NTNU – Trondheim
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Calculation of Service and Sea Margins

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Marine Technology

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MASTER THESIS
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MASTER THESIS IN MARINE TECHNOLOGY

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FOR

Egill Eide

Calculation of service and sea margins

The speed-power performance of ships is usually predicted for an idealized trial condition, with a clean hull and negligible waves and wind. When the ship is in normal operation, with some hull fouling as well as waves and wind, the power required to reach a certain speed is higher than the speed originally predicted and measured on the delivery sea trial. This increase is usually expressed as a sea margin, which is normally added to the power. A typical value for the sea margin is usually in the range 15-20%. The value of the sea margin is set according to tradition and some practical experience, but it is not normally based on proper calculations utilizing knowledge about the actual ship, her condition, and her operational profile. There might be other margins defined as well, and names might vary, like service margin, engine operational margin and light running margin. ITTC has a recommended procedure describing some of this. The service margin typically takes into account the added power due to fouling.

There is clearly a need to clarify the current practice with respect to use of these margins, and especially in light of increasing use of slow steaming and variable service speeds there is a need for developing simple speed dependence of the various margins. The formulation of the margins should maybe also take the actual draught (or displacement) into account.

Analysis of noon reports from ships operated by Kristian Gerhard Jebsen Skipsrederi (KGJS) indicate that the service margin decreases linearly with increasing speed. This seems to be contradictory to conventional theory, given that the main cause of the service margin is hull fouling.

The overall objective for the combined project and master thesis is therefore to develop improved formulations and methods to determine the most significant operational margins (sea margin and service margin) for conventional merchant vessels. Special emphasis shall be on understanding how the service margin (margin for hull and propeller roughness and fouling) depends on speed.

For the master thesis, the candidate shall:

- Give a thorough review of operational margins, based both on literature and on information from towing tank(s) and ship owner(s). The review should discuss different types of margins and how they are decided.
- Give a thorough review of available methods to compute sea margin (like methods to compute added resistance and speed loss due to waves, and how such methods can be used to compute the sea margin), and service margin, which means a survey on methods to account for hull and propeller fouling.
- Discuss the different operational margins in use and mentioned in the literature, and on that basis make clear definitions of margins used in own work with the master thesis.
- Make case studies of two representative merchant vessels to be provided by KGJS. One of these was preliminary analyzed in the project thesis. Compute the service margin and sea margin for

different speeds (including typical slow steaming speed) and routes based on the noon reports from KGJS, and compare with calculations based on current methods for predicting such margins.

- Propose alternative formulations for calculation of sea margin and service margin. Discuss the speed dependency of the margins. Try to identify the causes of the decrease of service margin with speed observed from noon reports.

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

The thesis work shall be based on the current state of knowledge in the field of study. The current state of knowledge shall be established through a thorough literature study, the results of this study shall be written into the thesis. 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 electronically (pdf) in DAIM:
- Signed by the candidate
- The text defining the scope (signed by the supervisor) included
- Computer code, input files, videos and other electronic appendages can be uploaded in a zip-file in DAIM. Any electronic appendages shall be listed in the main thesis.

The candidate will receive a printed copy of the thesis.

Supervisor : Professor Sverre Steen
Advisor : Willy Reinertsen (KGJS)
Start : 15.01.2015
Deadline : 09.06.2015

Trondheim, 23.01.2015

Sverre Steen
Supervisor

Preface

This is a master thesis written at NTNU. It was written during the spring semester of 2015. A project thesis was written during the autumn semester of 2014 on the same topic, but on a smaller scale. The project and master thesis was suggested by Willy Arne Reinertsen at Kristian Gerhard Jebsen Skipsrederi AS (KGJS).

Thanks to Professor Sverre Steen at NTNU for guidence and to Willy Arne Reinertsen for the trips I had visiting KGJS in Bergen and for help and providing material for the ships investigated.

