minute (RPM) is a measure of the frequency of a rotation.

[2] "...speed the vessel is optimized for in normal operation or capable to sustain in a typical sea condition" (Foreship; 2009).

[3] Kristian Gerhard Jebsen Skipsrederi AS (KGJS) is an international ship-owning and management company, with its head office located in Bergen. It is part of the Kristian Gerhard Jebsen Group and is a key international ship owning company. Their Ship Management division has expanded consistently over the years, and they are now managing about 50 vessels (KGJS; 2012).

corrections on this field, explain the large number of correction methods proposed in the literature.

Which correction methods to apply should be agreed upon between the shipyard and owner prior to the sea trial (ISO; 2002). Nevertheless, according to Reinertsen (2011), the shipyards are usually in charge of the whole sea trial process. As the ship-owners and shipyards have different interests, this can most certainly be advantageous for the yards. KGJS has had professionals within the company evaluating the resistance calculations performed by Hyundai. Haugan (2011) has calculated the wave resistance by the use of various methods. He has in general obtained results that are *30 %* lower than those found by the Hyundai shipyard. Consequently, KGJS questions Hyundai's procedures, mainly with regard to corrections for wave resistance.

1.0.1 Structure of thesis

In Part I the resistance components affecting ship performance during speed trial have been discussed, as a basis for the report.

In Part II, the standards ISO (2002), Perdon (2002), Bose (2005) and B. Henk (2006) have been summarized and compared. Based on these, Hyundai's procedures have been evaluated.

B. Henk (2006) claims that the wave - and wind resistance are the largest and most decisive resistance components, hence these have been selected for a more thorough evaluation. In Part III, a handful of correction methods for wave resistance proposed in the literature have been verified mathematically. The results provided a basis for assessing Hyundai's correction procedures for waves. There was also undertaken a technical evaluation of Hyundai's correction procedure for wind resistance. All calculations are thoroughly documented. This was a conscious choice, so that the computations will be verifiable for employees within KGJS.

In Part IV, the Energy Efficiency Design Index (EEDI) has been described. It was illuminated in what manner the implementation of this index will affect future speed trials.

Part I

Background information

Chapter 2

Qualitative background for corrections

Ideally, the speed trials should be conducted in calm, infinitely deep and current free water with smooth hull and propeller surfaces at design trim and draught with no wind and *zero* drift - and rudder angle. The reason is that the contractual service speed is based on such conditions. However, there will at all times be factors influencing the speed trials. All conditions deviating from the contractual basis should be corrected for. The two most important environmental effects are wind and waves, as these normally contribute to a greater additional resistance than the other factors. B. Henk (2006) states; "these corrections (small displacement deviations, shallow water and salinity deviations) are relatively small compared to wind and wave corrections". Bose (2005) writes; "Corrections should concentrate on essential environmental conditions such as wind, waves and shallow water; correction methods, which may lead to unreliable results should be avoided."

There are great scientific uncertainties associated with the corrections for the added resistance components, some being more inaccurate than others. Furthermore, the correction methods become increasingly more uncertain as the environmental conditions get more severe. A discussion on the different resistance components follows.

2.1 Resistance due to waves

2.1.1 First-order effects

The first-order forces acting on a body in regular waves can be dealt with as two sub-problems; the excitation force and the radiation force. The excitation force is the forces acting on the body when the body is restrained from oscillating with the incident waves. The radiation force is formed when the structure is forced to oscillate with the incident wave frequency. The loads acting on the ship are identified as added mass, damping and restoring terms.

The excitation force is further divided into a Froude Kriloff force and a diffraction force. The Froude Kriloff force is caused by the dynamic force penetrating the body surface with its undisturbed velocity, i.e. like the body was not there. The diffraction force is caused by the change in pressure field around the ship due to the presence of the body. Neither of these forces contributes mean drift (additional resistance when the ship has a forward speed), as the average value of these over one period is *zero*.

2.1.2 Second-order effects

Second-order wave effects (proportional to the square of the wave amplitude) contribute to mean drift force, hence added resistance. This implies that when a ship navigates in waves, the ship's forward speed decreases compared to that in calm sea. The mean loads are a direct consequence of the body's capability of generating waves. The waves can either be produced by diffraction or radiation. The diffraction is due to the reflection of the incident waves, and radiated waves are caused by the relative motion between the ship and the sea surface. Diffraction is dominant in the areas with small wavelengths compared to the length of the body[1]. In this region, roughly the whole wave will be reflected. The formation of radiated waves is dominant in the area of heave resonance. In this area, the ship will experience large vertical motion, as well as significant motion relative to the sea surface. The radiation is *zero* in very short waves, as these waves do not cause any vertical motion of the vessel. The radiation is also *zero* when the waves are very long ($\omega \to 0$). In this area, the ship will follow the wave motion, which implies that there will be no relative motion of importance. A graphical representation of the behavior of the mean drift force is given in Figure 2.1.

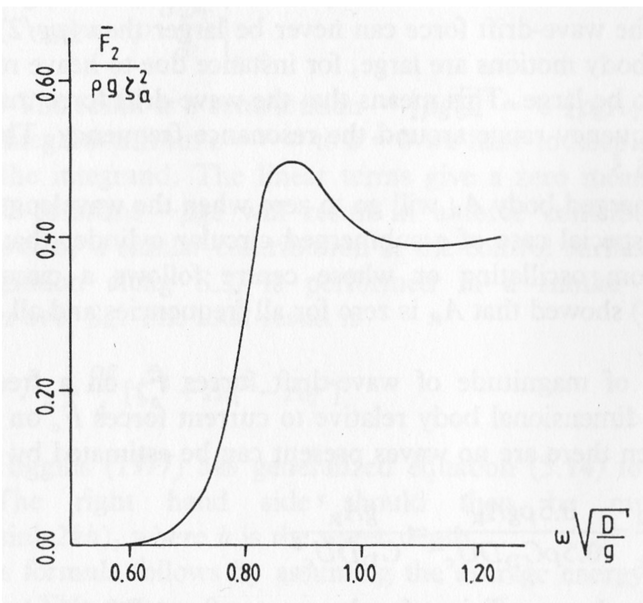

Figure 2.1: Example of behavior of mean wave drift force (ζ_a = Wave amplitude of incident wave, D = Draught and ω = circular frequency of oscillations) (Figure taken from (Faltinsen; 1990, p.140).

[1] λ / L < *0.5* are defined as short. L is the ship length and λ is the wavelength (B. Henk; 2006).

The forward speed of a vessel affects the added resistance. According to Faltinsen (1990); "An important effect for a ship at forward speed is the effect of the frequency of an encounter." The circular frequency of encounter, ω_e, between the ship and the waves can be written as;

$$\omega_e = \omega + \frac{\omega^2 \cdot U}{g} \tag{2.1}$$

where ω is the incident wave frequency, U is the forward speed of the ship and g is the acceleration due to gravity. When the ship has a forward speed, the wave diffraction near the ship bow is strengthened, and non-linear effects become more significant (Masashi Kashiwagi and Sasakawa; 2010).

2.1.3 Third-order effects

Viscous effects are third- order effects, meaning that they are proportional to the cube of the wave amplitude in regular waves. Viscous forces are mainly connected to flow separation behind a body, and they contribute to mean drift forces. However, according to (Greco; 2011); "In the case of a ship, if the waves are aligned with the vessel, the flow separation is not so strong so it is negligible." None of the standards studied in this report include the viscous effects, which based on this information seems reasonable.

2.2 Resistance due to wind

Wind resistance is a friction force caused by the relative speed between the superstructure of a ship and the wind. The ship speed, wind speed, wind direction, air density and size and shape of the superstructure affect the magnitude of this resistance component. The air resistance, also called drag, is due to the relative velocity between the air and ship in ideal conditions (meaning no wind). Wind resistance can be calculated by the drag equation, provided by all the standards;

$$W_{rw} = \frac{1}{2} \cdot \rho_{ar} \cdot C_{rw}\left(\psi_{rw}\right) \cdot A \cdot U_{rw}^2 \tag{2.2}$$

A	:	Area of maximum transverse section exposed to the wind $[m^2]$;
$C_{rw}(\psi_{rw})$	:	Relative wind resistance coefficient [-];
ψ_{rw}	:	Relative wind direction [°];
U_{rw}	:	Relative wind velocity [m/s];
ρ_{ar}	:	Density of the air in actual conditions $[kg/m^3]$

The relative wind speed, U_{rw}, is measured with an anemometer. The use of relative wind speed, relative wind direction and relative wind resistance coefficient, must be accounted for (by subtracting the air resistance). This because subtraction of the resistance component due to relative wind, gives a correction to a state of vacuum, which does not coincide with the contractual guidelines.

2.3 Resistance due to currents

Currents are large scale water movements that occur ubiquitously in the ocean. They may be driven by tides, winds or differences in water density. The tidal currents are horizontal water streams caused by the vertical rise and fall of the tides[2]. Most ocean areas experience two high tides and two low tides each day, while other locations experience only one high - and one low tide. Tidal currents do not flow as a continuous stream; their speed varies frequently in accordance with the state of the tide. In narrow straits, the tidal current speed can be several knots, whereas the open ocean areas are less affected by the tidal currents (Kartverket; 2012). The resulting current, consisting of contributions from the tide, differences in water density and wind is further affected by the bottom topography as well as the earth's rotation. The outcome is a current composed of many periodical and non-periodical movements that may change from hour to hour.

In practice, it is assumed that the current is fairly constant. By performing the speed trial runs in opposite directions within a short amount of time, the current is assumed compensated for. This may be an unfortunate simplification considering that the current speed and direction may change noticeably between the first and second run.

2.4 Other resistance components

2.4.1 Drift angle

The angle between the longitudinal axis of a vessel and its sailing path is called drift angle. This angle arises when a vessel is to maintain a straight course under the influence of forces acting at an angle on the direction of motion. A drift angle causes additional resistance. The value of the drift angle is easily obtained comparing the DGPS readings (showing the direction of the actual path) with the information from the gyrocompass (screening the angle of the longitudinal axis).

2.4.2 Rough surfaces

Hulls and propellers with a rough surface due to for example fouling or damages in the paint contribute to additional resistance.

2.4.3 Shallow water

The shallow water effect can be a large resistance contribution, and all the standards include correction methods for this phenomenon. STA-JIP (B. Henk; 2006) strongly recommends performing the speed trial in areas with sufficient deep water as to avoid a correction for shallow water. Reinertsen (2011) claims that shallow water corrections usually are not done in practice, seeing that speed trial areas are chosen laboriously.

[2]Tides are caused by the combined effects of the gravitational forces exerted by the moon, sun and rotation of the earth (Wikipedia; 2012e).

2.4.4 Rudder angle

Whenever there are forces acting with an angle on the direction of ship motion, a counter rudder angle is needed to maintain a straight course. If the forces are fairly moderate, only very small rudder angles are necessary for retaining the heading. Referring to Reinertsen (2011), such small angles (less than $3°$) contribute to very little additional resistance and are considered negligible.

2.4.5 Draught - and trim deviations

A vessel's draught and trim angle is decisive for the magnitude of the added resistance. Therefore deviations between the draught/trim achieved at the sea trial and that contractually specified shall be adjusted for. It may be challenging for container vessels, car carriers and dry cargo carriers to obtain design draught during sea trials. The reason is that their appropriate cargo rarely is available in the shipyard area, combined with the fact that their cargo holds usually are not suited to hold ballast water. Only their ballast tanks may be filled during sea trial, and these are usually not of sufficient volume to obtain the contractually specified draught.

2.4.6 Water temperature and salinity

There may be alterations in water temperature and salinity for different sea trial areas and seasons. As both these parameters affect the density of the water and hence the ship's resistance, a correction may be necessary. Bose (2005)'s reference condition is $25°$ and $1025\ kg/m^3$. According to Reinertsen, corrections of this kind are usually not performed in practice.

Part II

Standards and Hyundai's procedures

Chapter 3

Standards regarding speed trials

There are various standards published regarding speed trials. These provide guidelines and basic requirements concerning the execution of the speed trial, the measurements that are to be performed during the trial and the corrections that are to be made in retrospect. ISO (2002) is the most comprehensive on the topic. Other standards developed include B. Henk (2006), Bose (2005) and Perdon (2002) (the last two are technical ITTC reports). These three standards were chosen for discussion and comparison in this chapter. ISO (2002) and the ITTC standards were selected for evaluation, being well-known and recognized standards. B. Henk (2006) was included as it is a newer standard passing judgment on previous standards as well as illuminating new issues. Due to the complexity and scientific uncertainties connected to resistance corrections of this kind, no formula proposed in any standard is exact. There will consequently at all times be a certain degree of insecurity associated with the corrections and hence the computed service speed results. The main objective is to increase the accuracy of the calculated contractual speed.

3.1 Introduction of the standards

The International Organization for Standardization (ISO; 2002) is the world's largest and one of the most recognized publishers of international standards. Their standards are carried out through technical committees consisting of member institutes from 162 different countries.

"*ITTC (The International Towing Tank Conference)* is a voluntary association of worldwide organizations that have responsibility for the prediction of hydrodynamic performance of ships and marine installations based on the results of physical and numerical modeling" (Hon and Wang; 2011). In this thesis, Bose (2005) (being the newest technical report) will be utilized as reference whenever there is a deviation between Perdon (2002) and Bose (2005).

The Joint Industry Project regarding Sea Trial Analysis is a project carried out by MARIN in The Netherlands in close co-operation with leading ship-owners and yards. The results are summarized in The Speed-Power Performance of Ships during Trials and Service (B. Henk; 2006). The intention of the project was to improve the reliability of measurements and corrections performed in connection to speed trials. B. Henk (2006) criticizes ISO (2002) and Perdon (2002) for being too general, making it possible for the engineers in charge to choose improper formulas for corrections. This may cause a misleading calculation of the contractual speed, and the deviation can be as much as several tenths of knots. In B. Henk (2006), fewer formulas are presented with a clear guidance for when to apply which, leaving less room for personal interpretations. The aim of the project was to determine the computed contractual speed within *0.1 knots*.

3.2 Comparison of the content of the different standards

3.2.1 Execution of the speed trial

All the standards studied state that the speed trials should consist of double runs, being performed in exact opposite directions, at the same power settings. The trials shall be preceded by an approach run of sufficient length to achieve a steady running condition. The two individual runs must be conducted over the same ground area. Perdon (2002) recommends a speed trial duration of *5 - 10 minutes*, while B. Henk (2006) outlines the following suggestion;

$$U \geq \textit{18 knots} \quad \rightarrow \quad \text{Trial length} \geq \textit{3 nautical miles}$$
$$U < \textit{18 knots} \quad \rightarrow \quad \text{Trial length} \geq \textit{2 nautical miles}$$

ISO (2002) writes that the runs ideally should be conducted in head - and following wind. This deviates from the recommendations of Bose (2005) and B. Henk (2006), which both emphasize the importance of conducting the speed trial in head - and following waves. The basis for Bose (2005)'s claim is that; "the correction methods existing so far account for the influences of the waves only for these two conditions (head and following waves); in the case when the waves do not come from the bow or the stern the correction methods are not sufficiently reliable and the effects of steering and drift on the ship's performance may be underestimated (Bose; 2005, Chap. 4)". It is worth mentioning that there usually is a correlation between dominating wind - and wave direction, especially in areas without dominance of swell.

3.2.2 Measurements

3.2.2.1 Ship speed

All the standards agree that the speed over ground most accurately is measured with a Differential Global Positioning System (DGPS). The average speed determined over one run is to be used as input value in the service speed calculations. The speed of greatest interest, however, is the speed through water, as this accounts for a potential current. Referring to Bose (2005), there does not exist a device that is able to measure relative speed accurately. Turbulence tends to occur in the area of the speed log, disturbing the results.

3.2.2.2 Wind speed and direction

The relative wind speed for each run is to be measured with an anemometer. The average relative wind speed for each run is to be applied in the wind resistance calculations. Knowing the relative wind speed, the relative wind direction, the ship speed and the direction of heading, the absolute true wind speed and direction can be determined, adopting vectors. In B. Henk (2006), there are guidelines concerning the proper location of the anemometer. The first directive is that one should account for the shielding effect of the super structure. Additionally, the vertical location of the anemometer is decisive for the results, as the wind speed varies significantly over the height. The reference height for the wind resistance tables is usually *10 meters*, and the anemometer should be located accordingly. B. Henk (2006) presents a formula for correction of the height of the anemometer. Bose (2005) briefly mentions that a correction for the height of the anemometer is useful.

3.2.2.3 Wave data

When determining wave data, it is preferable that instruments are used, however, it is sufficient that multiple personnel onboard perform observation by eye (ISO (2002) and Bose (2005)). The instruments suggested by ISO (2002) are buoys and seaway analysis radars onboard the ship.

ISO (2002) states that if both sea and swell[1] is observed in the sea trial area, their wave characteristics should be found separately. The reason is that different wave spectra are to be used for sea and swell when calculating the added wave resistance for irregular waves.

3.2.2.4 Currents

Bose (2005) advises to determine the current speed and direction by a prognostic analysis for the area. ISO (2002), on the other hand, proposes to measure the the current with a current gauge buoy.

3.2.3 Limits for negligence of influencing factors

3.2.3.1 Displacement and trim deviations

A correction for a discrepancy between the speed trial - and contractually specified displacement may be neglected for deviations of less than *2 %*. It is appropriate to neglect trim deviations (between that contractually specified and that actually obtained at speed trial) smaller than *1 %* of midship draught (ISO (2002), B. Henk (2006) and Bose (2005)).

3.2.3.2 Effect of shallow water

Bose (2005) states that the effect of shallow water is negligible for the following water depth (h);

$$h > 3(B \cdot d)^{0.5} \tag{3.1}$$

[1]Swell is caused by a series of surface gravity waves. As these normally have relatively large wavelengths, swell will in general contribute to radiation rather than diffraction.

or

$$h > 2.75U^2/g \tag{3.2}$$

whichever is the largest. Here, B is the beam, d is the draught and U is the speed of the vessel.

3.2.3.3 Wind and Waves

Wind speeds and wave heights corresponding to below respectively Beaufort[2] *2* and Beaufort *1* are defined as ideal, thus no correction is needed (Bose; 2005).

3.2.3.4 Other

All the standards claim that the effect of hull - and surface roughness may be neglected if the sea trial is performed within reasonable period of time after the final hull painting. Bose (2005) states; "Methods to correct for roughness effects on propellers and for roughness and fouling on a ship's hull are of doubtful accuracy".

3.2.4 Restrictions for environmental conditions

The standards state that the speed trials must be conducted within a certain condition domain. When the trials are performed in severe weather conditions, the correction methods are no longer considered reliable. The standards specify boundaries for wind speed, rudder angle, significant wave height and water depth.

3.2.4.1 Wind speed

In B. Henk (2006) and ISO (2002) , the upper limit for wind speeds are given as;

$$\begin{array}{lll} \text{Beaufort number} < \mathit{6} & \text{for} & L_{pp} \geq \mathit{100\ m} \\ \text{Beaufort number} < \mathit{5} & \text{for} & L_{pp} < \mathit{100\ m} \end{array}$$

L_{pp} is length between perpendiculars.

Bose (2005) is somewhat more conservative, with *Beaufort number* $<$ *5* as a limit for all vessel lengths.

3.2.4.2 Total wave height

ISO (2002) informs that the upper boundary for the total wave height is;

$$\begin{array}{lll} H < \mathit{0.015} \cdot L_{pp} \text{ or } \mathit{3\ m}\text{, whichever is lower} & \text{for} & L_{pp} \geq \mathit{100\ m} \\ H < \mathit{1.5\ m} & \text{for} & L_{pp} < \mathit{100\ m} \end{array}$$

[2]"The Beaufort scale is an empirical measure that relates the wind speed to observed conditions at sea (or on land)...". Note that the wave heights in the scale are for conditions in the open ocean (Wikipedia; 2012a).

where

$$H = \sqrt{H_{1/3}^2 + H_{S1/3}^2} \tag{3.3}$$

H is the total wave height which is the sum of the significant wave height for sea ($H_{1/3}$) and swell ($H_{S1/3}$).

Bose (2005) claims that it is unreliable from a scientific standpoint to apply results from speed trials performed in sea states $\geq$ *5*. This is equivalent to significant wave heights of *2.5 – 4 meters.*

B. Henk (2006) reports an upper boundary equivalent to ISO (2002) for $L_{pp} \leq 100$ *meters*, however allows for larger wave heights for $L_{pp} > 100$ *meters*;

$$H \leq 0.015 \cdot L_{pp} \text{ or } 4\ m\text{, whichever is lower} \quad \text{for} \quad L_{pp} > 100\ m$$

3.2.4.3 Water depth

In accordance with ISO (2002), the water depth shall satisfy the following, in order to obtain reasonable service speed results;

$$\frac{\Delta U}{U} \leq 0.02 \tag{3.4}$$

where

$$\frac{\Delta U}{U} = 0.1242\left(\frac{A_M}{h^2} - 0.05\right) - \left(tanh\left(\frac{g \cdot h}{U^2}\right)\right)^{\frac{1}{2}} \tag{3.5}$$

for $\dfrac{A_M}{h^2} \geq 0.05$

A_M	:	Midship section area under water [m^2];
h	:	Water depth [m];
U	:	Ship speed [m/s];
$\triangle U$	:	Speed loss due to shallow water [m/s]

3.2.4.4 Other

ISO (2002) states that the counter rudder angle, used to maintain a straight course, should be kept within *5°* during the speed trial. The heading angle shall be kept within *3°*.

3.2.5 Corrections

The standards as a whole include correction approaches for resistance due to wind, waves, steering, drifting, current, water temperature, shallow water, salt content and deviations in displacement and trim.

3.2.5.1 Added resistance due to wind

All standards suggest determining the resistance increase due to wind by equation (2.2). They agree on the wind resistance coefficients, $C_{iw}(\psi_{iw})$ and $C_{rw}(\psi_{rw})$, most accurately being found by conducting model tests in wind tunnels. In cases where data from similar ship types is available, such information may be used instead. For this purpose, B. Henk (2006) and Bose (2005) recommend adopting the Blendermann databases[3], whereas ISO (2002) provides alternative sources (ISO; 2002, Annex A, Page 29).

3.2.5.2 Draught and trim deviations

All the three standards propose methods to account for draught deviations. However, they all strongly recommended conducting the speed trials at contractual draught, as all existing methods for such corrections are imprecise.

If for some reason the contractually specified draught is not achievable during sea trial, ISO (2002) presents following formula for correction;

$$R_{ADIS} = 0.65 \cdot R_T(\frac{\Delta_0}{\Delta} - 1) \tag{3.6}$$

where R_T is the total resistance, Δ_0 is the displacement as contractually specified and Δ is the displacement during trial.

Also the following is acceptable and recommended in both ISO (2002) and B. Henk (2006): Model tests are performed at design draught as well as at the draught expected to be reached during sea trial. The results from the full scale sea trial and the two model tests are corrected in accordance with relevant standards. The correlation between the speed measured during the speed trial and the model test speed (at equivalent draughts) is found. It is assumed that the same correlation holds for the speed at design draught. The unknown full scale speed (at design draught) is finally calculated based on this correlation and the model test speed found at design draught. B. Henk (2006) adds a requirement: if the method (described above) is to be applied, the draught and trim of the vessel at sea trial shall be within respectively *2* % and *3* % of the draught and trim used in the model tests.

Bose (2005) refers to ISO (2002) regarding corrections for draught deviations, however, presents one additional highly simple formula, named the Admiral-formula. This is only to be applied for displacement discrepancies within narrow limits (*3* - *5*%);

$$\frac{P_1}{U_1^3 \cdot \Delta_1^{2/3}} = \frac{P_2}{U_2^3 \cdot \Delta_2^{2/3}} \tag{3.7}$$

Δ is displacement, and P_1 and P_2 is the power corresponding to Δ_1 and Δ_2, in that order. U_1 and U_2 is the speed corresponding to respectively U_1 and U_2.

B. Henk (2006) includes a formula for correction of displacement deviations up to 5%;

[3] A wide range of statistical data concerning wind resistance coefficients of various ships are given by Blendermann (Blendermann; 1986)

$$\Delta P_{Disp} = ((\frac{\Delta_{ref}}{\Delta_{Trial}})^2 - 1)P_{measured} \tag{3.8}$$

The only directive given regarding trim deviations is that reference should be made from model tests (general for all the standards).

3.2.5.3 Drift

ISO (2002, Annex C, Page 39) outlines a formula for calculating resistance increase due to drifting. According to Bose (2005), this formula lacks scientific credibility and should not be used other than for general guidance. The effect of drifting is not commented on in the B. Henk (2006).

3.2.5.4 Current

ISO (2002) reports a formula to correct for a potential current. Bose (2005) writes that the effect of currents should be minimized executing the runs of the speed trial in opposite directions. If the speed difference between the two runs is large, the current should be corrected for in accordance with ISO (2002), based on prognostic analysis for the area. B. Henk (2006) claims that the current is accounted for when carrying the first and second run in opposite directions. Considering the fact that the current's speed tends to change frequently, this may be an unfortunate assumption (see section 2.3).

3.2.5.5 Other resistance components

ISO (2002, Page 43), Bose (2005) and B. Henk (2006) suggest using the Lackenby formula to correct for the shallow water effect. It is generally strongly encouraged to avoid such a correction by choosing trial areas with adequate water depths.

Added resistance due to a counter rudder angle (necessary for course keeping) is found in ISO (2002, Annex C, Page 38). Bose (2005) claims that this method is not scientific.

ISO (2002) provides one formula including a correction for both water temperature and salt content deviating from that contractually specified (Bose (2005) refers to this formula). B. Henk (2006) suggests a correction for salinity only, and this formula deviates from ISO (2002)'s.

3.3 Comparison of the correction methods for added wave resistance

In the literature, there are presented various formulas for calculation of added resistance in waves. It is intricate to assess the formulas on a general basis as they all have certain limitations and are suitable for different uses.

3.3.1 ISO (2002) on added resistance due to waves

ISO (2002) provides four formulas for calculating the added resistance; Maruo's theory, Fujii-Takahashi's formula, Faltinsen's formula and Kwon's formula. ISO (2002) is additionally open for the use of other theoretical methods if being agreed upon between ship-owner and shipyard. The methods are described below.

3.3.1.1 Maruo's theory

Referring to ISO (2002, Page 33), Maruo's theory is based on a slender ship approximation and is thus suitable for solving both diffraction - and radiation problems for slender ships. As it is based on a slender ship approximation, the formula might show poor results for calculation of *diffraction* for vessels with blunt bows. Reflection of the incoming waves occurs around the bow, which makes the bow shape essential for the diffraction. However, Maruo's slender ship theory is applicable for solving the *radiation* problem for vessels with blunt bows. This because the bow shape does not appreciably affect the wave making (caused by the relative motion between the vessel and sea surface), hence not the radiation. Maruo's formula is applicable for all wave headings (Zakaria and Baree; 2007).

3.3.1.2 Faltinsen's formula

Faltinsen's formula is restricted to short waves[4] and is best suited for blunt bows. It is limited "head to beam" waves, i.e. $90° < \beta < 270°$ (β is defined in Figure 3.1) (ISO; 2002). For $\beta <| 90° |$, ISO (2002) recommends to assume *zero* added resistance. This is a good approximation according to Steen (2011). In Faltinsen and Minsaas (1980), on the other hand, it is stated that Faltinsen's formula is applicable for all wave angles.

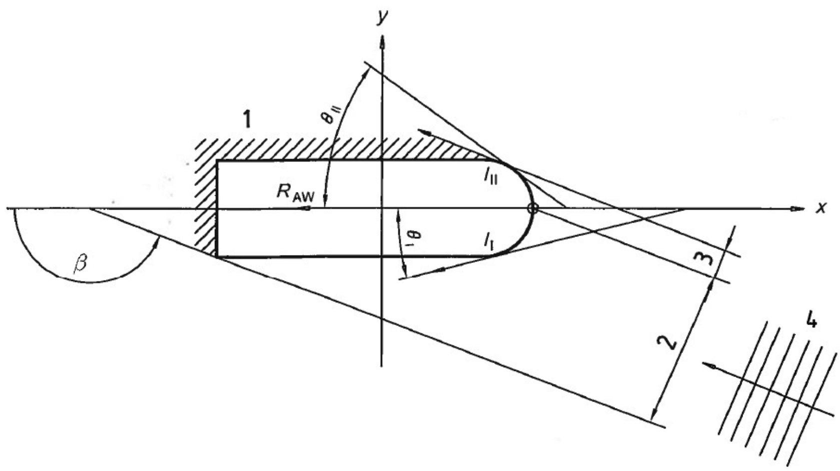

Figure 3.1: Definition of ship and wave parameters applied in equation (3.9) (ISO; 2002, page 35)

[4] $\frac{\lambda}{L} < 0.5$ are defined as short waves (L is the ship length and λ is the wavelength) (B. Henk; 2006)

Faltinsen's formula for *regular* waves is as follows (ISO; 2002);

$$\frac{\overline{F}_d}{\zeta_A^2} = \frac{1}{2}\cdot\rho\cdot g\cdot\alpha_1\left[\int_{L_1}[sin^2(\beta-\theta)-\frac{2\cdot\omega\cdot U}{g}\{cos\beta-cos\theta\cdot cos(\beta-\theta)\}]sin\theta dl\right.$$
$$\left.+\int_{L_1}[sin^2(\beta+\theta)-\frac{2\cdot\omega\cdot U}{g}\{cos\beta-cos\theta\cdot cos(\beta+\theta)\}]sin\theta dl\right] \quad (3.9)$$

$$\alpha_1 = \frac{\pi^2\cdot 1_1^2(1.5\cdot k\cdot d)}{\pi^2\cdot I_1^2(1.5\cdot k\cdot d)+K_1^2(1.5\cdot k\cdot d)} \quad (3.10)$$

ρ	:	Density of sea water [kg/m^3];
g	:	Acceleration due to gravity [m/s^2];
$\overline{F}_d$	:	Resistance increase due to diffraction in regular waves [N];
α_1	:	Draught influence factor [-];
β	:	Angle between the wave propagation direction and the x-axis. The angle is defined in Figure 3.1 [rad];
θ	:	Angle between waterline tangent of the hull and the body axis [rad] (Figure 3.1);
ω	:	Circular frequency of incidents waves [rad/s];
U	:	Forward speed of the vessel [m/s] ;
k	:	Wave number of incident waves [1/m]
d	:	Draught of the ship [m];
I_1, K_1	:	Modified Bessel functions [-];
l	:	Coordinate along the waterline [m];

3.3.1.3 Fujii-Takahashi's - and Kwon's formula

The two remaining equations; Fujii-Takahashi's formula and Kwon's formula, are also restricted to short waves[5] and are best suited for blunt bows. While Kwon's formula is applicable for all directions of the incoming waves, Fujii-Takahashi's formula is limited to "head to beam" waves. If this formula is applied for $\beta <| 90°\ |$, ISO (2002) proposes to neglect the resistance.

3.3.1.4 Added resistance due to irregular waves

Ocean waves are usually irregular. In order to calculate the mean added resistance in irregular waves, the response functions for the ship in regular waves are combined with a wave spectrum suitable for the area.

Referring to ISO (2002, page 35), formula (3.11) may be used for calculating the added resistance in short-crested irregular waves.

[5] Wavelengths corresponding to λ / L < 0.5 are defined as short (B. Henk; 2006)

$$\overline{F_d^s}(\beta) = 2 \int_{-\pi}^{\pi} G(\alpha - \beta) \left[\int_0^{\infty} S(f) \frac{\overline{F}_d(f, \alpha)}{\zeta_A^2} df \right] d\alpha \tag{3.11}$$

where

f	:	Frequency of the elementary incident wave $[1/s]$;
$G(\alpha - \beta)$	:	Direction distribution of incident waves [-];
$S(f)$	:	Frequency distribution of incident waves $[m^2/s]$;
α	:	Direction of the elementary incident wave $[rad]$;
β	:	See definition in Figure 3.1 $[rad]$;
$\frac{\overline{F}_d}{\zeta_A^2}$	:	Response function of resistance increase due to diffraction in regular waves $[N/m^2]$

3.3.2 Energy spectrum

The energy spectrum given by equation (3.12) is a standard ITTC energy spectrum, which is based on a visual determination of the average wave height and period of a wave system (Michel; 1999). ISO (2002) recommends this spectrum for seas for which the wave parameters are obtained by observations (not measurements).

$$S(f) = \frac{0.11 \cdot H_{\frac{1}{3}}^2 \cdot T_1}{(T_1 \cdot f)^5} \cdot exp\left(-\frac{0.44}{(T_1 \cdot f)^4}\right) \tag{3.12}$$

where $H_{\frac{1}{3}}$ is the significant wave height and T_1 is the mean wave period expressed as;

$$T_1 = \sqrt{\frac{\int_0^{\infty} S(f) df}{\int_0^{\infty} f \cdot S(f) df}} \tag{3.13}$$

According to Myrhaug (2007), spectra of the form;

$$S(\omega) = \frac{A}{\omega^5} exp\left(-\frac{B}{\omega^4}\right), \tag{3.14}$$

are often denoted as belonging to the Pierson-Moskowitz (PM) type of spectrum. For PM spectra, the following correlations between the peak period (T_p), middle wave period (T_1) and the mean zero crossing period (T_2) hold;

$$T_p = 1.41 \cdot T_2 \qquad\qquad T_p = 1.30 \cdot T_1 \tag{3.15}$$

where

$$T_2 = \sqrt{\frac{\int_0^\infty S(f)df}{\int_0^\infty f^2 \cdot S(f)df}} \tag{3.16}$$

ISO (2002) provides a different spectrum for seas when the wave data is determined by measurements. For information regarding this spectrum as well as the JONSWAP spectrum given for swell, please see ISO (2002, page 36).

3.3.3 ITTC on added resistance due to waves

Bose (2005) primarily refers to ISO (2002) concerning the wave resistance. In addition to the formulas presented by ISO (2002), Bose (2005) proposes a highly simple formula to estimate the diffracted wave resistance increase from the bow. This is given by Kreitner and is valid for wave heights up to *1.5 − 2 meters*;

$$\overline{F_d^s} = \frac{0.64 \cdot H^2 \cdot B^2 \cdot C_B \cdot \gamma}{L} \tag{3.17}$$

H is the wave height, γ is the specific weight[6] of water and L is the length of the ship.

3.3.4 B. Henk (2006) on added resistance due to waves

In B. Henk (2006), a handful of the existing methods for calculation of added wave resistance are evaluated. Results by the use of methods published by Fujii and Takahashi (1975), Nakamura (1977), Townsid (1993) and Jinkine (1974) are compared with results from model tests in both regular and irregular waves, for different ship types. As the results differ largely from one another, B. Henk (2006) concludes with the existing methods being unreliable. Fujii and Takahashi's formula, one of the methods being criticized, is recommended by ISO (2002). The remaining formulas for wave resistance given by ISO (2002) are not evaluated in B. Henk (2006). One could maybe question this. As ISO (2002) is one of the most well-known standards, these formulas should have been of great interest as well.

Based on model tests, B. Henk (2006) formulates two new methods for calculating added wave resistance; STAWAVE1 and STAWAVE2. STAWAVE1 is developed to calculate added resistance due to diffraction and is therefore applicable for trial conditions with mild waves and high forward speed. STAWAVE2 was developed to obtain resistance due to radiation and is therefore applicable for swell and long waves in general.

Two diagrams graphically comparing the different correction methods are shown in Figure 3.2 and 3.3. The columns to the far left are results from model tests.

[6] The specific weight (γ) is the weight per unit volume. The general formula for γ is $\gamma = \rho g$, where ρ is the density of the material and g is the acceleration due to gravity (Wikipedia; 2012b)

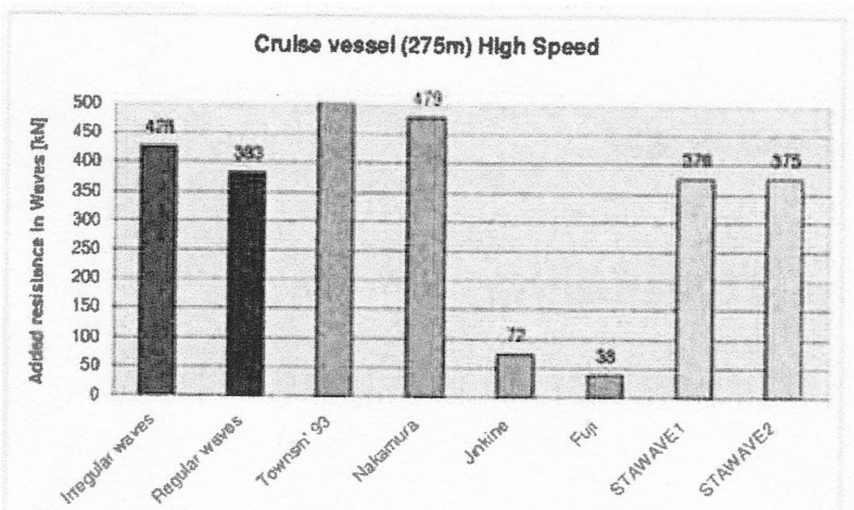

Figure 3.2: Comparison of added resistance in waves for a cruise vessel, taken from B. Henk (2006).

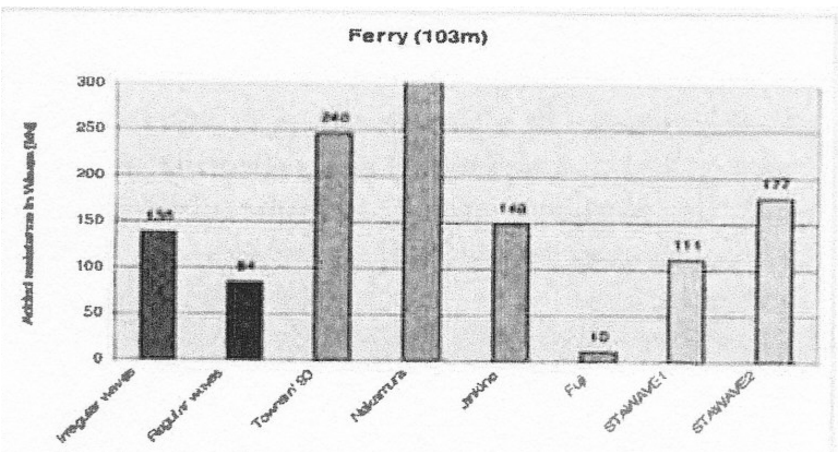

Figure 3.3: Comparison of added resistance in waves for a ferry, taken from B. Henk (2006).

It is evident from Figure 3.2 and 3.3 that STAWAVE1 and STAWAVE2 are most accurate compared to the model test results. B. Henk (2006) states that the other methods might give unsatisfactory results due to "differences in hull shapes between the regarded vessels and the vessels in the database on which these calculation methods were based" (B. Henk; 2006, Page 4).

Chapter 4

Hyundai Procedures

4.1 Hyundai Heavy Industries

Hyundai Heavy Industries Co is the world's leading shipbuilding company. Their head quarters are located in Ulsan in South Korea. The company is a daughter company of Hyundai Heavy Industries Group. KGJS has had all their tankers and OBO-vessels built by a Hyundai shipyard.

I visited the Hyundai shipyard located in Mokpo in South Korea for two weeks in the month of April. I attended the speed trial for the product carrier, S504, which was the last vessel, in a series of 10, delivered to KGJS. The following chapter regarding Hyundai's sea trial - and correction procedures will consequently be based on information received and observations made at this particular shipyard. However, according to Harsem (2012), Site Manager for KGJS New Buildings at Hyundai Shipyard in Mokpo, this information is representative for the procedures of Hyundai Heavy Industries in general.

4.2 Content of the contract made between Hyundai and KGJS

A shipbuilding contract is a contract written between an owner and a bidder. It broadly speaking includes commencement and completion dates, a technical specification[1], economical terms, performance requirements and a guarantee for the vessel that is ordered. The shipbuilder will normally prepare a technical building specification which is to be approved by the owner's technical staff or other representatives recognized by the owner. This specification will form an integrate part of the contract. Most shipbuilding contracts are based on one of many standard contract forms that have been evolved to obtain a certain uniformity in the contract relationship between purchaser and builder (Eyres; 2007).

[1] A technical specification usually includes; a brief description and essential qualities of the ship, principal dimensions, deadweight, cargo and tank capacity, stability requirements, survey and certificates, trial conditions, equipment and fittings, machinery details and accommodation details (Eyres; 2007).

The contract made between Hyundai Samho Heavy Industries Co and SKS OBO Holding LTD (Shipbuilding Contract; 2006) is based on a standard Hyundai contract. KGJS has not had further requirements added to the original contract scheme. The contract initially specifies the basic dimensions of the vessel (design draught, scantling draught etc.) and the service speed[2]. It informs that the sea trial is to be conducted at design draught, at *90 %* of Maximum Continuous Rating in calm and deep sea. The trial is to be run without Power Take-Off[3] with a sea margin[4] of *15 %*. Beyond this, there is no additional information regarding the execution of the speed trial. The contract finally details the magnitude of the fines that the Hyundai shipyard is to pay, if it fails to deliver in accordance with the contract. The trim at which to perform the speed trial is not specified. Referring to Harsem, the standard procedure is to have the sea trials performed at even keel for tankers. In near future, however, Harsem believes that there will be sharper focus on obtaining the trim giving minimum resistance. This because of the increasing fuel prices.

According to Johansson (2012), Wallenius Wilhelmsen Logistics had supplementary requirements implemented in the standard Hyundai contract. These demanded;

- the speed trial to be executed during the day. Performing the speed trial in daylight improves the visibility, thus the precision of the significant wave height, which is observed by the naked eye.
- the service speed to be measured over *three nautical miles* one way (instead of the standard *one nautical mile*). This is consistent with the recommendations of B. Henk (2006).
- the trial to be carried out straight towards and away from the dominating wave direction. B. Henk (2006) and Bose (2005) both emphasize the importance of this.

The reliability of the calculated service speed may be improved through the implementation of similar requirements. KGJS should therefore consider adding equivalent demands in future contracts.

4.3 Hyundai's procedure for the execution of the speed trial

In the Hyundai shipyard in Mokpo, the speed trials are conducted at night and consist of one double run; each run being performed in exact opposite direction. Both runs are preceded by a steady condition approach run of *5 - 6 nautical miles*, and the service speed is measured over *one nautical mile*. The duration of the speed trial is in total about two hours.

[2]"...speed the vessel is optimized for in normal operation or capable to sustain in a typical sea condition" (Foreship; 2009).

[3]"...a term for methods of taking power from an operating power source, such as a running engine, which can be used to provide power to attachments or separate machines" (Wikipedia; 2012c). "Without Power Take-Off" implies that the main engine is to be used for propulsion only during speed trial.

[4]In connection with service speed, a sea margin (powering margin) percentage is implemented to account for rough weather, hull fouling etc. The power needed to obtain the desired service speed in ideal sea trial conditions is calculated (see equation 8.3), and a sea margin percentage is added to this power. This way the vessel will be capable of sustaining the service speed in various realistic environmental conditions (Foreship; 2009).

The first sister ship in an order have speed trials performed at *50* -, *75* -, *90* - and *100* % of max continuous rating (MCR). This is done to obtain a "speed vs. power" - curve. The subsequent sister ships have speed trials conducted at normal continuous rating (NCR) only (given that the sister ships have similar hull design). NCR is *90* % of MCR .

The speed trial is neither performed straight towards or away from the dominating wind direction, nor the dominating wave direction (the wind - and wave direction are assumed equal in the Hyundai procedures). This deviates from the recommendations of the standards. As previously mentioned, B. Henk (2006) and Bose (2005) both suggest executing the speed trials in head or following waves. ISO (2002) advises to perform the speed trial straight towards or away from the dominating wind direction.