Trondheim, 2015

Egill Eide

Summary

In this thesis two tankers owned by Kristian Gerhard Jebsen Skipsrederi (KGJS) were investigated. A method of calculating service and sea margins for different speeds has been developed. When a ship is in normal operation, the additional power required to reach a certain speed will be higher than the predicted and measured on the delivery sea trial. This increase due to wind, waves and fouling is usually expressed as a sea margin. Typical values are 15-20% of the power required in ideal conditions.

The model in this thesis used noon reports provided by KGJS for the two ships. These are daily reports of fuel consumption, speed and weather conditions. For each report the added power due to waves, wind and roughness were calculated. The change in propeller efficiency due to the added resistance was calculated and the calm water power requirement was corrected for changes in draft. The calm water speed-power relation for the ships did not cover the whole speed range typical for the ships. Therefore the relation was extrapolated to also cover the lower speeds.

The results indicate that the total sea margin and the wave part of the margin both decrease with speed. The wind part of the sea margin seems to be negligible on average. The fouling part of the margin was modeled as roughness according to theory. This results in a constant fouling margin independent of speed of 15-20%. This was an underestimation for the lower speeds, which could indicate that the calm water speed-power relationship was underestimated for the lower speeds where model test data was not available and the relationship was estimated.

Approximate formulas were developed for calculating the different margins. The total sea margin and the wave margin are inversely proportional to the ship speed. The wind margin seems to be negligible.

Sammendrag

I denne oppgaven ble to tankskip eid av Kristian Gerhard Jebsen Skipsrederi (KGJS) undersøkt. En metode for beregning service- og sjømarginer for ulike hastigheter har blitt utviklet. Når et skip er i normal drift vil effektbehoved være høyere enn det som er estimert i modelltest og sjøtest. Denne økningen i effekt på grunn av vind, bølger og begroing er vanligvis uttrykt som en sjømargin. Typiske verdier er 15-20 % av effekten som kreves under ideelle forhold.

Modellen i denne oppgaven brukte rapporter fra KGJS for de to skipene. Dette er daglige rapporter om drivstofforbruk, hastighet og værforhold. For hver rapport ble tillegget i effekt på grunn av bølger, ble vind og ruhet beregnet. Endringen i propellens effektivitet på grunn av den ekstra motstanden ble beregnet og effektbehov for stillevann ble korrigert for endringer i dypgang. Effektbehovet for forskjellige hastigheter beregnet ved modelltest dekket ikke alle hastighetene som skipene seiler. Relasjonen effekt-hastighet ble derfor ekstrapolert for å dekke disse hastighetene.

Resultatene indikerer at den totale sjømarginen og bølgedelen av marginen begge synker med økende hastighet. Vinddelen av marginen synes å være neglisjerbar. Den delen av marginen som er på grunn av begroing ble modellert som ruhet i henhold til teorien. Dette resulterer i en konstant begroingsmargin uavhengig av hastighet på 15-20 %. Dette var en undervurdering for de lavere hastighetene, noe som kan indikere at det ekstrapolerte effekt-hastighetsforholdet ble undervurdert for lavere hastigheter der modelltest data ikke var tilgjengelig.

Formler ble utviklet for å beregne de forskjellige marginene. Den totale sjømarginen og bølgemarginen er omvendt proporsjonale med skipets hastighet. Vindmarginen synes å være neglisjerbar.

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Nomenclature

k_w	Dimensionless service margin coefficient
P_{TS}	Ship service power
P_T	Calm water power
R_{AV}	Long-term prognosis of resistance increase in waves
R_{AW}	Added resistance in waves
t	Thrust reduction coefficient in still water
V_E	Service speed
EEDI	Energy Efficiency Design Index
ITTC	International Towing Tank Conference
VLCC	Very Large Crude Carrier

Chapter 1

Introduction

1.1 Background

When a ship is built by a shipyard, the speed-power relationship is usually predicted for an idealized situation, with a clean hull and no or negligible wind and waves. This is however not very representative for the speed-power relationship for a ship in service, affected by environmental effects such as wind and waves, and aging effects such as fouling on hull and propeller. The additional power required, on top of the power for an ideal situation, to make a certain speed requirement is called sea margin or service margin. Often shipyards will include this as a fixed percent of the power in the speed-power relationship, typically 15 %.