The direction of the current is not taken into consideration when determining the speed trial route. Hyundai's main objective when choosing trial path is to minimize environmental effects (mainly wind and waves) while retaining a sufficient water depth at all times.

4.4 Hyundai's procedures for the measurements

The ship speed over ground is measured with a DGPS, which is consistent with the recommendations of the standards studied.

The relative wind speed and relative wind angle are determined using an anemometer. The measurements are conducted throughout the speed trial, and the average readings are used in the calculations for the contractual service speed. The anemometer is located *31.5 meters* above sea level. According to B. Henk (2006), the reference height for most wind resistance tables is *10 meters*. It is claimed that a position of the anemometer deviating from *10 meters* during sea trial will cause incorrect values of the calculated wind resistance, as the wind speed varies significantly over the height above the sea surface. B. Henk (2006, Page 7) provides a graphical representation of the relationship between the height above water level and wind velocities. This shows that the wind speed at *10 meters* is *16 m/s*, whereas the wind speed at *31.5 meters* (the location of the anemometer) is *18.8 m/s*. This corresponds to a speed increase of *17.5* %, which results in a considerable increase of the calculated added wind resistance as the wind speed is squared (see equation 2.2). This is most certainly advantageous for the shipyard, and KGJS should perhaps consider introducing a requirement regarding the location of the anemometer in upcoming contracts.

The significant wave height is determined based on observations made by eye. As the speed trials are performed at night, the visibility is poor, and the observation may suffer from great imprecision. Representatives from the Hyundai shipyard and KGJS are to agree on a significant wave height value. Due to their diverse interests, the personnel from Hyundai usually argue for a greater wave height, while the employees from KGJS attempt to minimize this value (Harsem; 2012). In case of a dispute between the two parts, a wave height forecast for the specific area may be applied for clarification (Lee; 2012). Alternatively, one can measure the wind speed and determine the corresponding wave height by use of the Beaufort Scale (Harsem; 2012).

In the Hyundai procedures, it is assumed that the wave direction equals the direction of the average true wind for the area (Lee; 2012). This practice conflicts with the recommendations of the standards. The standards advise to obtain the wave direction either by the use of instruments such as buoys or sea wave analysis radars or by making an observation by eye. The reasonableness of Hyundai's assumption depends on factors such as the wind speed and how frequently and to what extent the wind changes direction during and in advance of the sea trial. For higher wind speeds, the local wave field will be dominated by the local wind field, causing a higher correlation between the wind - and wave direction (Bierbooms; 2012). In Figure 4.1, the misalignment between the wind and wave direction for wind speeds below *5 m/s* and above *15 m/s* are graphically presented (Bierbooms; 2012, page 7).

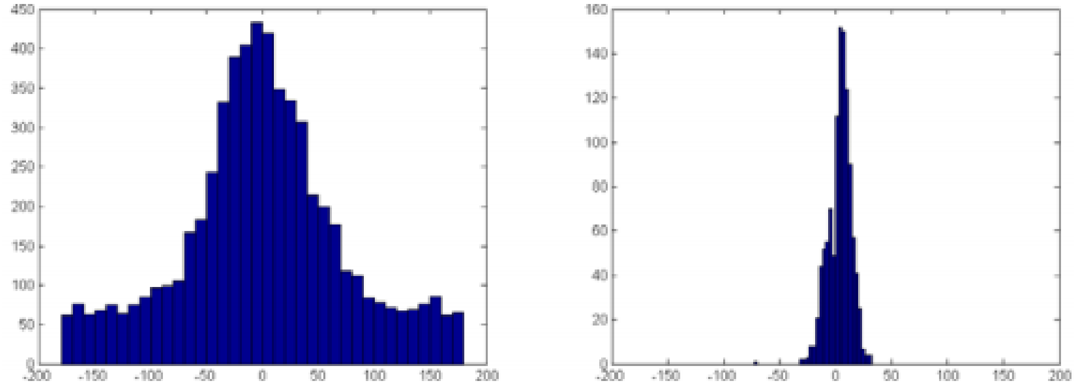

Figure 4.1: Histogram of the misalignment of wind and wave direction [deg] for mean wind speeds below *5 m/s* (to the left) and above *15 m/s* to the right (Bierbooms; 2012, page 7).

Both graphs are normally distributed about zero angular deviation between the two directions. For wind speeds above *15 m/s*, the distribution is fairly narrow banded, having extreme misalignment values of $\pm\ 40°$. The normal distribution for wind speeds below *5 m/s*, on the other hand, is quite broad banded, and there is a high degree of angular difference between the wind - and wave direction. These results indicate that the assumption of a coinciding wave - and wind direction may be unfortunate (note that these graphs may not be fully representative for the Hyundai sea trial region). According to Majchrzak (2012), the wind direction in the Hyundai speed trial area tends to be relatively constant over long time periods. This implies that there nevertheless is a fair chance of the wind - and wave directions being similar.

4.5 Hyundai's limits for negligence of the shallow water effect

The boundary for negligence of the shallow water effect is outlined below;

$$h > d \cdot 5 \tag{4.1}$$

h is water depth and d is the vessel's draught. This formula is proposed by SNAME 1989 from Det Norske Veritas Nautical Safety and is presented in Perdon (2002).

The resistance components such as rudder angle, drift etc. are disregarded at all times, hence Hyundai has not defined limits for negligence of these.

The added resistance due to waves and wind may be neglected whenever the trial speed is well within the service speed requirements contractually stipulated.

4.6 Hyundai's restrictions to the environmental conditions

According to Lee (2012), the limits for calling off a sea trial is a judgment call from speed trial to speed trial; there are no clearly defined boundaries. Beaufort number *6* is an indicative upper limit. However, if the owner wants more conservative limitations, the yard tries to meet these requests.

4.7 Hyundai's correction procedures

Factors such as drift, currents, roughness of the hull, rudder angle, water salinity and water temperature, are all excluded in the Hyundai correction procedure. The only resistance components included in the corrections are added resistance due to wind, waves and draught - and trim deviations.

The sea trials are at all times performed in areas with sufficient water depths, as to avoid a correction for the shallow water effect.

According to Lee (2012), the counter rudder angle needed to maintain a straight course is almost without exception below *3*°, usually fluctuating around *1*° during the speed trials. Although even small rudder angles contribute to some additional resistance, Hyundai has chosen to neglect this effect for the sake of simplicity.

The current is assumed to be compensated for as the first and second speed trial runs are performed in exact opposite direction. This is recommended by B. Henk (2006) and Bose (2005) (as long as the current is within reasonable limits). However, referring to Harsem, the tidal currents are strong in the speed trial area, and the speed of the current will most probably change in between the first - and second speed trial run (see section 2.3 for an explanation). Consequently, the current may not be compensated for after all. Harsem suggests evaluating the tidal current speed based on prognostic analysis for the area, which also is proposed by Bose (2005). ISO (2002) states that one can measure the current with a current gauge buoy and perform corrections based on the readings.

The Hyundai shipyard includes corrections for draught - and trim deviations (between the design draught/trim contractually specified and the draught/trim obtained at the speed trial). For the vessels ordered by KGJS, there is no draught and trim deviations to speak of, as the contractual specifications easily are obtained during sea trials for tankers, cement carriers and OBO-vessels. Referring to Papazoglou (2012), corrections for trim - and draught deviations for container vessels are done based on model tests in accordance with the procedures of ISO (2002) (please see section 3.2.5.2 for a detailed explanation of the method).

4.7.1 Added resistance due to waves

In the Hyundai procedure it is undertaken corrections for added resistance due to wave reflection (diffraction problem) and ship motion relative to the sea surface (radiation problem).

The total additional power due to waves is given by;

$$\triangle P_W = \frac{(\triangle P_{Wr} + \triangle P_{Wd}) \cdot U}{(\eta_S \cdot \eta_d)} \tag{4.2}$$

$\triangle P_{Wr}$	:	Added power due to radiation (Jinkine and Ferdinande's method) [Watts];
$\triangle P_{Wd}$	:	Added power due to wave reflection (Fujii and Takahashi's method) [Watts];
U	:	Ship speed [m/s];
η_s	:	Shaft efficiency [-];
η_d	:	Quasi propulsive efficiency (from model test report) [-]

4.7.1.1 Jinkine and Ferdinande method

The Jinkine and Ferdinande method is used for solving the radiation problem. This method is based on a combination of model test results and a mathematical approach. According to Hyundai Heavy Industries Co. (2002), the method is accurate for fine hull forms. The added resistance in *regular* waves is given by;

$$\bar{F_r} = \frac{C_{\bar{F_r}} \cdot \rho \cdot g \cdot \zeta_A^2 \cdot B^2}{L} \tag{4.3}$$

The added resistance $\overline{F_r^S}$ in *irregular* waves is given by;

$$\overline{F_r^S} = \frac{8 \cdot \rho \cdot g \cdot B^2}{L} \int_0^\infty S(\omega) \cdot \frac{\bar{F_r}}{\zeta_A^2} d\omega \tag{4.4}$$

$C_{\bar{F_r}}$	:	Added resistance coefficient [-];
ζ_A	:	Amplitude of incident wave [m];
B	:	Ship beam [m];
L	:	Ship length [m];
$S(\omega)$	:	Energy spectrum (see equation 3.12) [m^2/s];
ω	:	Circular frequency of elementary incident wave [rad/s]

The Jinkine and Ferdinande method is not recommended by any of the standards.

4.7.1.2 (Modified) Fujii and Takahashi method

The Fujii and Takahashi method is applied for estimating added resistance due to wave reflection. The formula is developed based on a theoretical approach, as well as model tests results. The added resistance in *regular* waves is calculated by;

$$\bar{F}_d = \alpha_1(1+\alpha_2)\frac{1}{2}\cdot\rho\cdot g\cdot\zeta_w^2\cdot B\cdot\frac{1}{B}\int sin^2(\theta-\beta)dy \tag{4.5}$$

where α_1 is a correction coefficient for finite draught given by;

$$\alpha_1 = \frac{\pi^2\cdot I_1^2(1.5\cdot k\cdot d)}{\pi^2\cdot I_1^2(1.5\cdot k\cdot d)+K_1^2(1.5\cdot k\cdot d)} \tag{4.6}$$

and α_2 is a correction coefficient for advance speed given by;

$$\alpha_2 = 3.5\cdot F_n^{\frac{1}{2}}\cdot cos\beta \tag{4.7}$$

$\bar{F}_d$	:	Added resistance in *regular* waves [N];
I_1	:	The first modified Bessel function [-];
K_1	:	The second modified Bessel function [-];
k	:	Wave number ($2\pi/\lambda$) [1/m];
d	:	Draught [m];
$\frac{1}{B}\int sin^2(\theta-\beta)dy$	:	The bow bluntness coefficient [-];
θ	:	Inclination at waterline section of the vessel [rad];
β	:	Angle between the wave propagation direction and the centerline of the vessel [rad];
ζ_A	:	Amplitude of incident wave [m]

Hyundai obtains the added resistance due to diffraction for short-crested *irregular* waves, $\overline{F_d^S}$, according to equation (3.11), proposed by ISO (2002) .

ISO (2002) recommends using the Fujii and Takahashi method for solving the diffraction problem, however emphasizes that the Fujii and Takahashi formula only is applicable for head to beam waves, i.e. $90° < \beta < 270°$. It is advised that the resistance due to diffraction equals *zero* for following waves ($\beta < |90°|$). Making reference to the service speed corrections performed by Hyundai shipyard for KGJS's tanker, S380, Fujii Takahashi's formula has been used for calculating added resistance in following waves as well as in head waves, which is against ISO (2002)'s advice. This discrepancy from ISO (2002) standard is advantageous for the Hyundai shipyard, as the calculated added resistance in following sea in this case give additional resistance, hence a higher calculated speed.

4.7.1.3 Energy spectrum

The energy spectrum applied by Hyundai is the standard ITTC spectrum recommended by ISO (2002) (equation (3.12)). Hyundai expressed the spectrum as a function of the wave frequency (ω), while ISO (2002) adopts the frequency (f). Knowing that $\omega = f\cdot 2\pi$ and $d\omega = df\cdot 2\pi$, it may be verified that the spectra are identical.

4.7.2 Resistance due to wind

The Hyundai correction procedure for wind is to subtract the air resistance (caused by the forward motion of the vessel relative to the air in ideal conditions) from the wind resistance found for the actual speed trial conditions. The following formulas are used (Hyundai Heavy Industries Co.; 2002):

$$\triangle W = \frac{(W_{rw} - W_{iw}) \cdot U}{(\eta_S \cdot \eta_d)} \tag{4.8}$$

where

$$W_{rw} = \frac{1}{2} \cdot \rho_{ar} \cdot U_{rw}^2 \cdot A \cdot C_{rw} \tag{4.9}$$

and

$$W_{iw} = \frac{1}{2} \cdot \rho_a \cdot U^2 \cdot A \cdot C_{iw} \tag{4.10}$$

$\triangle W$	:	Added power due to wind [Watts];
W_{rw}	:	Wind resistance due to relative wind [N];
W_{iw}	:	Air resistance in ideal conditions [N];
A	:	Transverse projected area [m^2];
C_{rw}	:	Relative wind resistance coefficient depending on geometry and angle of incidence [-];
C_{iw}	:	Wind resistance coefficient in ideal condition depending on geometry [-];
U	:	Ship speed [m/s];
U_{rw}	:	Relative wind velocity [m/s];
η_s	:	Shaft efficiency [-];
η_d	:	Quasi propulsive efficiency (from model test report) [-];
ρ_{ar}	:	Density of air in actual sea trial condition [kg/m^3];
ρ_a	:	Density of air under ideal condition [kg/m^3]

The coefficients C_{rw} and C_{iw} for container ships, tankers, bulkers, car carriers and Ro-Ros are based on statistical data given by Blendermann (also recommended by ISO (2002) and B. Henk (2006)). The coefficients for all remaining vessel types (passenger ships or ferry, cargo ships, trawlers and tugs) are found based on wind resistance tables published by Isherwood.

4.7.3 Other information

The Hyundai shipyard does only have model tests conducted at the request of the customer, and the buyer must cover all the financial expenses related to the tests. KGJS has had model tests carried out for at least the first vessel in a series of sister-ships. Such model tests normally include resistance tests at the ballast and design draught (on even keel), self propulsion tests at the ballast and design draught (on even keel) and optimum trim test at the design draught with *1 meter* trim by head and *3 meters* trim by stern. The tests are usually run at various speeds to obtain a "speed vs. power" curve (Harsem (2012) and Hyundai specification (2006)).

Part III

Calculations

Chapter 5

Background for the calculations

5.1 General

As written earlier, the Hyundai shipyard neglects all resistance components other than wave - and wind resistance (corrections for speed trial draughts deviating significantly from the design draughts are performed. This is rarely necessary for tankers as these normally are able to achieve design draught during the trial). The components that are omitted are claimed to be substantially smaller than the wave - and wind resistance (see chapter 2). However, summed together, they may nevertheless contribute considerably. Therefore it would have been informative to calculate the sum of all the minor resistance contributions. Unfortunately, this was not feasible as the Hyundai shipyard lacks information regarding several of the input values needed for such calculations. Negligence of these resistance elements is disadvantageous for the Hyundai shipyard. The computed contractual speed would have been larger if these were to be included.

As the wave resistance is a large resistance contribution, it was considered relevant to evaluate Hyundai's computation of this. The literature proposes several theories for calculation of added wave resistance. A handful of these were used as a basis for the assessment of the wave resistance found by Hyundai.

Equation (2.2) is the one and only formula proposed by the standards for calculation of added resistance due to wind. This formula is adopted by the Hyundai shipyard. The STA-JIP underlines the importance of the anemometer's location. The formula proposed by Hyundai for correction of an improper placement of the anemometer was adopted to get an understanding of its impact on the computed wind resistance.

5.2 Basis for the calculation of added wave resistance

Three of KGJS's S-class tankers (number S155, 1405 and 1374), built by the Hyundai shipyard in Mokpo were used as a basis for comparison of the different added wave resistance theories. As the resistance due to diffraction is sensitive to the bow shape, the line drawings were required for solving the diffraction problem. The Hyundai shipyard has only been willing to share the line drawings for the S-class, thus the computation of diffraction was restricted to this class. Hyundai has performed corrections for only three of the sister vessels. No corrections were done for the remaining ships of this class, as their trial speeds were well within the contract requirements before any corrections were made (a correction was hence considered excessive). The Hyundai shipyard has provided information concerning the speed trials as well as the vessels' geometry, collected in Table 5.1.

Table 5.1: Data regarding the S-class vessels' (S155, 1405 and 1374) geometry and speed trial results, provided by the Hyundai shipyard. (1^{st}) and (2^{nd}) correspond to the first and second run, respectively).

Ship no.	S155 (1^{st})	S155 (2^{nd})	1405 (1^{st})	1405 (2^{nd})	1374 (1^{st})	1374 (2^{nd})
Speed trial date	2003	2003	2002	2002	2002	2002
L_{PP} [m]	264	264	264	264	264	264
L_{WL} [m]	272	272	272	272	272	272
B [m]	48	48	48	48	48	48
d [m]	16.02	16.02	16.02	16.02	16.02	16.02
$H_{\frac{1}{3}}$ [m]	1.52	1.52	1.80	1.80	2.00	1.80
T [s]	4.50	4.50	4.50	4.50	2.80	2.70
β [deg]	0	180	-60	45	60	-30
U [knots]	15.61	17.30	16.29	16.17	15.52	16.89
B_N [-]	3.90	3.60	5.70	5.20	7.00	5.40
U_{rw} [m/s]	29.16	5.83	25.27	27.21	34.99	33.05
ψ_{rw} [deg]	0	20	60	45	60	-30
U_{aw} [m/s]	12.46	11.02	22.14	19.44	30.30	20.22
ψ_{aw} [deg]	180	190	119	119	293	254
$C_{rw}(\psi_{rw})$ [-]	-0.95	-0.96	0.48	0.77	0.48	0.95
C_B [-]	0.8168	0.8168	0.8168	0.8168	0.8168	0.8168
P_M [hp]	23316	22973	23136	23279	23398	22993
$\triangle P_W$ [hp]	338.70	0.34	294.70	356.77	189.73	212.88

L_{PP}	:	Length between perpendiculars [m];
L_{WL}	:	Length in the waterline at design draught [m]
B	:	Ship beam [m]
d	:	Design draught [-]
$H_{\frac{1}{3}}$	:	Significant wave height [m];
T	:	Period [s];
β	:	Angle between the wave propagation direction and the x-axis [rad] (see Figure 5.1);
U	:	Ship speed over ground [m/s];
B_N	:	Beaufort number [-];
U_{rw}	:	Relative wind velocity (measured) [m/s];
ψ_{rw}	:	Relative wind angle (measured) [deg];
U_{aw}	:	Actual wind speed (computed) [m/s];
ψ_{aw}	:	Actual wind angle (computed) [deg];
$C_{rw}(\psi_{rw})$	:	Relative wind resistance coefficient [-];
C_B	:	Block coefficient [-];
P_M	:	Measured power [hp];
$\triangle P_W$	:	Total additional power due to waves (see equation (4.2)) [hp]

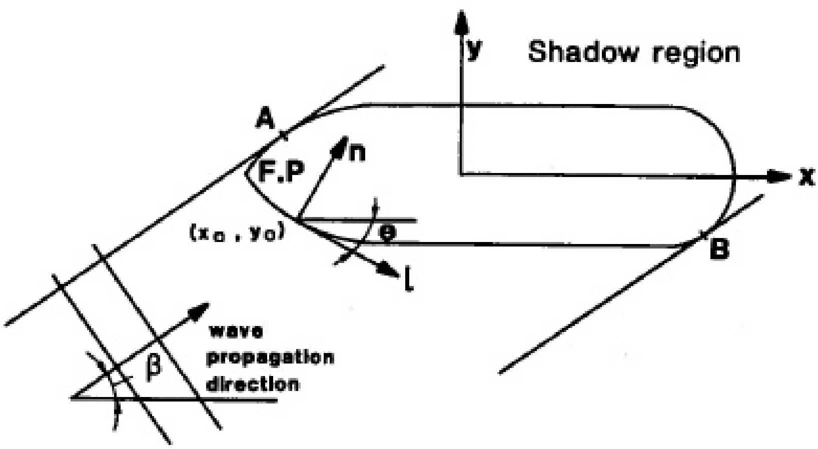

Figure 5.1: Definition of ship and wave parameters (Faltinsen; 1990, page 150).

5.2.1 The period, T

It is assumed that the periods, T, provided by Hyundai (see Table 5.1) represent mean wave periods, T_1 (equation (3.13)). The reason is that in the Hyundai procedures, T is only used as an input value in the ITTC energy specrum, given by equation 3.12 (T_1 is a spectral parameter in this spectrum). T will thus be utilized as T_1 in the forthcoming calculations. The possibility of T being T_p or T_2 cannot be excluded. Therefore, to cover all options, the mean wave loads will ultimately be calculated yet again adopting $T = T_p$ and $T = T_2$. This is considered necessary for obtaining a solid basis for the evaluation of Hyundai's methods.

5.2.2 The angle of the incoming wave, β

As disclosed in section 4.4, Lee claims that the Hyundai shipyard for the sake of simplicity assumes that the wave direction (β) is equivalent to the direction of the actual wind (ψ_{aw}). However, based on the values given for β, ψ_{rw} and ψ_{aw} in Table 5.1, it seems as if Hyundai does not do this in practice. It is not clear how the shipyard defines β, but it is reasonable to assume that β is defined with respect to the ship's heading. This because there is a significant discrepancy between β for the 1^{st} - and 2^{nd} run of each speed trial. If β was defined with respect to a fixed axis, it should have remained relatively constant for both speed trial runs (as the remaining wave data, as well as the actual wind direction are fairly similar for both runs). Assuming that β is defined with respect to the ship's heading, β equals the relative measured wind direction, ψ_{rw} (which also is defined with reference to the ship heading). This is quite illogical. ψ_{rw} is greatly affected by the ship's speed and direction. As the value of β obviously is not influenced by the vessel's movement, there should on a general basis be relatively little correlation between ψ_{rw} and β. In Figure 5.2, the relationship between relative - and true wind angle and the relative - and true wind speed for 1^{st} speed trial run of ship 1405 is given. It is evident that the relative wind angle, ψ_{rw}, may deviate significantly from the actual direction of the wind angle, ψ_{aw} (and thus β, as these are assumed to coincide). The exception is for following - and head wind, for which the relative and actual wind angles are equal.