There is a need for developing speed dependence of the various margins, as the are not necessarily well represented by a fixed percentage for all speeds. Analysis of noon reports by Kristian Gerhard Jebsen Skipsrederi (KGJS) indicate that the service margin decreases with speed, this is contradictory to conventional theory, given that the main cause of the service margin is hull fouling.

For shipowners it is important to be able to accurately predict the power requirements, and in turn fuel consumption, so that they can choose the most economic speed.

1.2 Scope

In this thesis two merchant vessels by KGJS will be investigated to develop improved formulations and methods to determine the most significant operational margins for conventional merchant vessels. Special emphasis is on the understanding of how the margins depend on speed.

1.3 Structure

In chapter two the operational margins and available methods to compute them will be reviewed

In chapter 3 a method for calculating the different margins will be developed

In chapter 4 the results will be presented along with alternative formulations for the different margins

Chapter 2

Prediction of Operational Margins

2.1 Definition of Margins

Sea margin is a margin to account for the average environmental condition the ship will encounter, as well as increase of roughness and fouling over time.

The following margins are defined by ITTC (2008):

Calm water powering margin: the power above the tow tank prediction to ensure that a ship meets its calm water speed - power requirement. If proper considerations are made for the selection of model-ship correlation factors to meet the calm water speed requirement, it is not necessary.
Sea margin, also called powering margin: the margin that has to be added to the estimation of speed - power relationship in ideal conditions in order for the ship to meet its speed requirements in other weather conditions. It should take into account effects such as wind and waves, steering effects and air- and water temperature as well as the effects of aging and fouling on the hull and propeller surface.
Engine operation margin: This margin describes the power reserve of the engine(s), with respect to reasonably low fuel and maintenance costs.
Light running margin: This is the margin in propeller revolution considered for a new ship to absorb 100% engine power in future service conditions.

If either no model tests or other reliable performance data are available, the following values can be used to determine the margins:

- Sea margin: 15 to 25 % on the specified MCR power

- Engine Operation Margin: 10 to 15 % on the specified MCR power
- Light Running Margin: 5 to 7 % on the specified MCR power

Arribas (2007) uses sea margin or weather margin to describe the margin due to weather. It is stated that this value is often 15-30 % of the ship calm water power. Fouling is not mentioned. Arribas suggests that ship motions and other parameters should be obtained through numerical calculations or towing tank tests to obtain a more accurate value of the sea margin.

Nabergoj and Prpic-Orsic (2007) claim that the performance evaluation of a ship in a seaway usually does not properly consider the weather conditions on the operating route. The value of the sea margin is usually states at the design stage by the ship owner or ship designer based on tradition or experience of similar ships sailing on the same route. 15-30 % of the ship calm water power is mentioned as a typical value.

Stasiak (2004) is critical of the service margin method and thinks the method slows down improvement in designing more efficient ships. *The need of revising the "service margins" is a consequence of an obvious need for most efficient ships from the technical as well as economic point of view.* According to Stasiak, ship design and research is mainly focused on the ideal part of the problem, the calm water conditions. Although methods exist for calculating added resistance in waves this does not seem to be used in the design process. Stasiak says it may and should be assumed that even modern sea-going ships carry at least a dozen or so per cent reserve of never used main propulsion system horsepower due to this problem. Stasiak thinks the reason for this situation is connected with the ship delivery-acceptance procedures. The shipyard will not benefit from optimizing the ship for the most common operating conditions because the contract requirements are in calm water conditions.

In Molland et al. (2011) it is stated that the margins to account for the increase in power due to roughness, fouling and weather are derived in a scientific manner for the purpose of installing propulsion machinery with an adequate reserve of power. According to other litterature this does normally not seem to be the case. In an example the margin due to roughness and fouling is estimated to be around 10 %.

2.1.1 Definition of margins for this thesis

In this thesis the following definitions of margins will be used:

Sea margin The total added power in service

Wave margin The added power due to waves

Wind margin The added power due to wind

Fouling margin The added power due to fouling on hull and propeller

2.2 Methods of Calculating Margins

Up to the 1960s the service margin method, meaning adding a fixed percentage margin to the power predicted in calm sea to account for weather and fouling, was a justified practical approach (Stasiak, 2004). It was at that time a complex problem that was not sufficiently investigated. Sticking to that method later, as the resistance prediction tools have improved and become more avaliable, has according to Stasiak held back development of ship design.

The simplest way to predict ship service power P_{TS} is using a service margin on the form:

$$P_{TS}(V_E) = (1 + k_w)P_T(V_E) \tag{2.1}$$

where $PT(V_E)$ is the calm water power as a function of the service speed V_E and k_w is the dimensionless service margin coefficient.

2.2.1 Stasiak Method for Calculation of Wave Margin

Stasiak (2004) proposes a method for calculating the wave part of the service margin that consist of a generalization of the long-term prognosis of additional ship resistance from sea waves R_{AV}. Where the wave margin is a function of hull geometry and ship speed. The resistance increase of a ship moving with constant speed was determined as probabilistic estimation of a mean value of a set of random short-term additional resistance R_{AW}:

$$R_{AV} = \Sigma R_{AW}(x)p(x) \tag{2.2}$$

where $p(x)$ is a probabilistic model discrete sailing conditions x. Elements of the x are: ship loading conditions, sailing regions and sea states.

The short term added resistance $R_{AW}(x)$ were determined as:

$$R_{AW}(x) = 2\int_{\omega} r_{aw}(\omega, a)S(\omega, b, c)\mathrm{d}\omega \tag{2.3}$$

$r_{aw}(\omega, a)$ dimensionless resistance increase coefficient determined from ship model tests carried out in regular head waves with different frequencies ω

$S(\omega, b, c)$ wave specter of stationary irregular waves. Assigned to a sea region b and sea state characteristics $c = c(H_{1/3}, T_1)$: significant wave height $H_{1/3}$ and characteristic period T_1

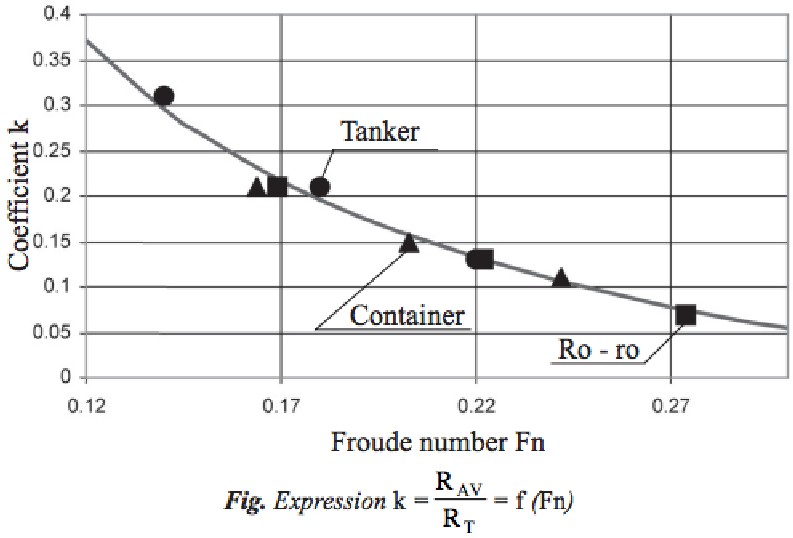


Figure 2.1: Dimensionless wave margin coefficient **k** as a function of Froude number for a tanker, container and a ro-ro ship from calculations by Stasiak (2004). Figure from Stasiak (2004).