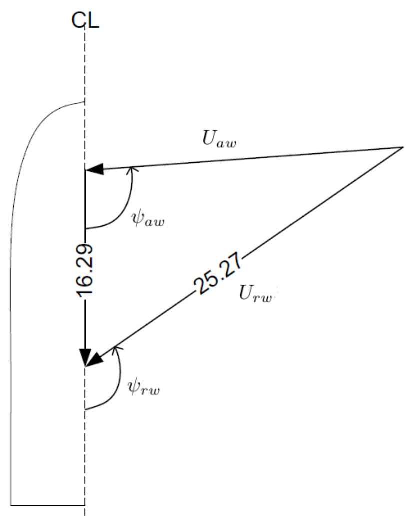

Figure 5.2: Correlation between relative - and true wind angle and speed for the 1^{st} speed trial run of ship 1405.

The values for β, given in Table 5.1 will be used as input values in the calculations of added wave resistance performed in this chapter. To account for all possibilities, the added resistance will ultimately be calculated for $\beta = \psi_{aw}$ (which was claimed to be done by Lee). There is a lot more sense in applying $\beta = \psi_{aw}$.

5.2.3 Diffraction vs. radiation

As explained in section 2.1, the added wave resistance consists of two components; mean wave load due to reflection of the incoming waves (diffraction) and resistance due to relative movement between the vessel and the sea surface (radiation). Diffraction dominates in the area of small wave lengths, defined as $\lambda/L < 0.5$. Wavelengths of this magnitude will normally not cause significant vertical motion of the ship, thus no appreciable radiation. The exception is cases in which the period of the incoming waves coincides with the eigenperiod of the vessel, causing resonance, hence large vertical movement. In order to determine whether the mean wave loads during the speed trials most likely were dominated by diffraction or radiation, the wave - to ship length ratio was calculated. This was done adopting the period (T), the dispersion relation in deep water (equation (5.1)) and the two definitions given in (5.2);

$$\omega^2 = kg \tag{5.1}$$

$$k = \frac{2\pi}{\lambda} \qquad \omega = \frac{2\pi}{T} \tag{5.2}$$

The results are given in Table 5.2.

Table 5.2: Wave- to ship length ratio for the wave data recorded at the speed trial for vessel S155, 1405 and 1374.

Speed trial runs	T_1 $[s]$	Corresponding λ $[m]$	λ/L_{WL} $[-]$
S155, 1405 (1^{st} and 2^{nd})	4.50	31.62	0.116
1374 (1^{st})	2.8	12.24	0.045
1374 (2^{nd})	2.7	11.38	0.042

As $\lambda/L_{WL} = 0.116, 0.045$ and 0.042 are $\ll 0.5$, it is reasonable to neglect the added resistance due to radiation.

5.2.4 The value of $\triangle P_{Wd}$

The Hyundai shipyard provides the total added wave resistance in *horsepowers* according to equation (4.2). To obtain a common platform for comparison, it was essential to find the added resistance due to diffraction ($\triangle P_{Wd}$) only (as this is the resistance contribution calculated in this report). Hyundai has not provided the values for the shaft efficiency, η_s, and the quasi propulsive efficiency, η_d. $\triangle P_{Wd}$ was found by the use of equation (4.2) and the following assumptions; $\eta_s = 0.97$, $\eta_d = 0.7$ (realistic values according to Steen) and mean wave load due to radiation, $\triangle P_{Wr}$=0. $\triangle P_{Wd}$ was converted to Newtons, according to equation (5.3);

$$\overline{F_d^s} = \frac{\triangle P_{Wd} \cdot 750}{U} \tag{5.3}$$

$\overline{F_d^s}$ is the mean wave load component due to diffraction for irregular waves, U is the ship speed and *750* is a conversion factor[1].

The computed $\overline{F_d^s}$ values are collected in Table 5.3. Also the measured power, P_M, was converted to Newtons (F_M), adopting equation (5.3) and the same assumption of η_s and η_d being *0.97* and *0.7*, respectively.

Table 5.3: $\overline{F_d^s}$ and F_M values for the S-class vessels S155, 1405 and 1374, converted from respectively $\triangle P_{Wd}$ and P_M..

Ship no.	S155 (1^{st})	S155 (2^{nd})	1405 (1^{st})	1405 (2^{nd})	1374 (1^{st})	1374 (2^{nd})
$\approx\overline{F_d^s}$ [kN]	21.480	19.456	17.909	21.842	12.102	12.477
$\approx F_M$ [kN]	1478.70	1314.62	1406.04	1425.23	1492.51	1347.71

5.2.5 Simplifications

A vessel's drift angle (section 2.4.1) alters the direction of the vessel's centerline. As β is defined with respect to the centerline, β is changed correspondingly. The magnitude of the drift angle is not provided in the Hyundai documentation, as the shipyard neglects its influence. Consequently, it will be disregarded in this report.

5.2.6 Other

It was assumed a ρ of $1025\ kg/m^3$.

[1]The most common definition of horsepower (hp) is that 1 hp = between 735.5 and 750 Watts (Wikipedia; 2012d)

Chapter 6

Calculations for added resistance due to diffraction

6.1 Faltinsen's formula for head waves

6.1.1 General

In Faltinsen (1990), equation (6.1) is provided for calculation of added wave resistance due to diffraction in *irregular*, head sea. The formula is assumed to be valid for small Froude numbers, i.e. $F_n < \approx 0.2$, blunt ship forms and sea states for which there is no significant wave energy for wavelengths larger than half the ship length.

The formula is expressed as;

$$\overline{F_d^s} = \rho \cdot g \cdot \frac{H_{\frac{1}{3}}^2}{16} \left(1 + F_n \cdot \frac{4\pi}{T_1} \sqrt{\frac{L_{WL}}{g}} \right) \int_{L_1} sin^2(\theta) \cdot n_1 dl \tag{6.1}$$

where

$$F_n = \frac{U}{\sqrt{L_{WL} \cdot g}} \tag{6.2}$$

and

$$n_1 = sin(\theta) \tag{6.3}$$

$H_{\frac{1}{3}}$	:	Significant wave height [m];
T_1	:	Mean wave period [s];
θ	:	The angle between the waterline tangent and the body axis (see Figure 5.1) [rad];
n_1	:	sin(θ) (Faltinsen; 1990, page 144) [-];
L_{WL}	:	Ship length in the waterline at design draught [m];
l	:	The coordinate along the waterline [m];
ρ	:	The density of the fluid [kg/m^3];
g	:	Acceleration due to gravity [m/s^2];
F_n	:	Froude number [-];
U	:	Ship speed [m/s];

Note that the energy spectrum $S(\omega)$ is included in the formula for T_1 (equation (3.13)). This way the *irregular* waves are accounted for.

6.1.2 Calculation procedure

Equation (6.1) is suitable for calculation of the added wave resistance for the 1^{st} speed trial run of vessel S155, due to the reasons listed below;

- the speed trial was conducted in head waves.
- the Froude number (F_n) is $\approx$ *0.155*, thus well within the required limits being $F_n < \approx 0.2$.
- vessel S155 has a blunt bow with a block coefficient (C_b) of *0.8168*.
- it is realistic to assume that there is no significant wave energy for wavelengths larger than half the ship length, as the wavelength corresponding to the period T is a lot smaller than the ship length (λ/L=*0.116* $\ll$ *0.5*).

The input values used in equation (6.1) are given in Table 6.1.

Table 6.1: Input values for equation (6.1).

ρ [kg/m^3]	$H_{\frac{1}{3}}$ [m]	L_{WL}[1] [m]	T_1 [s]	F_n [-]	(U [knots])	(β [deg])
1025	1.52	272	4.50	$\approx$ 0.158	15.61	0

The angle, θ, varies along the waterline section and is sensitive to the hull shape (see Figure 5.1 for a definition of θ). In order to obtain the θ-values for the S-class vessel, the following was done: Based on the line drawing, (x, y)-coordinates for the waterline section at design draught were plotted in a matrix in Matlab. Only coordinates in the bow area were included, as the θ-values and consequently the added resistance along the straight shipside is *zero* (see equation (6.1) for mathematical understanding). By taking advantage of the symmetry, it was only needed to plot coordinates for half the bow. To improve the accuracy of θ-values that are to be estimated based on the (x, y)-coordinates, interpolation was applied for constructing additional coordinates within the range of the known data (*interp1*-function in Matlab). The step between the interpolated coordinates along the x-axis was *0.1 meters*. A graphical representation of the interpolated waterline section is supplied in Figure 6.1.

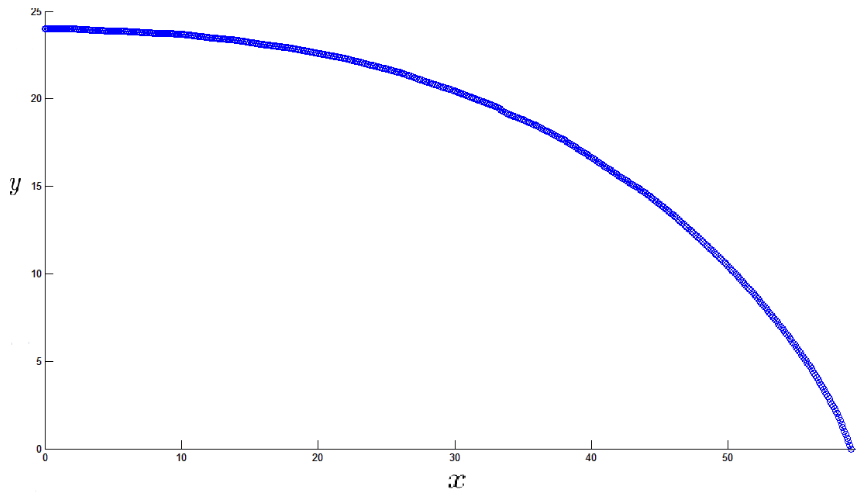

Figure 6.1: Interpolated waterline coordinates at the design draught for the S-class vessel, S263.

θ was found by equation (6.4);

$$\theta = tan^{-1}(\frac{dy}{dx}) \tag{6.4}$$

The tangent $\left(\frac{dy}{dx}\right)$ was obtained by differentiating y with respect to x in every coordinate along the waterline section, using a diff-function in Matlab.

n_1 was found by decomposing the normal vector, n (see Figure 5.1), in the x-direction, adopting equation (6.3).

The integral within equation (6.1), was to be integrated along the waterline section of the bow, l. dl was expressed in terms of dx, making use of the formula for arc length given by equation (6.5) (Rottmann; 2006);

$$ds = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx \tag{6.5}$$

The integral was solved numerically adopting the trapezoidal rule[2], which is an integrated function in Matlab.

(The result of the integral was 8.4541.)

6.1.3 Verification

The calculation of the integral within equation (6.1) was relatively intricate and was thus a potential source of error. A verification of the Matlab program was considered essential. To detect possible faults, the Matlab script was tested adopting a quarter of a circle. The shape of a circle is representative for the form of a blunt bow. Additionally, the circle has a known geometry, so that an analytical, exact solution can be checked against the numerical result obtained by the Matlab script.

6.1.3.1 The numerical solution

The procedure of computing the numerical solution was as follows: A matrix with x-values from *-1* to *0* with a step of *0.001* was made. The corresponding y-values for a quarter of the circle were computed adopting the following equation;

$$y = \sqrt{1 - x^2} \tag{6.6}$$

The Matlab script created for solving the integral included in equation (6.1) was run with the $(x,\ y)$-coordinates of the circle as input values. The only modification done to the original script was to reduce the step between the interpolated x-values to *0.0001*, as the circle is of a smaller scale than the vessel. The solution of the integral solved numerically was *0.6667*.

6.1.3.2 The analytical solution

The following relation between the angle, θ, and the arc, l, was applied;

$$dl = d\theta \cdot r \tag{6.7}$$

where r is the radius of the circle ($r = 1$). The upper and lower integration limit of θ for a quarter of a circle is respectively *0* - and *90°*. The integral within equation (6.1) could then be expressed as (Rottmann; 2006);

$$\int\limits_0^{90} sin^3(\theta)d\theta = \left[cos(\theta) - \frac{cos^3(\theta)}{3}\right]_0^{90} = \frac{2}{3} \approx 0.6667 \tag{6.8}$$

[2]"In numerical analysis, the trapezoidal rule (also known as the trapezoid rule or trapezium rule) is an approximate technique for calculating the definite integral $y = \int\limits_a^b f(x)dx$. The trapezoidal rule works by approximating the region under the graph of the function as a trapezoid and calculating its area. It follows that $y = \int\limits_a^b f(x)dx \approx (b-a)\frac{f(a)+f(b)}{2}$" (Wikipedia; 2012f).

As the numerical - and analytical solutions are identical, we can conclude with the Matlab script working satisfactorily. There may still be some degree of inaccuracy due to imprecise readouts of the waterline coordinates from the line drawings.

6.1.4 Result

Equation (6.1) gave an added resistance of $\approx 8.07 \cdot 10^4$ *Newtons* for the S-class vessel, S155.

6.2 Faltinsen's formula for oblique waves

6.2.1 General

In Faltinsen and Minsaas (1980), a procedure for calculating added resistance on a ship in *regular*, short waves of any wave direction is presented. The formula is based on a theoretical approach and is referred to as the *Asymptotic low wavelength case* or the *the asymptotic theory* and is valid for low Froude numbers ($F_n < 0.2$), short waves ($\lambda/L < 0.5$) and blunt bows. The geometry of the waterline section has great influence on the added resistance results when adopting this theory. The equations included are given by (6.9), (6.10), (6.11) and (6.12)). In the asymptotic theory, it is among other things assumed that the hull surface behaves like a semi-infinite wall, which implies that $z \to -\infty$ at the water surface (z is defined upwards). Equation (6.9) calculates the normal average force per unit length of the wall. There will not be given detailed information regarding the derivation of the formulas here. The interested reader may find advanced information regarding this in Faltinsen and Minsaas (1980).

$$\bar{F}_d = \frac{1}{2} \cdot \rho \cdot g \cdot \zeta_A^2 \left\{ \left[\frac{k_1}{2k} - \frac{1}{2} \cdot cos^2(\theta + \beta) \right] + \frac{k_2}{2k} \cdot sin(\theta + \beta) \right\} \tag{6.9}$$

where

$$k_1 = \frac{[\omega_e - V \cdot k \cdot cos(\theta + \beta)]^2}{g} \tag{6.10}$$

and

$$k_2 = \sqrt{k_1^2 - k^2 \cdot cos^2(\theta + \beta)} \tag{6.11}$$

ω_e	:	Frequency of encounter (see equation (2.1) [rad/s];
k	:	Incident wave number (see equation (5.1)) [1/m];
ζ_A	:	Incident wave amplitude [m];
θ	:	The angle between the waterline tangent and the body axis (see Figure 5.1) [rad];
β	:	Angle between the wave propagation direction and the x-axis (see Figure 5.1 [rad];
V	:	Steady fluid velocity [m/s]

V is generally hard to obtain. Therefore Faltinsen and Minsaas (1980) proposes to set;

$$V = U \cdot cos(\theta) \tag{6.12}$$

where U is the mean forward speed. Referring to Faltinsen and Minsaas (1980), equation (6.12) is; "consistent with slender body theory. It also gives the right answer for extreme blunt ships".

6.2.2 Calculation procedure

6.2.2.1 *Regular* waves

Skejic (2012) has developed a Fortran program for solving equation (6.9).

The input values needed for his script are F_n, β_s, L_{WL} and the beam (B) of the waterline section. Additionally, the waterline geometry of the vessel at design draught in terms of (x, y)-coordinates is requested. Skejic (2012) defines β so that 180 ° represents head sea. This is the opposite of Faltinsen's definition (see Figure 5.1). To avoid confusion, β_s will be used for expressing incoming wave angles defined in accordance with Skejic.

Arbitrary coordinates along the waterline section (obtained from the line drawings) were written in an input text file that was further incorporated in the Fortran program. Based on the coordinates, the complete hull in the waterline was created (see Figure 6.2).

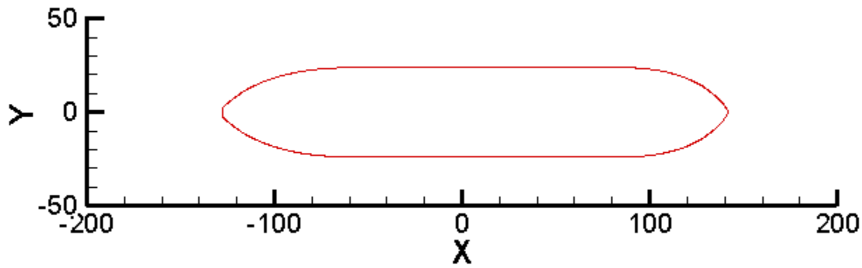

Figure 6.2: The complete waterline section at design draught for the S-class vessel S263. The origin is located in the area of the center of gravity.

Further one was to specify a lower - and upper λ_j/L_{WL}-value as well as a desired number, j, of intermediate λ_j/L_{WL}-values. For each wave component, j, the program calculated the dimensionless added wave resistance (equation (6.13)), for a *regular* wave (for a given β_s). As the asymptotic theory is valid for short wavelengths only, the upper λ_j/L_{WL} value was naturally chosen to be *0.5*. The lower value of λ_j/L_{WL} was set to *0.05*. This because the dimensionless added wave resistance approaches a vertical asymptote as $\lambda_j/L_{WL} \to 0$. Consequently, Faltinsen's formula for oblique waves will produce unrealistically high values for $\lambda_j/L_{WL} \approx< 0.05$. The number of wave components, j, was set to *150*.

$$\bar{F}_{d,dim}(\lambda_j/L_{WL};\beta_s) = \frac{\bar{F}_d(\lambda_j/L_{WL};\beta_s)}{\rho \cdot g \cdot \zeta_A^2 \cdot \frac{B^2}{L}} \tag{6.13}$$

6.2.2.2 *Irregular* waves

Equation (6.9) calculates the mean drift load for *regular* waves. In order to obtain the added wave resistance for *irregular* waves, the *regular* wave resistance components were combined with an appropriate energy spectrum. The energy spectrum applied was the ITTC spectrum, as this is adopted by the shipyard. In Faltinsen (1990), there is a provided a formula for calculation of mean wave load in *irregular* waves, given by;

$$\overline{F_d^s} = 2\int_0^\infty S(\omega)\left(\frac{\bar{F}_d(\omega;\beta)}{\zeta_A^2}\right)d\omega \tag{6.14}$$

Here $\bar{F}_d(\omega_j;\beta)$ is the mean wave load component in regular incident waves of circular frequency ω_j, wave amplitude ζ_{Aj} and wave propagation direction β. Note that since $\bar{F}_d(\omega_j;\beta)$ is divided by (ζ_A^2), the equation is independent of the amplitude. Equation (6.14) is based on an assumption of long-crested waves, which distinguishes the formula from equation (3.11), recommended by ISO (2002) (make a note of the direction distribution of the incident waves, $G(\alpha-\beta)$ not being inlcuded in equation (6.14)). Equation (6.14) was solved numerically, adopting Matlab, and the procedure was as follows:

The mean wave load components were expressed as;

$$\frac{\bar{F}_d(\lambda_j/L_{WL};\beta)}{\zeta_A^2} = \frac{\bar{F}_{(dim)}(\lambda_j/L_{WL};\beta)\cdot\rho\cdot g\cdot B^2}{L_{WL}} \tag{6.15}$$

Each of the 150 different values found by equation (6.15) was multiplied with its corresponding value of S(ω_j). The association between ω_j and λ_j/L_{WL} was found through the dispersion relation given by equation (5.1). The products were summarized according to equation (6.16);

$$\overline{F_d^s} = 2\sum_{j=1}^{150} S(\omega_j)\left(\frac{\bar{F}_d(\lambda_j/L_{WL};\beta)}{\zeta_A^2}\right)\triangle\,\omega_j \tag{6.16}$$

$\triangle\omega_j$ was calculated by equation (6.17);

$$\triangle\omega_j = \sqrt{\frac{2\pi\cdot g}{(\frac{\lambda_{(j+1)}}{L_{WL}} - \frac{\lambda_j}{L_{WL}})\cdot L_{WL}}} \tag{6.17}$$

6.2.3 Verification

6.2.3.1 Verification of Skejic's Fortran program

It was considered necessary to verify Skejic's Fortran program (section 6.2.2.1) for equation (6.9) to some extent.

Initially, the program was tested for *zero* forward speed. For $U = 0$, λ is not included in equation (6.9) (not in terms of ω, T or k either). The dimensionless drift load, $\bar{F}_{d,dim}$ (equation (6.13)), should hence be equal for all λ_j/L_{WL}.

A mathematical derivation of this by the use of equation (6.9), (6.10), (6.11) and (6.12)) is given below;

$$V = U\cdot cos(\theta) = 0 \qquad \rightarrow \qquad \omega_e = \omega + k\cdot U\cdot cos(\beta) = \omega \tag{6.18}$$

k_1 (equation (6.10)) can then be written;

$$k_1 = \frac{\omega_e^2}{g} = \frac{\omega^2}{g} = k \tag{6.19}$$

(dispersion relation)

Knowing that $cos^2(\theta - \beta) + sin^2(\theta - \beta) = 1$ (Rottmann; 2006), k_2 (equation (6.11)), can further be expressed as;

$$k_2 = \sqrt{k^2(1 - cos^2(\theta - \beta))} \rightarrow \quad k_2 = \sqrt{k^2 \cdot sin^2(\theta - \beta)} \rightarrow \quad k_2 = k \cdot sin(\theta - \beta) \tag{6.20}$$

Equation (6.9) can finally be written as;

$$\overline{F}_d = const. \left\{ \frac{1}{2} \left[1 - cos^2(\theta - \beta) \right] + \frac{1}{2} \cdot sin^2(\theta - \beta) \right\} \rightarrow \quad \overline{F}_d = const. \cdot sin^2(\theta - \beta) \tag{6.21}$$

const. is the term given by $\frac{1}{2} \cdot \rho \cdot g \cdot \ \zeta_A^2$. For U=*0*, it is evident that equation (6.9) is independent of λ.

The Fortran program was run for $U = 0$, with the remaining input values corresponding to data from the 1^{st} speed trial run of vessel S155. Figure 6.3, shows that the computed $\bar{F}_{d,dim}$ as a function of λ_j/L_{WL} is constant.

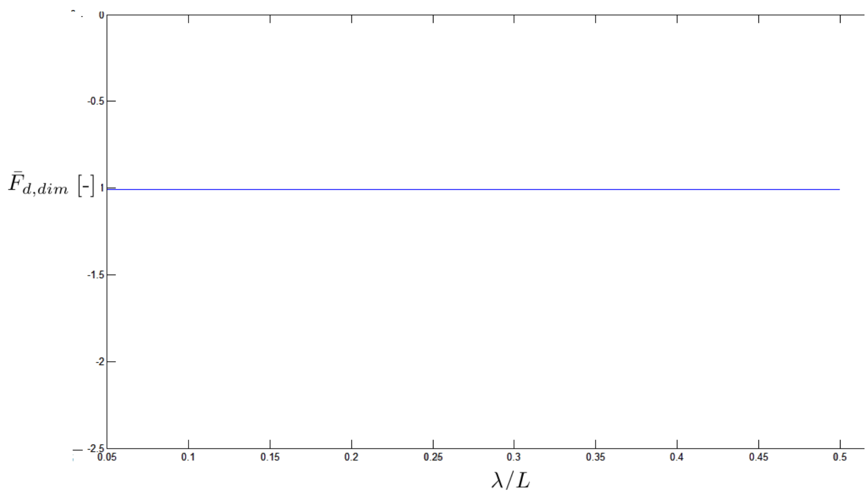

Figure 6.3: Calculation of the dimensionless mean drift load $\bar{F}_{d,dim}$ as a function of λ/L_{WL}-values from *0.05* til *0.5*. U=*0*, and the other input values corresponds to data from the the 1^{st} speed trial run of S155.

Further, it was of importance to clarify that the Fortran program works properly for all incoming wave angles, β_s. In Faltinsen and Kjaerland (1979, Page 202), there is provided a graph illustrating the dimensionless added resistance, $\bar{F}_{d,dim}$, as a function of the wave heading, β, for an arbitrary tanker. This graph was used as a basis for the verification. The waterline section for the arbitrary tanker (given in Faltinsen and Kjaerland (1979, Page 193)), was used as input value in Skejic's Fortran program. The wave drift obtained by the Fortran program is shown in Figure 6.4, and the graph provided by Faltinsen and Kjaerland (1979, Page 202)) is displayed in Figure 6.5. As the two graphs provide similar results, the Fortran program is regarded as verified for *zero* forward speed. It can be seen that the resistance peaks at around $\beta = 50°$ (β is defined according to Figure 5.1).

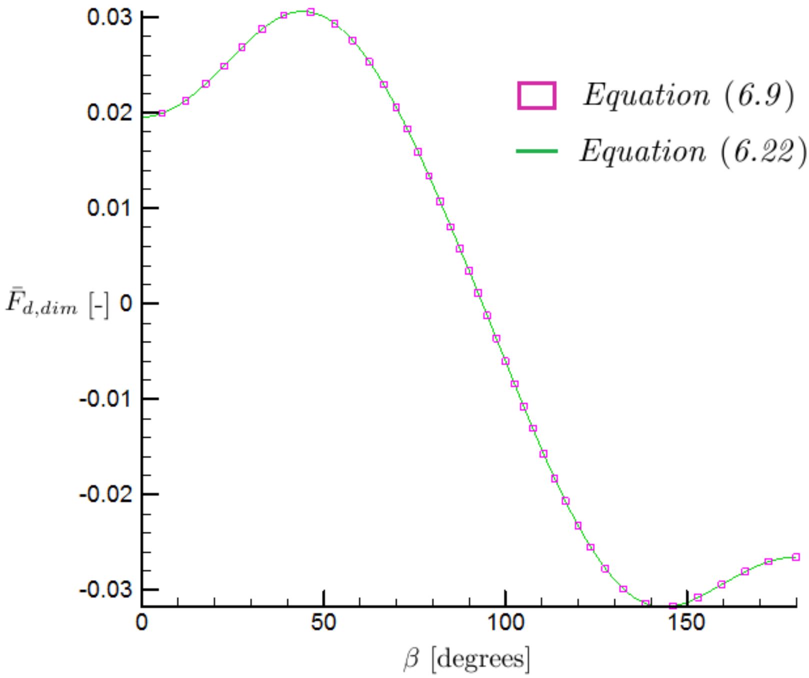

Figure 6.4: Wave drift load as a function of wave heading for an arbitrary tanker. Equation (6.9) and (6.22) (soon to be introduced) was calculated by Skejic's Fortan program. U=*0* and λ/L_{WL}=*0.175* (keep in mind that equation (6.9) and (6.22) provide equivalent results as U=*0*).

Further, $\bar{F}_{d,dim}$ as a function of β_s was found for the *S-class tanker*. The program was run at $U = 0$ and $\lambda/L_{WL} = 0.1$ (green curve in Figure 6.6) to verify that the graph resembles the curve in Figure 6.4. Additionally, $\bar{F}_{d,dim}$ was found for $U = 15.61$ *knots* and $\lambda/L_{WL} = 0.1$ (pink curve in Figure 6.6). This was done to confirm that the resistance increases with increasing speed, and that the shape of the curve still bears a resemplence to Figure 6.4. Ultimately, $\bar{F}_{d,dim}$ was obtained for $U = 15.61$ *knots* and $\lambda/L_{WL} = 0.1$ (see the red curve in Figure 6.6). This to confirm that $\bar{F}_{d,dim}$ varies for different values of λ/L_{WL} when $U \neq 0$. The results provided in Figure 6.6, seems reasonable, and the Fortran program is thus regarded as validated.

6.2.3.2 Verification of the Matlab program

It was additionally necessary to verify the Matlab program made for solving equation (6.14) (the program is described in section 6.2.2.2). The added resistance for the 1^{st} speed trial

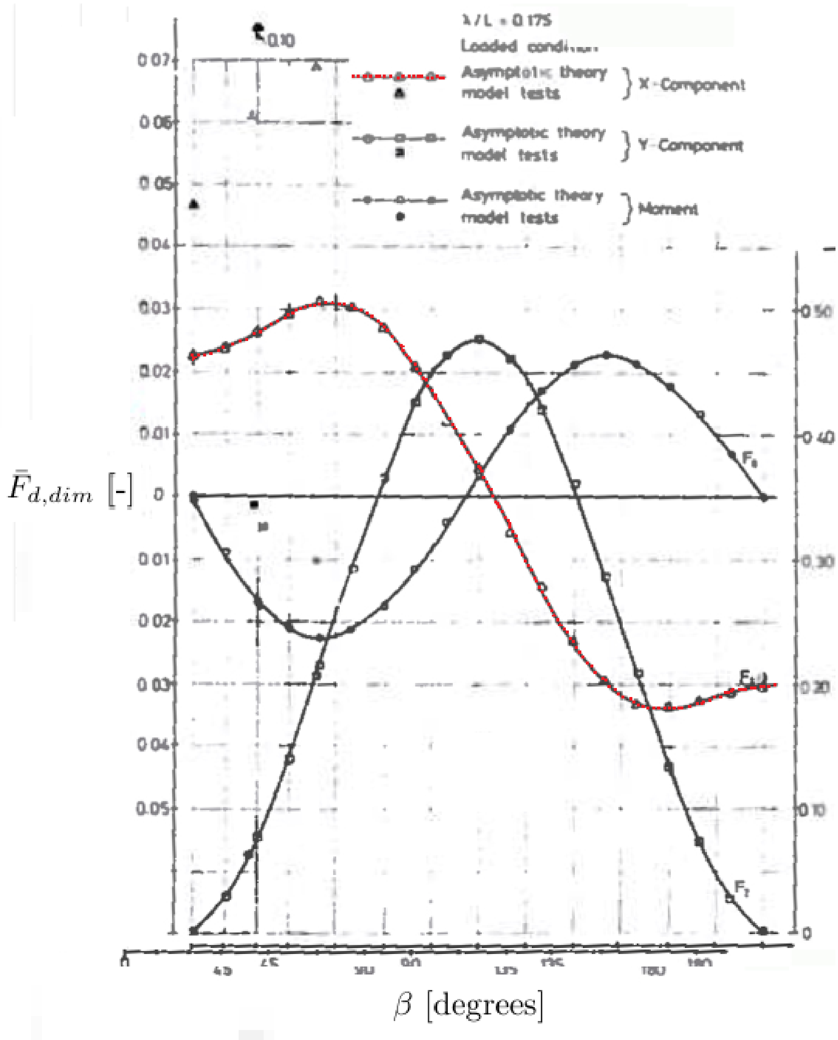

Figure 6.5: Figure given in Faltinsen and Kjaerland (1979). The graph marked in red illustrates the dimensionless wave drift load $\bar{F}_{d,dim}$ (in x-direction) as a function of wave heading for an arbitrary tanker. U=0 and λ/L_{WL}=0.175.

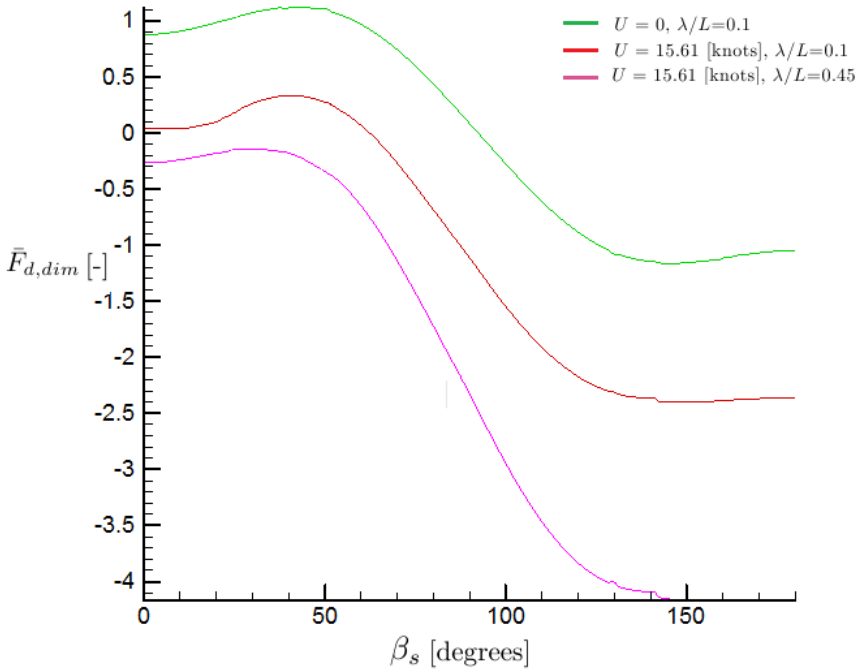

Figure 6.6: Wave drift load for the geometry of a S-class tanker, for a variation of input values.

Table 6.2: $\overline{F_d^s}$ values for an arbitrary selection of incoming wave angles, β_s (*180* ° represents head sea). The remaining input values used were data from the 1^{st} speed trial run of vessel S155 (these were kept constant).

β_s [deg]	180	150	120	90	60	30	0
$\overline{F_d^s}$ [kN]	77.21	78.64	74.58	45.08	10.95	1.375	4.029

run of vessel S155 was computed by the use of equation (6.9) for regular waves, combined with the Matlab program for irregular waves (equation (6.14)). The added resistance for the exact same input values was calculated by the use of Faltinsen's equation for head sea (equation (6.1). As equation (6.1) and (6.9) are based on the same theory, they should provide relatively equivalent results for similar input values. The mean added wave resistance $\overline{F_d^s}$ found by equation (6.1) was $\approx 8.07 \cdot 10^4$ *Newtons*, and the added wave resistance obtained by a combination of equation (6.9) and (6.14) was $\approx 7.72 \cdot 10^4$ *Newtons*. The percentage deviation between the two resistances is *4.5* %. This is a relatively small deviation, which indicates that the Matlab program for equation (6.14) works satisfactorily.

As an additional check, $\overline{F_d^s}$ was calculated by equation (6.9) and (6.14) for seven evenly spread angles (β_s) between *0*° and *180*°. Data from the first speed trial run of vessel S155 were used as input values (with exception of the incoming wave angle). The results are presented in Table 6.2.

Based on the information graphically presented in Figure 6.5, the results in Table 6.2 seem reasonable.

6.2.4 Results

The mean wave load, $\overline{F_d^s}$, was calculated for both speed trial runs of vessel S155, 1405 and 1374. The results are presented in Table 6.3.

Table 6.3: Mean wave load, $\overline{F_d^s}$, for both speed trial runs of vessel S155, 1405 and 1374 by equation (6.9).

Vessel No.	S155		1405		1374	
Run	1^{st}	2^{nd}	1^{st}	2^{nd}	1^{st}	2^{nd}
$\overline{F_d^s}$ [kN]	77.2	4.66	108.4	113.7	107.4	93.1

6.3 Faltinsen's simplified formula for all incoming wave angles

In Faltinsen and Minsaas (1980), a simplified version of Faltinsen's formula for all incoming wave angles (equation 6.9) is provided. This formula is based on a low speed assumption, and is also valid for short waves and blunt bows. According to Faltinsen and Minsaas (1980): "In case of small U-values and by using equation (6.9), we will find by Taylor expansion that;"

$$\bar{F_d} \approx \frac{1}{2} \cdot \rho \cdot g \cdot \zeta_a^2 \left\{ sin^2(\theta + \beta) + \frac{2 \cdot \omega_0 \cdot U}{g} [1 - cos(\theta) \cdot cos(\theta + \beta)] \right\} \tag{6.22}$$

Faltinsen and Minsaas (1980) emphasizes that equation (6.22), being based on a low speed assumption, is inappropriate for resistance computations at high speeds.

Equation (6.22) is recommended by ISO (2002).

6.3.1 Calculation procedure

Skejic (2012) has developed a program for solving equation (6.22). The calculation approach for equation (6.22) was identical to the procedure followed for solving equation (6.9) (described in section 6.2.2).

6.3.2 Verification

According to Skejic, the typical speeds obtained at trials (for tankers) are considered as relatively high. Equation (6.22) will consequently most likely give inaccurate results in this speed range. It is of interest to confirm or reject his claim, as to get an understanding of whether ISO (2002)'s recommendation is unfortunate. According to Faltinsen and Minsaas (1980), equation (6.9) is a general formula without such speed limitations ($F_n < 0.2$ is the only speed requirement). Therefore this formula is suitable as a reference for the evaluation of equation (6.22).

For $U = 0$, equation (6.9) and equation (6.22) are identical, and the Fortran program should give identical results for the two formulas. For $U = 0$, equation (6.22) can be written as;

$$\bar{F_d} \approx \frac{1}{2} \cdot \rho \cdot g \cdot \zeta_a^2 \cdot sin^2(\theta + \beta) \tag{6.23}$$

(This is equivalent to equation (6.21) derived for $U = 0$.)

To identify the deviation tendency between equation (6.9) and equation (6.22) for increasing speeds, the following was done: The added wave resistance was calculated by the two formulas for six scattered speed values between *0* - and *30 knots* (see the Table 6.4). *15.61 knots* (the measured trial speed) gives the deviation between the two equations in the relevant speed area. *30 knots* is an unrealistically high speed, and was only integrated to emphasize the trend of the deviation. The remaining input values were taken from the speed trial data from the 1^{st} run of vessel S155.

Table 6.4: $\overline{F_d^s}$ found by equation (6.22) and (6.9) for different speeds. The remaining input values used were data from the 1^{st} speed trial run of vessel S155 (these were kept constant).

Speed [knots]	$\overline{F_d^s}$ by eq. (6.9) [N]	$\overline{F_d^s}$ by eq. (6.22) [N]	Deviation [%]
0.00	$2.25 \cdot 10^4$	$2.25 \cdot 10^4$	0.00
4.00	$3.49 \cdot 10^4$	$3.50 \cdot 10^4$	0.29
8.00	$4.82 \cdot 10^4$	$4.66 \cdot 10^4$	3.43
12.00	$6.28 \cdot 10^4$	$5.86 \cdot 10^4$	7.17
15.61	$7.72 \cdot 10^4$	$6.96 \cdot 10^4$	10.92
30.00	$1.46 \cdot 10^5$	$1.13 \cdot 10^5$	29.20

Table 6.4, shows that the discrepancy between the two equations increases significantly with increasing input speed. For *zero* speed, the two equations provide equivalent results. At *15.61 knots*, the deviation is as high as *10.92* %. This indicates that the Taylor expanded formula (equation (6.22)) might be a poor choice for calculating added resistance for the typical speed range obtained at speed trials. At *30 knots*, the speed deviation is as high as *29.20* %, which clearly confirms that equation (6.22) is unsuitable for high velocities. As the equation gives consistently too low added wave resistance values for higher speeds, the formula is advantageous for the shipping companies. Since the recommendation of ISO (2002) seems to be adverse, equation (6.22) will not be included in the evaluation of the Hyundai procedures.

6.4 Fujii and Takahashi method

6.4.1 General

In Fujii and Takahashi (1975), an approximate method for calculating the added resistance for large, full ships in regular, short[3] waves was developed. This method is based on a combination of Havelock's formula[4] for drifting force and empirical corrections. Fujii and Takahashi (1975) divided the total resistance for a full ship in waves into two separate constituents; the added resistance due to wave reflection at the bow and the resistance increase due to ship motion. In Faltinsen and Minsaas (1980), the following is stated regarding such an approach; "From a rational point of view, one can argue against dividing the added resistance into two parts in the way that Fujii and Takahashi did. Generally speaking, the reflection of the waves and the ship motions may interact in a more complicated way on the added resistance. But their procedure makes some sense for certain wave lengths regions, i.e. for small wave lengths where the effect of ship motions may be disregarded...". As speed trials in general are performed in relatively short waves, the method proposed in Fujii and Takahashi (1975) should provide quite good correction results in connection with these. In Fujii and Takahashi (1975), model tests for a tanker and a container vessel were carried out to verify the method, and fairly good agreement was shown between the model tests results and the computed values.

Fujii and Takahashi (1975) provides equation (6.24) for calculating the resistance increase due to reflection at the bow. The formula

$$\overline{F}_d = \alpha_3(1+\alpha_4)\frac{1}{2}\cdot\rho\cdot g\cdot\zeta_A^2\int\limits_{-\frac{B}{2}}^{\frac{B}{2}} sin^2\theta dy \tag{6.24}$$

where

$$\alpha_3 = \frac{\pi^2\cdot I_1^2(k\cdot d)}{[\pi^2\cdot I_1^2(k\cdot d)+K_1^2(k\cdot d)]} \tag{6.25}$$

and

$$\alpha_4 = 5\sqrt{\frac{U}{g\cdot L_{WL}}} \tag{6.26}$$

---

[3] i.e. $\lambda/L < 0.5$

[4] The Havelock formula expresses the drifting force from very short waves on a vertical cylinder. The interested reader may find further details in Havelock (1940).

$\overline{F}_d$	:	Resistance increase due to diffraction in regular waves [N];
α_3	:	Empirical correction factor considering the effect of finite draught [-];
α_4	:	Empirical correction factor considering the effect of the forward speed [-];
ζ_A	:	Amplitude of the incoming wave [m];
θ	:	Angle between waterline tangent of the hull and the body axis [rad] (see Figure 5.1);
U	:	Ship speed [m/s];
k	:	Wave number [1/m];
$I_1(k \cdot d)$	:	Modified Bessel function of the first kind [-];
$K_1(k \cdot d)$	:	Modified Bessel function of the second kind [-];
d	:	Ship draught (design draught here) [m];
L_{WL}	:	Ship length in the waterline at design draught [m];

α_3 and α_4 are derived from experiments with blunt ships.

6.4.2 Calculation procedure

The mean drift load was computed for the 1^{st} speed trial run of vessel S155.

The integral contained in equation (6.24) is identical to the integral included in Faltinsen's formula for head sea (equation (6.1)). This can be shown mathematically, adopting the geometric relationship between *dy* and *dl*, expressed in equation (6.27);

$$dy = sin(\theta) \cdot dl \tag{6.27}$$

(See Figure 5.1 for a definition of *dy* and *dl*))

The integral can with this be written as; $\int_{L_1} sin^2(\theta) \cdot sin(\theta) dl$. Remembering that n_1 in equation (6.1) equals $sin(\theta)$, we see that the two integrals are equal. The value of the intergral obtained in section 6.1.2, was used in this calculation. The modified Bessel Functions of the first - and second kind are integrated functions in Matlab (written as *besseli(1,kf)* and *besselk(1,kf)*, respectively). These were solved as a function of the wave number, k. The minimum value of k applied corresponds to $\lambda/L = 0.5$, as equation (6.24) only is valid for short waves. The step of k corresponds to $\triangle\omega = 0.1$.

$\overline{F}_d$ for the regular waves, combined with the ITTC spectrum (equation (3.12)) and equation (6.14) was used for obtaining the resistance for *irregular* waves. The integration of the energy specter was solved numerically.