Based on these formulations a universal function for the wave margin k for the ships investigated in the paper (a tanker, a container carrier and a ro-ro ship) was proposed:

$$k = \frac{R_{AV}}{R_T} = \frac{0.0635}{Fn} - 0.157 \tag{2.4}$$

2.2.2 ITTC Method for Calculation of Sea Margin

In ITTC (2008),the following procedure is recommended for calculating sea margin. The effect of thrust and torque from change of propeller submergence in waves is taken into account in addition to the added resistance in waves.

Thrust K_T and torque K_Q coefficients are corrected for reduction in propeller submergence due to waves and ship motions. The average propeller thrust in a regular wave can be expressed as

$$K_T^* = \frac{R_{T0} + R_{AW}}{\rho n^2 D^4 (1-t)} \equiv constant \cdot J_0^2 \tag{2.5}$$

where R_0 is the still water resistance, R_{AW} is the added resistance in waves and t is the thrust deduction coefficient in still water..The wind resistance and increase in resistance due to increase in roughness and fouling should also be included, so the total added resistance is considered.

Relative increase in propulsion power in a regular wave can be expressed as:

$$\frac{P_{DS}}{P_{DSC}} = \frac{K_Q}{K_{QC}}(\frac{J_{0C}}{J_0})^3 = \frac{K_Q}{K_{QC}}(1-w)^3 \tag{2.6}$$

where subscript C is used for the calm water values.

Calculating the sea margin

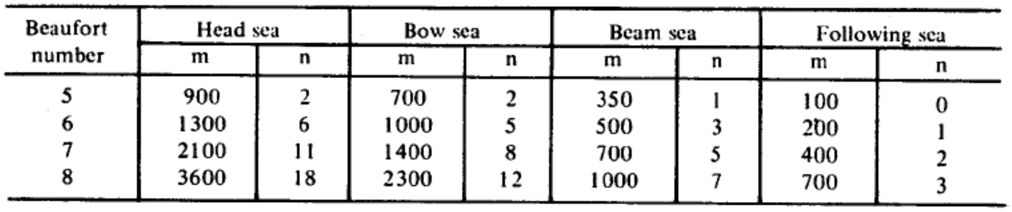
It is assumed that the waves are consistent with a narrow banded process and that they are long-crested. The average power increase in a given sea state can be expressed as:

$$\frac{P_{DS}}{P_{DSC}} = \int_0^{\infty} \mathrm{d}\zeta \int_{-\infty}^{\infty} \mathrm{d}\omega f(\zeta,\omega) \frac{K_Q}{K_{QC}}(1-w)^3 \tag{2.7}$$

The average long term value of the power increase can be found as

$$PM = \left(\sum_i \sum_j \sum_k p(H_{1/3}^{(i)}, T_P^{(j)}, \alpha^{(k)}) \cdot \int_0^{\infty} \int_{-\infty}^{\infty} f(\zeta,\omega) \frac{K_Q}{K_{QC}}(1-w)^3 \mathrm{d}\omega \mathrm{d}\zeta - 1 \right) \cdot 100\% \tag{2.8}$$

where $p(H_{1/3}^{(i)}, T_P^{(j)}, \alpha^{(k)})$ is the probability that a certain sea state occurs, with mean significant wave height $H_{1/3}$, mean peak period T_P and wave direction α. $p(H_{1/3}^{(i)}, T_P^{(j)}$ can be found in wave atlases (without the effect of α).