6.4.3 Results

The added resistance found by the use of equation (6.24) was $7.2404 \cdot 10^4$ *Newtons.*

6.5 Modified Fujii and Takahashi method

6.5.1 General

Sakamoto and Baba (1986), provides a modified version of Fujii and Takahashi's method (equation (6.24)). The empirical expressions in equation (6.25) and (6.26) were improved based on additional experimental data obtained in the Nagasaki Experimental Tank. The "modified" Fujii and Takahashi formula is adopted by the Hyundai shipyard and is given by equation (4.5).

6.5.2 Calculation procedure

Once again, data from the 1^{st} speed trial run of vessel S155 was used as input value. As this particular speed trial run was performed in head waves, the integral included in equation (4.5) was simplified considerably. In head sea, the incident wave angle, β, is zero, and the integral included in equation (4.5) can be written as;

$$\int_{-\frac{B}{2}}^{\frac{B}{2}} sin^2(\theta)dy$$

This is identical to the integral included in Faltinsen's formula (equation (6.1)) and Fujii and Takahashi's formula (equation (6.24)) and is thus previously solved. The remainder of equation (4.5) was computed in Matlab, following the exact same procedure as described in section 6.2.2.2.

6.5.3 Results

The added wave resistance obtained by equation (4.5) was $5.80 \cdot 10^4$ *Newtons.* This deviates from the resistance found by Hyundai, being $2.15 \cdot 10^4$ *Newtons.* This is noteworthy as the exact same formula was adopted.

6.6 Kreitner's formula

6.6.1 General

Bose (2005) provides an extremely simple formula for calculation of added wave resistance due to diffraction from the bow (equation (3.17)). The formula is limited to wave heights up to *1.5 - 2 meters*. β is not included in the Kreitner's formula, thus the method is primarily appropriate for "head to beam" waves, i.e. $90° < \beta < 270°$.

6.6.2 Assumption

It is sensible to assume that the wave height, H, included in equation (3.17), represents the significant wave height, $H_{\frac{1}{3}}$.

6.6.3 Results

The results are provided in Table 6.5. The mean wave load was not calculated for the 2^{nd} speed trial run of S155, as this was conducted in following waves.

Table 6.5: Mean wave load, $\overline{F_d^s}$, for both speed trial runs of vessel S155, 1405 and 1374 by equation (6.9).

Ship no.	S155 (1^{st})	1405 (1^{st})	1405 (2^{nd})	1374 (1^{st})	1374 (2^{nd})
$\overline{F_d^s}$ [kN]	102	143	143	177	143

6.7 Summary of the results

A summary of the mean wave load results obtained by the different theories presented in this report is given in Table 6.6. The 1^{st} speed trial run of S155 is used as input value.

Table 6.6: Comparison of added wave resistance for irregular waves for the 1^{st} speed trial run of vessel S155.

ADDED WAVE RESISTANCE, $\overline{F_d^s}$ for S155 (1^{st})					
Hyundai [kN]	Eq. (6.1) [kN]	Eq. (6.9) [kN]	Eq. (6.24) [kN]	Eq. (4.5) [kN]	Eq. (3.17) [kN]
21.48	80.7	77.2	72.40	58.0	102

Eq. (6.1) : Faltinsen's formula for head waves [kN];
Eq. (6.9) : Faltinsen's formula for oblique waves [kN];
Eq. (6.24) : Fujii and Takahashi method [kN];
Eq. (4.5) : Modified Fujii and Takahashi method [kN];
Eq. (3.17) : Kreitner's method [kN]

A general tendency observed in Table 6.6 is that the mean drift load obtained by the Hyundai shipyard is substantially smaller than those computed in this report. It is worth noting that the results found in this thesis do not deviate greatly from one another, which strengthens the credibility of the computations. Additionally, the results are found through different calculation approaches and theories, which support the trustworthiness of the calculations further. The Hyundai shipyard claims to apply the modified Fujii and Takahashi method (equation (4.5)). However their result is about half of the value obtained in section 6.5 when adopting precisely the same equation.

These findings disprove Reinertsen's suspicion of Hyundai's added wave resistance calculations being unrealistically high.

In Table 6.7, $\overline{F_d^s}$ values found for the remaining speed trial runs by the use of equation (6.9) are given. The results are compared to those obtained by the Hyundai shipyard.

Table 6.7: Comparison of added wave resistance found according to Faltinsen's method for all oblique waves (equation (6.9) and Hyundai's results. F_M is the force corresponding to the power, P_M, measured at speed trial. *PP* is percentage point.)

	Equation (6.9)		Hyundai values		
Vessel No.	$\overline{F_d^s}$ *[kN]*	% of F_M	$\overline{F_d^s}$ *[kN]*	% of F_M	*PP* deviation
S155 (1^{st})	77.2	5.22	21.48	1.45	3.77
S155 (2^{nd})	4.66	0.35	0.0195	0.0015	0.35
1405 (1^{st})	108.4	7.71	17.91	1.27	6.44
1405 (2^{nd})	113.7	7.98	21.84	1.53	6.45
1374 (1^{st})	107.4	7.20	12.10	0.81	6.39
1374 (2^{nd})	93.1	6.91	12.48	0.93	5.98

Also in Table 6.7, Hyundai's results are significantly smaller than those found by equation (6.9).

Possible explanations of the large descrepancies include;

- The shipyard follows other procedures in practice than those stated in the documentation (Hyundai Heavy Industries Co.; 2002).
- Hyundai adopts other input values than those provided in the speed trial reports (given in Table 5.1).
- Hyundai makes errors in their calculations.
- It is assumed that the period in Hyundai's speed trial documentation, T equals T_1. It may also be T_p and T_2 (see discussion in section 5.2.1).
- So far all the calculations have been conducted adopting $\beta = \psi_{rw}$. However, the shipyard may use that $\beta = \psi_{aw}$ in practice (see explanation in section 5.2.2).
- There are errors in the calculations performed in this report.

6.8 Added wave resistance computed with $T = T_2$ and $T = T_p$

6.8.1 Values of T_1

As described in section 5.2, there were uncertainties associated with the period, T, given by the shipyard. In all previous computations, it was assumed that $T = T_1$. Considering the large deviations witnessed between the results obtained in this report and the values given by Hyundai, it was of interest to calculate the mean wave loads, adopting $T = T_2$ and $T = T_p$. This may be a possible source of error. The additional T_1 values are given in Table 6.8. These were found from the correlation between T_1, T_2 and T_p, given by the equations in (3.15).

Table 6.8: Possible values of the mean wave period, T_1, depending on the definition of T given by Hyundai.

	If $T = T_2$	If $T = T_p$	(If $T = T_1$)
T_1 of S155 (1^{st})	4.86	3.465	(4.5)
T_1 of S155 (2^{nd})	4.86	3.465	(4.5)
T_1 of 1405 (1^{st})	4.86	3.465	(4.5)
T_1 of 1405 (2^{nd})	4.86	3.465	(4.5)
T_1 of 1374 (1^{st})	3.024	2.156	(2.8)
T_1 of 1374 (2^{nd})	2.916	2.079	(2.7)

6.8.2 Results

$\overline{F_d^s}$ was calculated for the 1^{st} speed trial run by the equations previously adopted, now with the $T_1 = \mathit{4.86}$ and $\mathit{3.465}$. The results are given in Table 6.8.

Table 6.9: $\overline{F_d^s}$ calculated for $T_1 = \mathit{4.86}$ and $\mathit{3.465}$ with the equations previously used. The percentage deviation between the largest and smallest value of $\overline{F_d^s}$ is given.

Theory	$\overline{F_d^s}$ [kN]			Deviation [%]
	$T_1 = 4.5$	$T_1 = 4.86$	$T_1 = 3.465$	
$\overline{F_d^s}$ [kN] by equation (6.1)	80.7	76.51	97.4	27.3
$\overline{F_d^s}$ [kN] by equation (6.9)	77.2	75.0	78.1	4.1
$\overline{F_d^s}$ [kN] by equation (6.24)	72.05	71.6	71.6	0.6
$\overline{F_d^s}$ [kN] by equation (4.5)	58.0	58.1	57.4	1.2
$\overline{F_d^s}$ [kN] by equation (3.17)	102	102	102	0.0

Equation (6.1) : Faltinsen's formula for head waves;
Equation (6.9) : Faltinsen's formula for all incoming wave angles;
Equation (6.24) : Fujii and Takahashi method;
Equation (4.5) : Modified Fujii and Takahashi method;
Equation (3.17) : Kreitner's method

As T_1 is not a included in equation (3.17), $\overline{F_d^s}$ will consequently be equal for all values of T_1. In general there are relatively small discrepancies between the $\overline{F_d^s}$ values for the maximum and minimum value of T_1.

$\overline{F_d^s}$ for the remaining speed trial runs were calculated adopting equation (6.9). The results are provided in Table 6.10.

Table 6.10: $\overline{F_d^s}$ calculated for T_1 corresponding to $T = T_2$ and $T = T_p$ with equation (6.9). The percentage deviation between the largest and smallest value of $\overline{F_d^s}$ is found.

	$\overline{F_d^s}$ [kN]			Deviation [%]
	$T_1 = 4.5$	$T_1 = 4.86$	$T_1 = 3.465$	
S155 (1^{st})	77.2	75.0	78.1	4.1
S155 (2^{nd})	4.66	4.31	4.85	12.5
1405 (1^{st})	108.4	105.2	109.9	4.5
1405 (2^{nd})	113.7	110.5	115.0	4.1
	$T_1 = 2.8$	$T_1 = 3.024$	$T_1 = 2.156$	
1374 (1^{st})	107.4	118.8	45.6	160.5
	$T_1 = 2.7$	$T_1 = 2.916$	$T_1 = 2.079$	
1374 (2^{nd})	93.1	105.3	34.1	208

In Table 6.10, it can be observed that for the speed trials of vessels S155 and 1405, the percentage deviations are relatively small. In comparison, the percentage discrepancy for ship 1374 seems to be unrealistically large. In order to get an understanding of these diverging results, the ITTC spectrum was plottet for the different values of T_1 (and its related $H_{\frac{1}{3}}$). The results are presented in Figure 6.7.

The red - and blue graphs are the energy spectrums for respectively the 1^{st} and 2^{nd} run of vessel 1374. The green curves are the energy spectrums for the 1^{st} - and 2^{nd} run of ship S155. The vertical line is the value of ω, corresponding to $\lambda/L_{WL} = 0.05$ (found adopting the dispersion relation). Faltinsen's theory does not provide satisfactory results for $\lambda/L_{WL} < 0.05$ (Skejic; 2012), thus $\lambda/L_{WL} = 0.05$ was defined as lower limit in Skejic's program. Consequently, there are no values for the dimensionless added wave resistance for $\lambda/L_{WL} < 0.05$ which corresponds to $\omega > 2.13$. This implies that a significant portion of energy is lost for the runs of vessel 1374, especially for the minimum value of T_1. This explains the large percentage deviation between $\overline{F_d^s}$ for the maximum - and minimum value of T_1 for vessel 1374 (see Table 6.10). The added wave resistance results for vessel 1374 (at least for the minimum value of T_1), should be disregarded as the computed values are unrealistically low. (Note that as T_1 increases, the energy spectrum shifts towards the right.)

According to Skejic (2012), there should be little wave energy for $\lambda/L_{WL} < 0.05$. Therefore, one might question the validity of the periods (T), provided by Hyundai. In Hogben (1986), there is provided statistical wave data (typical correlation between $H_{\frac{1}{3}}$ and T_2) for the whole globe, divided into 104 parts. Data given for area 28, which is the relevant area for the trial, for the months of September and October (the sea trial for vessel 1374 was conducted 15^{th} of October) was used as a basis for the evaluation of T. It was assumed that T given by Hyundai represents T_1 and that the correlation given by (3.15) holds. The table showed that;

- there is between *2.09* - and *4.56* % probability for $T_1 < 4.34$ *seconds* for $H_{\frac{1}{3}} = 2$ *meters*

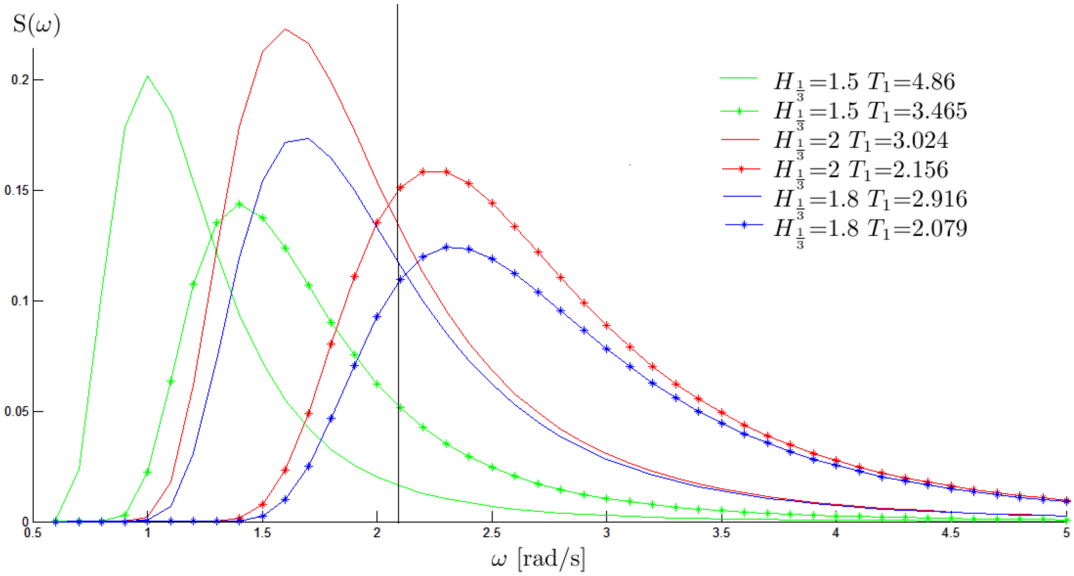

Figure 6.7: The ITTC spectrum plotted for T_1, found by assuming that $T = T_2$ and $T = T_p$, and their corresponding $H_{\frac{1}{3}}$ values. The black, vertical line illustrates the value of ω, corresponding to λ/L_{WL} = *0.05*.

(T_1 for the 1^{st} run was *2.8 seconds*)

- there is *4.56* % probability for $T_1 <$ *4.34 seconds* for $H_{\frac{1}{3}}$ = *1.8 meters* (T_1 was *2.7 seconds* for the 2^{nd} run).

Based on this, the periods provided by Hyundai seem to be somewhat unrealistic. As these wave statistics are found for open seas, they may not be fully representative for the Hyundai speed trial area which is more sheltered. However, they indicate that it may be useful to look into Hyundai's procedures for finding T.

6.8.3 Conclusion

Based on the values found for $\overline{F_d^s}$ for the maximum and minimum value of T_1 (presented in Table 6.9 and 6.10), it can be concluded that "an improper use of T" is not the source of the large discrepancies between $\overline{F_d^s}$ found by Hyundai and those found in this report (the results for vessel 1374 are disregarded). On the other hand, it is of interest to investigate Hyundai's procedure for finding T.

6.9 Added wave reistance computed with β=actual wind angle

6.9.1 General

Lee (2012) claims that the shipyard assumes that β = actual wind angle (ψ_{aw}). Based on the information provided in the speed trial documentations, this claim may be rejected. The Hyundai documentation reveals that β equals the relative wind angle (ψ_{rw}). For the 1^{st} and 2^{nd} run of S155 (respectively head and following wind), this has no practical relevance as $\psi_{aw} = \psi_{rw}$ for these. However; for the speed trials of ship 1405 and 1375, there is a large deviation between ψ_{rw} and ψ_{aw}. Due to the large discrepancies witnessed between the results obtained in this report and the values given by Hyundai (especially for ship 1405 and 1375), it is considered relevant to calculate the added resistance once again, now adopting that $\beta = \psi_{aw}$.

6.9.2 Calculation approach

The Hyundai ship yard provides values for ψ_{aw}, with reference to the north direction. As the heading of the vessel is unknown, ψ_{aw} in relation to the x-axis (definition of β) of the vessel is still unknown. In order obtain this, geometric considerations of the wind vectors were adopted. Figure 6.8 shows the angles and lengths adopted for the calculation of ψ_{aw}.

The known parameters are ψ_{rw}, U (ship speed over ground) and U_{rw} (the relative wind speed).

The following equations were used (Rottmann; 2006, Page 40);

$$U_{aw}^2 = U^2 + U_{rw}^2 - 2 \cdot U \cdot U_{rw} \cdot cos(\psi_{rw}) \tag{6.28}$$

and

$$U_{rw}^2 = U_{aw}^2 + U^2 - 2 \cdot U_{aw} \cdot U \cdot cos(\psi_{aw}) \tag{6.29}$$

The values of the computed ψ_{aw} are presented in Table 6.11.

Table 6.11: Values of the calulated ψ_{aw}.

	S155 (1^{st})	S155 (2^{nd})	1405 (1^{st})	1405 (2^{nd})	1374 (1^{st})	1374 (2^{nd})
ψ_{rw} [deg]	180	0	80.52	99.07	93.73	125.37

$\overline{F_d^s}$ was computed for ψ_{aw}=β_s. The results are collected in Table 6.12.

The results in Table 6.12 clearly show that the value of β *may* be highly decisive for the outcome of $\overline{F_d^s}$. Therefore it is of importance that the shipyard and the shipping companies agree on how β is to be determined.

The values $\overline{F_d^s}$ found by β_s=ψ_{aw} are smaller, and therefore closer to the added resistance values given by Hyundai, however there are still large discrepancies.

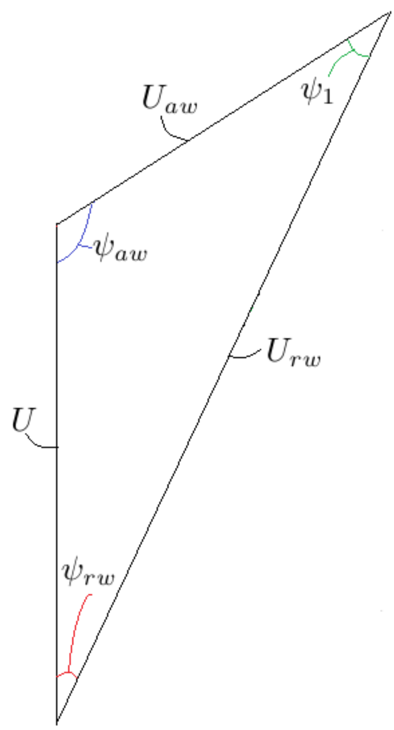

Figure 6.8: Definition of the parameters adopted in (6.28) and (6.29) for the computation of ψ_{aw}.

Table 6.12: $\overline{F_d^s}$ calculated by equation (6.9) for β_s=ψ_{aw} and β_s=180°-ψ_{rw} (previously used). The percentage deviation between the two is found.

	S155 (1^{st})	S155 (2^{nd})	1405 (1^{st})	1405 (2^{nd})	1374 (1^{st})	1374 (2^{nd})
$\overline{F_d^s}$ (β_s=ψ_{aw}) [kN]	77.2	4.66	57.55	95.17	73.46	91.1
$\overline{F_d^s}$ (β_s=180°-ψ_{rw}) [kN]	77.2	4.66	108.4	113.7	107.4	93.1
Deviation [%]	0	0	88.4	19.5	46.2	2.1
(Hyundai's $\overline{F_d^s}$ [kN])	(21.480)	(19.456)	(17.909)	(21.842)	(12.102)	(12.477)

6.9.3 Error found in the Hyundai documentation

The actual wind speed (U_{aw}) for each speed trial run was calculated adopting equation (6.29). The computed values obtained for ship 1405 and 1374 coincided with the the numbers given by Hyundai. However for ship S155, discrepancies were observed. For the 1^{st} speed trial run of S155, the computed value of U_{aw} was *13.55 knots*, while the actual wind speed given by Hyundai was *12.46 knots*. For the 2^{nd} speed trial run, the value found was *11.99 knots* which differed from Hyundai's value of *11.02 knots*. As U_{aw} is not implemented in any of Hyundai's equations, this error does not influence the resistance calculations. However, it indicates that the quality of the Hyundai's procedures is questionable. Moreover it is peculiar that such mistakes appear, as Hyundai's computations are performed in pre-programmed software.

Chapter 7

Location of the anemometer

7.1 General

The B. Henk (2006) emphasizes the importance of the anemometer being located in the correct altitude. The height of the anemometer should equal the reference height for the wind resistance table applied. Referring to B. Henk (2006), the reference height for most wind resistance tables is *10 meters*. Equation (7.1) can be used to correct for an improper placement of the anemometer. The formula accounts for the speed varying significantly over the height above sea level.

$$U_{ref} = U_{aw}(z)\left(\frac{z_{ref}}{z}\right)^{\frac{1}{7}} \tag{7.1}$$

where z_{ref}, is the reference height of the wind resistance table, and z is the altitude of the anemometer.

7.2 Calculation procedure

For the S-class vessels, the anemometer was located *31.5 meters* above sea level. The shipyard adopts wind resistance tables given by Blendermann, and it is reasonble to assume that the referance height for this table is *10 meters*. As the wind resistance is such a large resistance contribution, it was of interest to compute the added wind resistance accounting for the improper location of the anemometer according to equation (7.1). Hyundai makes no such corrections. If the magnitude of the wind resistance is reduced considerably, KGJS should have stronger focus on the placement of the anemometer in the future.

The transverse projected area, A (included in the wind resistance equation), was unknown for the S-class vessels. For KGJS's vessel S380, on the other hand, all information necessary for the calculation was provided in documentation (2007). This vessel was hence used as a basis for the evaluation of equation (7.1). Vessel S380 is of similar size as the S-class, thus it is realistic to presume that the location of the anemometer equals that of the S-class vessel.

The input values given for vessel S380 are collected in Table 7.1.

Table 7.1: $\overline{F_d^s}$ calculated by equation (6.9) for β_s=ψ_{aw} and β_s=180°-ψ_{rw} (previously used). The percentage deviation between the two is found.