Beaufort number	Head sea		Bow sea		Beam sea		Following sea	
	m	n	m	n	m	n	m	n
5	900	2	700	2	350	1	100	0
6	1300	6	1000	5	500	3	200	1
7	2100	11	1400	8	700	5	400	2
8	3600	18	2300	12	1000	7	700	3

Figure 2.2: Aertssen values for m and m. Head seas range from 30 degrees starboard to 30 degrees port, bow seas range from 30 degrees starboard/port to 60 degrees starboard/port. Figure from Aertssen (1969)

2.3 Calculation of Speed Loss

Another way of thinking about the effects of weather on a ship is speed loss. While the wave and wind margin discussed are the additional power required to maintain speed in weather conditions, speed loss is the speed lost for a given power.

Aertssen (1969) formula:

$$\frac{\Delta V}{V} \cdot 100\% = \frac{m}{L_{pp}} + n \tag{2.9}$$

where L_{pp} is the ship length between perpendiculars and m and n are coefficients depending upon heading and severity of the sea (Beaufort number). The formula does not account for ship type, condition or fullness. The formula was made as an attempt to establish a weather allowance (margin) for merchant ships from information obtained at sea. It assumes relatively high speed of 16-18 knots, slow ships being ignored.

Approximate formulas for the speed loss in bad weather was developed by Townsin and Kwon (1983). The weather was described simply in terms of Beaufort scale. Kwon (2008) updated the formula:

$$\alpha \cdot \mu \cdot \frac{\Delta V}{V} \cdot 100\% \tag{2.10}$$

where

ΔV speed loss due to head weather

V design service speed

α is the correction factor for block coefficient (C_B and Froude number (F_n)

μ is the weather direction reduction factor

The head weather percentage loss for $C_B = 0.75, 0.80$ and 0.85, vessel in loaded condition (all

Table 2.1: The Beaufort scale (Pettersen, 2007) Pettersen (2007)

Beaufort number	Description	Wind speed [m/s]	Wave height [m]
0	Calm	0-0.2	0
1	Light air	0.3-1.5	0-0.2
2	Light breeze	1.6-3.3	0.2-0.5
3	Gentle breeze	3.4-5.4	0.5-1
4	Moderate breeze	5.5-7.9	1-2
5	Fresh breeze	8.0-10.7	2-3
6	Strong breeze	10.8-13.8	3-4
7	Moderate gale	13.9-17.1	4-5.5
8	Fresh gale	17.2-20.7	5.5-7.5
9	Strong gale	20.8-24.4	7-10
10	Whole gale	24.5-28.4	9-12.5
11	Storm	28.5-32.6	11.5-16
12	Hurricane	32.7-	>14

ships except container ships):

$$\frac{\Delta V}{V} \cdot 100\% = 0.5BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}} \tag{2.11}$$

For $C_B = 0.75, 0.80$ and 0.85, vessel in ballast condition (all ships exept container ships):

$$\frac{\Delta V}{V} \cdot 100\% = 0.7BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}} \tag{2.12}$$

For $C_B = 0.55, 0.60, 0.65$ and 0.70, vessel in normal condition (container ships):

$$\frac{\Delta V}{V} \cdot 100\% = 0.7BN + \frac{BN^{6.5}}{22\nabla^{2/3}} \tag{2.13}$$

The head weather formulas are derived for container ships in their normal service condition and for tankers in loaded and ballast condition. Kwon (2008) assumes formulas derived from tankers are applicable for *all ships except container ships.* He also says the formulas are unlikely to be accurate for Beaufort numbers above 6.

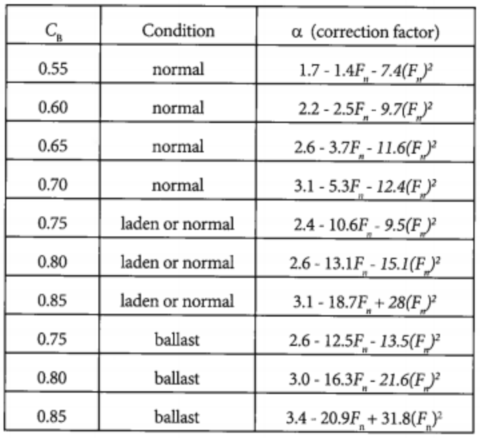
Molland et al. (2011) compares the Aertssen and Townsin-Kwon formulas for a container ship with a length of 220 m, $C_B = 0.60, \nabla = 36,500 m^3 and Fr = 0.233$.