U	U_{rw}	ψ_{rw}	ρ_a	ρ_{ar}	A	$C_{rw}(\psi_{rw})$	$C_{iw}(\psi_{iw})$
[knots]	[knots]	[deg]	$[kg/m^3]$	$[kg/m^3]$	$[m^2]$	[-]	[-]
13.92	26.44	10	1.226	1.293	750	-0.860	-0.950

U	:	Ship speed [m/s];
U_{rw}	:	Relative meausured wind speed [m/s];
ψ_{rw}	:	Relative measured wind angle [deg];
ρ_a	:	Density of air in ideal condition $[kg/m^3]$;
ρ_{ar}	:	Density of air in actual speed trial condition $[kg/m^3]$;
A	:	The transverse projected area $[m^2]$;
$C_{rw}(\psi_{rw})$	:	Relative wind resistance coefficient [-];
$C_{iw}(\psi_{iw})$	:	Wind resistance coefficient for ideal conditions [-]

Initially the actual wind velocity, U_{aw}, was calculated, to be used as input value in equation (7.1). The reason for not using U_{rw} as input value is that U (which forms a part of U_{rw}) is constant over the height and should thus not be a included in the correction. The value of U_{aw} was found adopting the geometrical consideration provided in section 6.9.2. This gave an actual wind speed (U_{aw}) of *12.96 knots* (this coincides with the calculated true wind speed given by Hyundai).

Equation (7.1) with z_{ref} = *10* and z = *31.5* $\rightarrow$ U_{ref} = *11 knots*

As the length of the U_{ref} vector was reduced, the length and angle of U_{rw} vector is altered. As a step towards obtaining the *modified* relative wind speed ($U_{rw,ref}$), the angle of the true wind with respect to the ship heading (ψ_{iw}) was found (ψ_{iw} = *160.74°*) (note that ψ_{iw} is constant). In order to compute $U_{rw,ref}$, equation (6.29) was applied.

This gave $U_{rw,ref}$ = *24.57 knots*. The value of the *modified* relative wind angle ($\psi_{rw,ref}$) was computed to be *8.49°*.

As the relative wind angle is modified, the coefficient $C_{rw}(\psi_{rw})$ will consequently change. Adopting Blendermann (1986, Page 64), the C_{rw} value corresponding to $\psi_{rw,ref}$ = *8.49°* was found from graphs presented. The value was approximately *-0.84*.

Further, equation (4.9) was used for calculating the resistance due to relative wind, W_{rw}. The result obtained was W_{rw} = *-65.08 kN*.

Equation (4.10) was applied for calculating the added resistance in ideal conditions (W_{iw}), which gave a resistance of *-22.4 kN*.

The computed value of the added resistance due to the wind only ($W_{rw} - W_{iw}$) was *-42.68 kN*. The added resistance calculated without correction for the height of the anemometer was *-54.7 kN*. This gives a percentage deviation of *28.26* %, which is not insignificant.

Part IV

Energy Efficiency Design Index, EEDI

Chapter 8

EEDI

8.1 The attained EEDI value

The International Maritime Organization (IMO) is developing an Energy Efficiency Design Index (EEDI) as a part of a regulatory framework to reduce CO_2 emissions from shipping. The EEDI is to be implemented for all new ships above *400 gross tons (gt)*, 1^{st} of January 2013. The definition of a "new ship" is either a vessel for which the building contract is placed on or after 1^{st} of January 2013 or for which the delivery is on or after 1^{st} of July 2015. The EEDI estimates a ship's CO_2 emission per ton-mile of goods transported; put differently, the vessel's impact on the environment in relation to its benefit for society (Hon and Wang; 2011). The index provides a common platform so that one can easily compare different vessels' CO_2 efficiency and thus carbon footprint. It is calculated from a highly intricate empirical formula that still subjects to improvement (IMO; 2009b, page 4). A simplified formula for the attained EEDI value is expressed as;

$$EEDI = \frac{C_{Fa} \cdot SFC \cdot P}{Capacity \cdot U_{max}} \tag{8.1}$$

The *EEDI* is measured as gram per ton mile. *P* is the ship's power demand, *SFC* is specific fuel consumption, and C_{Fa} is a carbon emission factor. The *Capacity* is either specified as gross tonnage or deadweight, depending on ship type. Gross tons is a unit less index related to a ships overall internal volume, and deadweight is the sum of the weights of fuel, cargo, fresh water, ballast water and crew. U_{ref} is the speed measured during speed trial at maximum draught (scantling draught) and *75 %* of maximum continuous rating (MCR). According to IMO and the EEDI specifications, the speed is to be found in calm weather conditions without the presence of wind, tides and waves. The measurements are to be collected in accordance with requirements given by ISO (2002) or equivalent standards (IMO; 2009a). The extended formula includes a weather factor f_w in the denominator, which is to account for the environmental effects mentioned. Referring to Tonnesen (2012), there are at the present time no clear guidelines on how to determine this factor.

8.2 Reference lines

To establish the required EEDI values, IMO has divided the existing fleet by ship type and derived EEDI reference lines unique for each vessel category. The attained EEDI must be on or below these base lines in order for the ship to be EEDI certified. The reference lines are defined as $a \cdot W^{-c}$, where W is gross tonnage or deadweight, and a and c are coefficients based on regression analyses of attained EEDI values in the existing world fleet. These curves are functions of ship capacity. Therefore the acceptable EEDI value depends solely on two factors; the deadweight or gross tonnage of the vessel and ship type. IMO has published reference line values for seven ship types; bulk carriers, tankers, gas tankers, container ships, general cargo vessels, refrigerated cargo vessels and combination carriers (ABS; 2012). An IMO reference line for tankers above *400 gross tons* is shown below (Figure 8.1). The green dot is an attained EEDI value for the appropriate ship type;

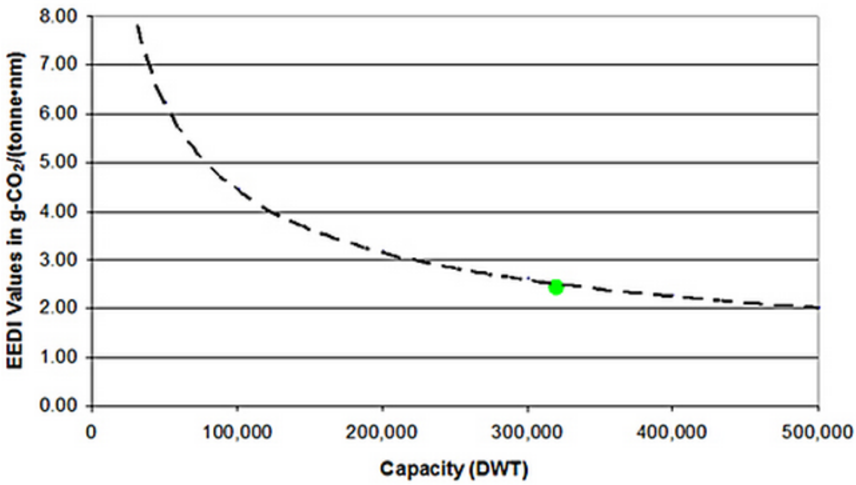

Figure 8.1: Reference line for tankers larger than *400 gt* (DNV; 2011).

8.3 Verification of the EEDI

Verification of the EEDI will be done in two stages. The first verification will take place at design stage based on tank tests and manufacturers data. The second EEDI verification will be based on the sea trial results. During the sea trial, the speed versus engine power will be measured and the technical file[1] updated. Based on the technical file, engine certificates and

[1]Throughout the design phase, ship owners and shipbuilders will work together to develop the EEDI Technical File, a reference document of ship particulars that will be used to calculate the vessel's attained EEDI value. This document will contain information such as engine particulars, estimated power curves and a detailed description of energy saving equipment installed. Any variance between the attained EEDI calculated during the design and that obtained at sea trials will need to be explained in the EEDI Technical File and

other relevant documentation, the second verification is conducted. The verification will be conducted by classification societies on behalf of the flag state and the authorities, based on IMO's guidelines.

Up until now, the ship yards and shipping companies have been responsible for both the speed measurements during the speed trials and the corrections for added resistance. The classification societies have been passive in this regard. From 2013, however, the class will be actively involved in both these processes to be able to EEDI approve the vessel. No longer will this matter only be of interest for the buyer and the ship yard; it will become a matter for the authorities.

8.4 Draughts

The following paragraph is based on information from Reinertsen. The reason for the attained EEDI being found at maximum draught rather than at design draught, is that the maximum draught is considered a defined term. This entails that it cannot be chosen "liberally". Maximum draught is defined as the smaller of the following; the largest draught allowed according to the free board rules or the largest draught that forms the basis for the vessels strength calculations (scantling draught). A vessel should for safety reasons never carry load causing a draught exceeding maximum draught. The design draught is the expected average loaded draught for which the propellers and bulb is designed and optimized for. As the design draught in principle might be "any" draught, it can be specified tactically, so that the EEDI is satisfied without undertaking any environmentally friendly measures. An indicative value of the difference between design - and scantling draught is about *0.7 meters* for a vessel with a length overall of *250 meters* (Shipbuilding Contract; 2006).

8.5 Motivation for the introduction of the EEDI

The motivation for the EEDI initiative is to proactively approach the environmental challenges we are facing today. The goal is to reduce fuel consumption, hence proportionally the CO_2 emission from vessels that are to be built in the future. There is a strong political drive to reduce green house gases, and the EEDI is the first step towards a regulation of emissions in the shipping industry. The following statement illustrates the importance of the project; "Shipping today represents about *3* % of global greenhouse gas emissions. Worldwide seaborne trade has been growing about *4* % a year for decades. A recent study by IMO projects that emissions from shipping will increase *150* % to *250* % by 2050 in the absence of policies to reduce emissions" (EPA; 2011). Several estimates predict that implementation of the EEDI will reduce emissions significantly. Referring to Koren (2012); "By some estimates, the measure (EEDI) will help remove *45* to *50 million tones* of CO_2 from the atmosphere annually by 2020, depending on the growth in world trade. From 2030, the reduction will be between *180* and *240 million tons* annually since the introduction of the EEDI."

In addition to the environmental interest related to the EEDI, the rising costs of fuel have increased the industry focus on fuel efficiency. The EEDI is by most shipping companies considered an opportunity to implement measures that lead to cost effectiveness and long

verified before any certificate may be issued (ABS; 2012).

term gain. According to Tonnesen (2012), fuel is the largest cost element for most shipping companies, often of the same magnitude as the total costs of insurance, repair and maintenance, administration and crew. Furthermore, a CO_2 emission fee could soon be imposed on the shipping companies, an aspect also strengthening the interest of designing fuel efficient vessels (Reinertsen; 2011).

8.6 Phases of the EEDI

There will be four phases in the introduction of the EEDI, each phase with more stringent requirements, forcing the new building to be ever more fuel efficient. The reason is that efficiency gains through new technology and design improvements are expected in near future. The reference lines for 2013 (phase zero) are determined based on the emission average of existing ships in the world fleet. The reference lines in the first, second and third phase will be respectively *10* %, *20* % and *30* % lower than in phase zero. The phases are to be implemented in 2015, 2020 and 2025 (DNV; 2012). The graph below (Figure 8.2) illustrates reference lines for four different phases for a given ship type;

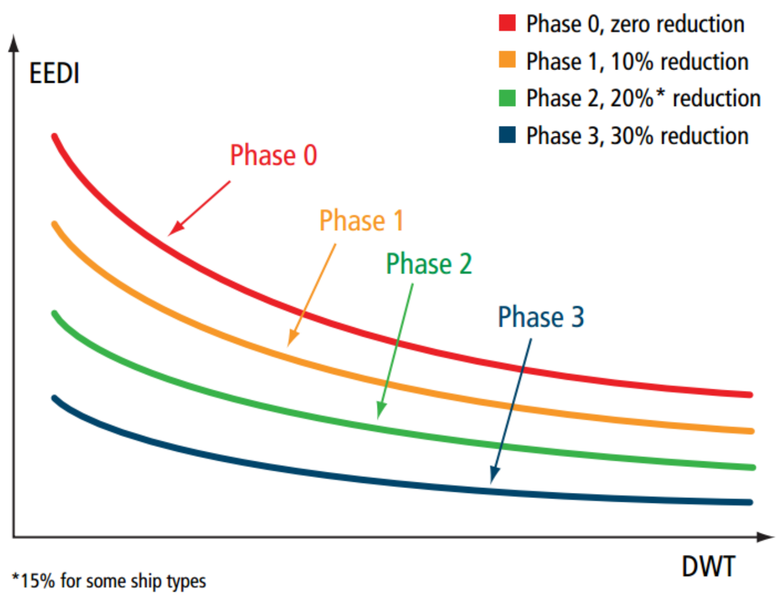

Figure 8.2: Reference lines for an arbitrary ship type (ABS; 2012)

8.7 Ways of satisfying the EEDI

Tonnesen (2012) (on behalf of DNV) has suggested various methods on how to minimize the attained EEDI value. Some are optimization of propellers and hull, flow devices, contra-rotating propellers, hybrid electric power and propulsion concepts, reduction of design speed, engine efficiency improvement and reduction of on-board power demand.

8.8 Speed dependency of the attained EEDI value

Graphs presented by Tonnesen (2012) illustrate that the EEDI is very sensitive to a ship's speed, meaning that only small speed reductions contribute to a significantly lower attained EEDI value. This can be shown mathematically, beginning with the simplified formula for EEDI;

$$EEDI = \frac{C_F \cdot SFC \cdot P}{Capacity \cdot U_{ref}} \tag{8.2}$$

C_F (carbon emission factor), *SFC* (specific fuel consumption) and *Capacity* (deadweight or gross tonnage) are hardly dependent on the speed. In order to obtain the proportionality between the power, P, and the speed, one can think of P as the power demand required to maintain a certain speed. The power is then expressed as,

$$P = U \cdot R \tag{8.3}$$

or

$$P = U \cdot C_T \cdot \frac{1}{2} \cdot \rho \cdot U^2 \cdot S \tag{8.4}$$

or

$$P = C_T \cdot const. \cdot U^3 \tag{8.5}$$

R is resistance, U is speed and S is wetted surface. C_T is the total resistance coefficient, and it includes three main resistance components; viscous resistance, wave resistance and air resistance (does not account for environmental wind, only relative wind due to the ship speed).

Viscous resistance is a general term including all resistance components related to the fluids viscosity, such as:

- Frictional resistance - arises between the sea water and hull.
- Form resistance - a correction of the frictional resistance due to 3D - and displacement effects of the vessel. The water speed along the ship side increases in order to "make room" for the ship volume, which causes additional frictional resistance.
- Surface roughness - additional frictional resistance due to fouling, weld joints etc. The formulas used for calculating frictional resistance do not account for roughness and irregularities in the ship hull, thus a correction is needed. In practice, surface roughness only causes additional resistance for high Reynolds number values.

- Appendix resistance - often a combination of frictional resistance and viscous pressure resistance due to "appendages" on the vessel, such as rudder, shaft etc.
- Transom resistance - occurs when the transom is partly under the water line. At low ship speeds, the transom gets wet, and the surrounding water is characterized by backflow and a chaotic flow pattern. This causes a resistance component called base drag.

The term *wave resistance* includes the three following scenarios;

- Wave breaking in the bow area - for most ships, bow breaking occurs, causing energy loss, hence additional resistance.
- Dry transom - when the ship speed is high, the transom gets dry. The resistance corresponds to the loss of hydrostatic pressure.
- Generation of the steady (Kelvin) wave pattern around the hull[2] (note that this wave resistance does not include added resistance due to environmental waves).

The magnitude of the different resistance components depend on the ship type and the design of each individual ship. As an example, the magnitude of wind resistance depends to a large extent on the size of a vessel's superstructure. Generally, the wave - and frictional resistance coefficient are the two largest and most essential among all the different resistance coefficients. Therefore, only these will be evaluated when examining the relationship between the total resistance coefficient C_T and speed.

C_T can in a simplified manner be written;

$$C_T = C_W + (C_F + \triangle(C_F) \cdot (1 + k_w) \tag{8.7}$$

or

$$C_T = C_W + C_V \tag{8.8}$$

C_T is the wave resistance coefficient, C_F is the frictional resistance coefficient, $\triangle\ C_F$ is the surface roughness coefficient, k_w is the form factor and C_V is the viscous resistance coefficient.

[2]The water speed along the shipside of the vessel is not constant, due to the presence of the ship. In the forepart of the ship, the water is forced out to the ship sides, and in the stern of the vessel, the water flows back towards the centerline of the ship. Consequently, the water flows slower in the front and the rear of the vessel than around the mid ship area. Bernoulli's equation expresses the relationship between the water speed V, pressure p and water level ζ_A:

$$\frac{1}{2} \cdot \rho \cdot U^2 + \rho \cdot g \cdot \zeta_A + p = const. \tag{8.6}$$

On the water surface, the pressure cannot exceed the atmospheric pressure and can therefore be treated as a constant. To compensate for the reduction in speed around the bow and stern, a wave elevation (increase of ζ_A) occurs in this area. Around the mid ship section, the water speed is higher. Similarly, as compensation, a wave trough occurs in this area.

8.8.1 Speed dependency of C_F

The frictional resistance coefficient C_F decreases gradually with increasing Reynolds number[3] (i.e. increasing speed). The surface roughness does not cause noteworthy additional friction until a relatively high Reynolds number. The surface roughness coefficient $\triangle C_F$ is therefore approximately *zero* for low R_e. Due to the roughness, a "fully rough flow" is formed around the ship hull when the Reynolds number exceeds a certain value (Steen; 2011). The R_e value at which this phenomenon occurs mainly depends on the degree of roughness of the hull. A "fully rough flow" implies that $C_F + \triangle C_F$ reaches a constant asymptotic value, hence is speed independent within this area. The value of the constant asymptote increases with increasing degree of surface roughness. The Reynolds number at which the fully rough flow occurs, decreases with increasing roughness. As full scale vessels normally will experience fully rough flow during the speed trials, $C_F + \triangle C_F$ can be considered a constant in connection with the EEDI (Steen; 2011).

8.8.2 Speed dependency of C_W

The wave resistance coefficient C_W on the other hand, increases with increasing speed. For very low Froude numbers[4] ($F_n < 0.1$), the wave resistance is approximately *zero*, and the total resistance is almost entirely viscous in character. As the Froude number increases, the wave resistance coefficient increases exponentially within a certain interval. According to Prohaskas method[5] (see equation (8.11)), C_W is typically proportional to the speed of the 3^{rd}-7^{th} power for relatively low speeds (Steen; 2007). Eventually, the slope of the C_W-curve starts decreasing gradually, until it becomes negative. This turning point tends to occur at very large Froude numbers, corresponding to ship speeds so large that they are not realistic for vessels that are to satisfy the EEDI. Hence, C_W (in the relevant speed interval associated with the EEDI) is proportional the speed of the 3^{rd}-7^{th} power.

8.8.3 Speed dependency of C_T

The proportionality between the speed and the total resistance coefficient C_T is reliant on two factors; the speed dependency of each individual addend (C_W and C_V), and the ratio between the two. As a step towards obtaining this proportionality, C_T was calculated applying equation (8.11), equation (8.13), equation (8.7) and equation (8.12). C_T was plotted for speeds between *9* - and *16.4 knots* with a step of *0.2 knots*, in Excel. This speed range was chosen as it covers realistic ship speeds values for speed trials run at *70* % of MCR (the MCR specified in the Energy Efficiency Design Standard).

3
$$R_N = \frac{U \cdot L_{WL}}{\upsilon} \tag{8.9}$$
U is the mean velocity of the fluid relative to the object, L_{WL} is the length in the waterline (characteristic length) and ν is the kinematic viscosity.

4
$$F_N = \frac{U}{\sqrt{g \cdot L_{WL}}} \tag{8.10}$$
U is the mean velocity of the fluid relative to the object, g is the acceleration due to gravity and L_{WL} is the length of the ship at the water line level.

5 A method applied to determine the form coefficient k. One assumes that the wave resistance coefficient C_W at relatively low speeds can be expressed as (equation (8.11)).

The different coefficients within the formula for C_T (equation 8.7) were calculated applying the following formulas given in Steen (2007);

$$C_W = m \cdot {F_N}^{C_p} \tag{8.11}$$

(Prohaska's method)

m and C_p are constants, and the exponent C_p has normally values between *3* and *7*.

$$C_F = \frac{0.075}{(logR_N - 2)^2} \tag{8.12}$$

$$\triangle C_F = (110 \cdot (Q \cdot U)^{0.21} - 403) \cdot {C_F}^2 \tag{8.13}$$

Q is the roughness in μm, which is typically 50-150 μm for a new ships (150 μm was used). U is the speed.

The constants k and m (see equation (8.7) and (8.11) respectively) affect the ratio between C_W and C_v, hence the speed dependency of C_T. These constants were varied in the Excel script to obtain *speed vs.* C_T - graphs for several realistic ratios of C_v/C_T. The ratios used for plotting were *0.5*, *0.75* and *0.9*.

The exponent C_p in the equation for C_W (equation (8.11)) may as mentioned vary from *3* to *7*, and its value will naturally affect the proportionality between C_T and the speed. Therefore C_T was graphed for C_p= *3*, *4*, *5*, *6* and *7* for all the chosen C_v/C_T - fractions. This way, an adequate basis for finding the speed dependency of C_T was obtained.

The next step was to calculate approximated expressions for C_T on the form

$$C_T = a \cdot U^e + c \tag{8.14}$$

The value of e gives the speed dependency of C_T in the relevant speed area. The slope s of the actual curve was estimated by;

$$s = \frac{C_{Tmax} - C_{Tmin}}{U_{max} - U_{min}} \tag{8.15}$$

e is the unknown exponent. C_{Tmax} and C_{Tmin} are the calculated values of C_T at a typical realistic trial speed (*16.4 knots*) and minimum realistic trial speed (*9 knots*).

The estimated expressions for C_T were found using the equation;

$$C_T = s \cdot (U - U_{min})^e + C_{Tmin} \tag{8.16}$$

U is the speed variable from *9 16.4 knots*.

The anticipated expressions of C_T (equation (8.16)) were graphed together with the empirical values of C_T (equation (8.7)). In order to find the "best fit" between the two graphs, various values for the exponent e were attempted. The most suitable value of e gave very satisfying

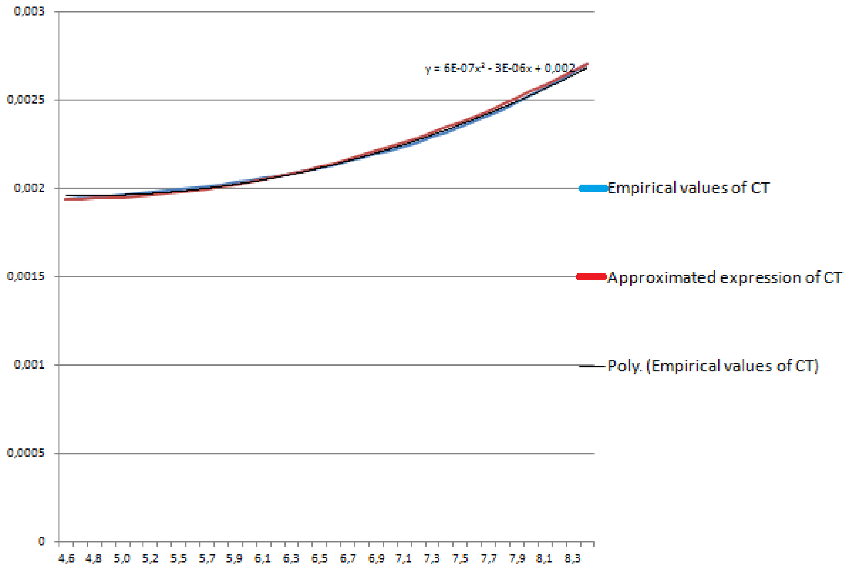

Figure 8.3: Graphical representation of estimated - and empirical values of C_T. *x-axis*: U, *y-axis*: C_T

results with typical deviations of only *0 - 3%*. An example of a graphical representation is shown in Figure 8.3;

The estimated C_T was found to be proportional to the speed of the *first, second* or *third* power.

Hence, the power (equation (8.3)) is proportional to the speed of the *fourth, fifth* or *sixth* power, and the EEDI (equation (8.2)) is proportional to the speed of the *third, fourth* or *fifth* power. Reducing U_{max} (speed at maximum draught and *75 %* of MCR) by installing less propulsion power is therefore an easy way to comply with the EEDI requirements.

In order to prevent shipping companies from installing critically low power attempting to satisfy the EEDI, there will be guidelines for minimum allowed power. These rules are predicted to be ready by March 2012 (Tonnesen; 2012). Low installed power will at a certain point cause difficulties navigating in poor weather, which jeopardizes the vessel's safety.

8.9 Reducing the deadweight

For most ship types, the capacity term in the EEDI denominator is deadweight. A designer can by reducing the lightweight (the actual weight of the ship with no fuel, passenger etc.), increase the deadweight without increasing the displacement. This way, the only term affected in the EEDI equation is the capacity, and the EEDI will consequently be reduced. It is far less effective to increase the deadweight than to reduce design speed when meeting EEDI requirements. This is because the deadweight is inversely proportional to the EEDI, whereas the speed is proportional to the EEDI to a higher power. Additionally, today's fleet has small structural margins, which implies that it will be challenging to minimize the lightweight and still meet the class requirements (Krueger; 2011).

8.10 Challenges regarding speed trials

The classification companies will face a number of challenges regarding the full scale sea trial, some similar to those ship owners and yards have been facing when confirming the contractual speed. First and foremost it may be a challenge to obtain maximum draught at the speed trials, primarily for car carriers, dry cargo ships and container vessels. Maximum draught normally corresponds to a load condition of one hundred percent fuel and cargo. For most tankers, maximum draught is easily obtained loading most ballast tanks and cargo tanks with ballast water (ballast water is used instead of cargo, as the appropriate cargo rarely is readily accessible at the shipyard location). This is not feasible for car carriers, dry cargo vessels and container ships, as their cargo holds usually are not suited to hold ballast water. The consequence is a sea trial draught deviating greatly from maximum draught. Some car carriers and dry cargo - and container vessels have so called emergency ballast tanks that may be applied to obtain a somewhat larger draught. Nevertheless, even with all ballast tanks as well as emergency tanks in use, these vessels will not be able to reach maximum draught at sea trials.

It is at present a common procedure that the shipping companies buy fuel after delivery of the vessel, and sea trials are therefore carried out without full bunker tanks. An approach to increase the draught slightly, would be to have the shipping companies buying and filling fuel in advance of the sea trial (Reinertsen; 2011).

Currently, DNV has planned to solve draught deviations by making reference to model tests performed at the draught expected during sea trial as well as the contractually specified draught (please see section 3.2.5.2 for a thorough explanation of the method). The approach described is recommended by ISO (2002) and the Bose (2005); however both standards emphasize that the procedure is somewhat inaccurate, especially for large draught deviations. It should for that reason be avoided if possible. A challenge in relation to this procedure is following (primarily relevant for car carriers, dry cargo vessels and container ships): Model tests are at all times conducted before both the detail design and the sea trial. During the detail design, there may be alteration concerning the light ship weight and the design of the ballast tanks. Such modifications will affect the draught that the ship maximally will be capable of obtaining during the sea trial. Due to this, it is intricate to predict the realistic full scale maximum draught at the stage of the model test. It is essential that expected maximum draught (used at the model test) does not deviate greatly from the actual maximum draught (obtained at the full scale trials), as this will cause highly inaccurate results. A resolution to the problem is to run model tests at various draughts and adopt interpolation. This way one would have is information for a wide range of draughts available.

If one applies the procedure described when correcting for displacement deviations, it is essential that the model tests and the sea trial are conducted at similar trim; otherwise the correlation found is not applicable. It is difficult to predict the vessels trim in advance of the actual sea trial, and even small trim deviations can affect the speed greatly. The speed is generally more sensitive to trim deviations than to displacement discrepancies (Steen; 2011).

According to Reinertsen, one can solve this conducting model tests at various trim angles at a fixed draught and graphically present the results, adopting interpolation. This procedure needs to be repeated for various displacements, as also the draught is intricate to predict. Model tests were in the past usually run at one selected stern trim in ballast condition and on even keel in loaded condition (design draught), and it was in practice rare to conduct model tests at a series of different trim angles. Today, many ship yards conduct model tests at various trim angles for each draught, as there is more focus on optimal trim. The additional measurements, including various draughts and trim angles, increase the model test costs with about *10,000* to *15,000 USD*.

Referring to Steen (2011), it is satisfactory to conduct model tests at only two draughts and three different trim angles for each draught. He claims that this procedure gives a solid framework for interpolation and provides significantly more accurate results than when conducting model tests at only one trim angle. As this procedure requires only six different model tests runs, it costs considerably less than *10,000* to *15,000 USD*, the prize suggested by Reinertsen. Steen therefore believes this should be implemented as a minimum standard for all model tests associated with large trim deviations.

8.11 Additional challenges

The fact that the required EEDI values can easily be obtained by reducing the design speed has been criticized. Koren (2012) states; "...INTERTANKO believes that compliance should be achieved through other means (than reducing the speed). Our position is that compliance should focus on improved hull design, propulsion efficiency and energy optimization, rather than predominantly on reduced speeds." Similar criticism reads; "...this (EEDI) might also shift the focus on action from designing the best possible hull forms, engines and propellers, to just reducing service speed at the design level. With the current formulations any bad or totally inefficient design can be made acceptable with an easy way out: a rather small reduction in design speed (and power)" (IMO; 2010). A counter-argument is that it is more profitable for the shipping companies to make design improvements rather than to reduce design speed in a long term perspective. Transport of goods is their source of income, and reduced speed will delay transit and their transport ability. Again according to IMO (2010), enhancement is a simple matter; "...some simple "low tech" real design and hydrodynamic improvements can immediately be applied by any design office or ship yard resulting in serious reductions of the hydrodynamic resistance of the ship and propeller efficiency. As one example one can rethink very full bows featured in current bulk carriers."

China, Brazil, Saudi Arabia and South Africa have secured a six and a half years delay implementing the EEDI. This has raised concern as ship owners can avoid the EEDI, choosing to have their ships flagged in developing countries (Vidal; 2011).

At present, the EEDI is not applicable to all ship types such as passenger ships, ro-ro passenger ships and ro-ro cargo ships. It is not appropriate for turbine propulsion, hybrid or diesel electric engines, and does not yet include vessels below *400 gross tons*.

Chapter 9

Conclusion

Based on the standards (ISO (2002), Perdon (2002), Bose (2005) and B. Henk (2006)), it is evident that performing measurements during speed trials and correcting for environmental added resistance contributions, are complex matters with certain scientific shortcomings. Consequently, there is a wide range of correction procedures suggested in the literature and several contradictory recommendations in the standards.

Corrections for resistance due to wind and waves seem to be most essential for the end result (with the exception of large discrepancies between the trim/draught obtained at speed trial and that contractually stipulated. This is however not relevant for tankers which are able to obtain design trim and draught at speed trials). B. Henk (2006) writes; "these corrections (small displacement deviations, shallow water and salinity deviations) are relatively small compared to wind and wave corrections". Perdon (2002) supports this statement: "corrections should concentrate on essential environmental conditions such as wind, wave and shallow water". As Hyundai at all times conduct the speed trial in areas of sufficient water depths, the wave - and wind resistance remain as most vital. Based on the resistance calculations performed by Hyundai, the wind - and wave resistance are on a general basis of equal importance.

ISO (2002), Bose (2005) and B. Henk (2006) all provide the same equation for correction of wind resistance. B. Henk (2006) emphasizes that the location of the anemometer[1] has great impact on the computed wind resistance. The altitude of the anemometer should equal the reference height for the wind resistance table adopted. B. Henk (2006) provides a formula for correction of improper placements of the anemometer (equation (7.1)). Hyundai makes no corrections of this kind. In this thesis, the added wind resistance for KGJS's vessel S380 was calculated adopting equation (7.1). The reference height for the wind table and the altitude of the anemometer were assumed to be *31.5 meters* and *10 meters*, respectively. The computed wind resistance was reduced by 28 %. This is relevant as the wind resistance normally is a key resistance contribution.

Bose (2005) refers to ISO (2002) regarding correction procedures for waves. B. Henk (2006), criticizes previously published methods for calculation of wave resistance, claiming these are inaccurate. In B. Henk (2006), a newly developed method for estimation of mean wave loads

[1] An anemometer is a device for measuring wind speed

is suggested (this has not been evaluated mathematically in this report).

Two formulas developed by Faltinsen (equation (6.1) and (6.9)), two versions of the Fujii and Takahashi's method (equation (6.24) and (4.5)) and Kreitner's formula (equation (3.17)) were adopted for calculation of added wave resistance (due to diffraction) for the 1^{st} speed trial run of ship S155. The results obtained were respectively *81 -, 77 -, 72 -, 58* - and *102 kN*. With exception of Kreitner's method (which is considered to have less scientific credibility than the other formulas), the results correspond fairly well with one another.

Hyundai adopts Fujii and Takahashi's method for calculation of added wave resistance due to diffraction (equation (4.5)). The added wave resistance found by Hyundai for the 1^{st} speed trial run of ship S155 was *21 kN*. The result achieved applying the exact same formula in this report was more than twice as large (*58 kN*). The reason for this large discrepancy is unclear. The value obtained by Hyundai is substantially smaller than all the results obtained in this report. As there is relatively good agreement between the results found here, there is reason for questioning Hyundai's procedures. Continued, the mean wave load was calculated by the use of equation (6.9) for the runs of vessel 1405 and 1374. Once again the results obtained in this thesis were significantly larger than those found by Hyundai (about five times larger). These findings disprove Reinertsen suspicions of Hyundai's added resistance calculations being unrealistically high.

Hyundai's procedure Hyundai neglects all resistance contributions, except the added wave - and wind resistance. This is consistent with the recommendations of Perdon (2002) and B. Henk (2006). A concern is that the currents in the speed trial area in Mokpo usually are strong (Harsem; 2012). As currents tend to change speed and direction within short time periods, it may be detrimental to assume that the current is compensated for by simply conducting the speed trial runs in opposite directions. To increase the precision of the computed contractual speed, it may be sensible to determine the current speed and direction based on prognostic analysis for the area (Bose; 2005); alternatively by the use a current gauge buoy (ISO; 2002).

There a several discrepancies between Hyundai's procedures and those outlined in the standards. The two most relevant are;

- The shipyard does not have the speed trials conducted in head - or following waves, nor head - or following wind. B. Henk (2006) and Bose (2005) underline the importance of executing the speed trials in head - or following waves. Perdon (2002) argues; "in the case when the waves do not come from the bow or the stern the correction methods are not sufficiently reliable and the effects of steering and drift on the ship's performance may be underestimated". ISO (2002) recommends performing the trials in head and following wind (note that there usually is a correlation between true wind - and wave direction).
- The Hyundai shipyard assumes that the wave direction with respect to the ship's centerline equals the relative wind angle. This conflicts with the recommendations of the standards. They advise to obtain the wave direction by visual observations or instruments such as buoys or sea wave analysis radars. Furthermore, Hyundai's assumption is highly illogical from a scientific standpoint.

Recommendations to KGJS

- In future contracts it may be useful to implement a requirement that the speed trials are to be conducted in head - and following waves. This will increase the reliability of the computed added resistance (Bose; 2005). Furthermore, it will simplify the calculation of mean wave loads considerably. This way, KGJS will be able to verify Hyundai's calculations, relatively effortless (given that the line drawings are available).
- It should be identified how Hyundai determine the period. The period seems to be unrealistically low for certain speed trials (based on the statistical correlation between T_2 and $H_{\frac{1}{3}}$ given by Hogben (1986)). A lower period results in a larger added wave resistance due to diffraction.
- The contract should specify how the incoming wave angle is to be determined, as Hyundai's procedure for obtaining the wave angle is doubtful.
- KGJS ought to introduce a requirement in the contract demanding the speed trials to be carried out during the day. This will improve the visibility, hence the precision of the visually determined significant wave height. $H_{\frac{1}{3}}$ is included in all equations for added wave resistance, thus influences the value of the mean wave loads.

Bibliography

ABS (2012). *Energy Efficiency for Ships, Improving Efficiency by Design*, www.eagle.org. Online, accessed 05.10.2011.

B. Henk, Ivo van der Hout, M. F. (2006). Speed-power performance of ships during trials and service, *MARIN* .

Bierbooms, W. (2012). *WIND AND WAVE CONDITIONS*, www.ecn.nl/fileadmin/ecn/units/wind/docs/dowec/10047002.pdf. Online, accessed 20.03.2012.

Blendermann, W. (1986). *DIE WINDKRAFTE AM SCHIFF*.

Bose, N. (ed.) (2005). *ITTC-Recommended Procedures and Guidelines*, ITTC.

DNV (2011). www.dnv.ae/press_area/press_releases/2011/dnvissuedeediverificationforasuper-largetanke Online, accessed 20.09.2011.

DNV (2012). *EEDI - IMO Energy Efficiency Design Index*, www.dnv.ae/Binaries/1010-046%20flyer%20EEDI_tcm150-455598.PDF. Online, accessed 05.08.2011.

documentation, H. (2007). *HISTAP HYUNDAI INTEGRATED SPEED TRIAL ANALYSIS PROGRAM*. HYUNDAI HEAVY INDUSTRIES CO.,LTD.

EPA (2011). United States Environmental Protection Agency, *Adoption of an Energy Efficiency Design Index for International Shipping*, www.epa.gov/otaq/regs/nonroad/marine/ci/420f11025.pdf. Online, accessed 20.11.2011.

Eyres, D. J. (2007). *SHIP CONSTRUCTION*.

Faltinsen, O. (1990). *Sea Loads on Ships and Offshore Structures*, Cambridge University Press.

Faltinsen, O. M. and Kjaerland, O. (1979). *HYDRODYNAMIC ANALYSIS OF TANKERS AT SINGLE-POINT MOORING SYSTEM*, Norwegian Institute of Technology, Norway.

Faltinsen, O. M. and Minsaas, K. J. (1980). *Prediction of Resistance and Propulsion of a Ship in a Seaway*. Norway.

Foreship (2009). *SOME IMPORTANT NAVAL ARCHITECTURAL TERMS*, www.foreship.com/documents/fs-naterms.pdf. Online, accessed 12.11.2011.

Fujii, H. and Takahashi (1975). *Experimental Study on the Resistance Increase of a Large Full Ship in Regular Oblique Waves*.

Greco, M. (2011). NTNU, professor, marine hydrodynamics. In person meeting.

Harsem, L. (2012). KGJS, site manager new buildings. In person meeting.

Haugan, H. (2011). In person meeting.

Havelock, T. H. (1940). *The Pressure of Water Waves upon a Fixed Obstacle*. P. R. S. Series A.

Hogben, N. (1986). *GLOBAL WAVE STATISTISCS*, British Marine Technology Limited.

Hon, G. and Wang, H. (2011). *The Energy Efficiency Design Index (EEDI) for New Ships*, www.theicct.org/eedi-new-ships. Online, accessed 11.10.2011.

Hyundai Heavy Industries Co., L. (2002). *HYUNDAI STANDARD SPEED TRIAL ANALYSIS METHOD*, *Technical report*, Hyundai Maritime Research Institute.

Hyundai specification (2006). *SPECIFICATION FOR 120,000 DWT CLASS PRODUCT CARRIER*. HYUNDAI SAMHO HEAVY INDUSTRIES CO., LTD.

IMO (2010). *FURTHER IMPROVEMENT OF THE DRAFT TEXT FOR MANDATORY REQUIREMENTS OF EEDI AND SEEMP*, www.martrans.org/documents/2009/sft/EE-WG%201-2-7.pdf. Online, accessed 07.08.2011.

IMO, I. M. O. (2009a). *INTERIM GUIDELINES FOR VOLUNTARY VERIFICATION OF THE ENERGY EFFICIENCY DESIGN INDEX*, *Technical report*, IMO.

IMO, I. M. O. (2009b). *INTERIM GUIDELINES ON THE METHOD OF CALCULATION OF THE ENERGY EFFICIENCY DESIGN INDEX FOR NEW SHIPS*, *Technical report*, IMO.

ISO (2002). *ISO 15016*, *Technical report*, International Organization for Standardization.

Johansson, P. (2012). *Site Manager New Buildings, Wallenius Marine Site Office*. In person meeting.

Kartverket (2012). *Currents*, vannstand.no/index.php/nb/english-articles/currents. Online, accessed 01.05.2012.

KGJS (2012). www.kgjs.no. Online, accessed 14.03.2011.

Koren, J. (2012). *Intertanko and the EEDI: seeking a level playing field*, *Technical report*, Intertanko.

Krueger, S. (2011). *Mathematical Evaluation of the Applicability of the EEDI- Concept for RoRo- vessels*, www.c4tx.org/ctx/pub/krueger_roro.pdf. Online, accessed 05.09.2011.

Lee, T.-H. (2012). *Deputy General Manager/Professional Engineer*. In person meeting.

Majchrzak, W. (2012). *Master, KGJS*. In person meeting.

Masashi Kashiwagi, T. I. and Sasakawa, T. (2010). *Effects of Forward Speed of a Ship on Added Resistance in Waves*, www.isope.org/publications/journals/ijope-20-3/abst-20-3-p196-jc506-Kashiwagi.pdf. Online, accessed 06.05.2012.

Michel, W. (1999). ultramarine.com/hdesk/document/papers/sea_spectra_revisited.pdf.

Myrhaug, D. (2007). *TMR4180 MARIN DYNAMIKK, Uregelmessig sj*, publisher.

Papazoglou, J. (2012). Superintendent. In-person meeting.

Perdon, P. (ed.) (2002). *The Specialist Committee on Speed and Powering Trials*, The 23rd ITTC.

Reinertsen, W. (2011). *KGJS, Assistant Vice President in the Technology Support Department*. In person meeting.

Rottmann, K. (2006). *MATEMATISK FORMELSAMLING*, Spektrum forlag.

Sakamoto, T. and Baba, E. (1986). *Minimization of Resistance of Slowly Moving Full Hull Forms in Short Waves*. Nagasaki Technical Institute, Mitsubishi Heavy Industries, Ltd., Japan.

Shipbuilding Contract (2006). Between SKS OBO Holding Limited and Hyundai Samho Heavy Industries Operations Co.LTD.

Skejic, R. (2012). In-person meeting.

Steen, S. (2007). *Motstand og Propulsjon Propell- og foilteori*, Institutt for Marin Teknikk.

Steen, S. (2011). In person meeting.

Tonnesen, A. (2012). *Consultant at Det Norske Veritas*. In-person meeting.

Vidal, J. (2011). Maritime countries agree first ever shipping emissions regulation, www.guardian.co.uk/environment/2011/jul/18/maritime-countries-shipping-emissions. Online, accessed 25.10.2011.

Wikipedia (2012a). en.wikipedia.org/wiki/Beaufort_scale. Online, accessed 03.04.2012.

Wikipedia (2012b). en.wikipedia.org/wiki/Specific_weight. Online, accessed 26.05.2012.

Wikipedia (2012c). en.wikipedia.org/wiki/Power_take-off. Online, accessed 15.03.2012.

Wikipedia (2012d). en.wikipedia.org/wiki/Horsepower. Online, accessed 15.05.2012.

Wikipedia (2012e). *Tide*, en.wikipedia.org/wiki/Tide. Online, accessed 01.05.2012.

Wikipedia (2012f). *Trapezoidal rule*, en.wikipedia.org/wiki/Trapezoidal_rule. Online, accessed 05.05.2012.

Zakaria, N. M. G. and Baree, M. S. (2007). *ALTERNATIVE METHODS ON ADDED RESISTANCE OF SHIPS IN REGULAR HEAD WAVES*, dspace.unimap.edu.my/dspace/bitstream/123456789/13668/1/015-022_Alternatice%20Methods%20