If we assume the ship resistance varies as V^2 then we can approximate the speed loss from the change in resistance ΔR as:

$$\frac{\Delta V}{V} = \left[1 + \frac{\Delta R}{R}\right]^{1/2} - 1 \tag{2.14}$$

Table 2.2: Comparison of Aertssen and Townsin-Kwon formulae. From Molland et al. (2011).

Beaufort number BN	Aertssen $\frac{\Delta V}{V}$ (%)	Townsin-Kwon $\frac{\Delta V}{V}$ (%)
5	6.1	5.4
6	11.9	9.7
7	20.5	19.4
8	34.4	39.5



C_B	Condition	α (correction factor)
0.55	normal	$1.7 - 1.4F_n - 7.4(F_n)^2$
0.60	normal	$2.2 - 2.5F_n - 9.7(F_n)^2$
0.65	normal	$2.6 - 3.7F_n - 11.6(F_n)^2$
0.70	normal	$3.1 - 5.3F_n - 12.4(F_n)^2$
0.75	laden or normal	$2.4 - 10.6F_n - 9.5(F_n)^2$
0.80	laden or normal	$2.6 - 13.1F_n - 15.1(F_n)^2$
0.85	laden or normal	$3.1 - 18.7F_n + 28(F_n)^2$
0.75	ballast	$2.6 - 12.5F_n - 13.5(F_n)^2$
0.80	ballast	$3.0 - 16.3F_n - 21.6(F_n)^2$
0.85	ballast	$3.4 - 20.9F_n + 31.8(F_n)^2$

Figure 2.3: Values for correction factor α. Figure from Kwon (2008)

Where V is the calm water speed and R is the calm water resistance. If the same approach is used the speed loss may be converted to power increase under the assumption that P varies as V^3:

$$\frac{\Delta P}{P} = \frac{1}{\left(1 - \frac{\Delta V}{V_S}\right)^3} - 1 \tag{2.15}$$

2.4 Calculation of Resistance

2.4.1 Added Resistance in Waves

Theoretical added resistance for a ship in regular waves can be derived in two ways. Directly integrating the pressure over the wetted ship surface or by using equations for conservation of momentum and/or energy in the fluid. The wave induced motions and loads are a first order approximation of the problem. The added resistance is then found as the mean longitudinal second order forces Faltinsen et al. (1980).

Direct pressure integration by Faltinsen et al. (1980)

$$\overline{F_1} = \int \_L_1 \overline{F_n} \sin(\theta) \mathrm{d}l \tag{2.16}$$

$$\overline{F_n} = \frac{1}{2}\rho g \zeta^2 \left(\left[\frac{1}{2}\frac{k_1}{k_0} - \frac{1}{2}\cos^2(\theta+\alpha) \right] \frac{1}{2}\frac{k_2}{k_0}\sin(\theta+\alpha) \right) \tag{2.17}$$

$$k_1 = \frac{[\omega_e - V k_0 \cos(\theta+\alpha)]^2}{g} \tag{2.18}$$

$$k_2 = \sqrt{k_1^2 - k_0^2 \cos^2(\theta+\alpha)} \tag{2.19}$$

$\overline{F_n}$ force per unit length normal to the hull

ζ wave amplitude

$theta$ angle between the tangent of the waterline and the fore- and aft axis (x-axis)

α wave direction ($\alpha = 0$ is head sea)

L_1 the part of the waterline that experiences the incoming waves

ω_e circular frequency of encounter

V forward speed of the ship

k_0 wave number

Radiated energy method

Gerritsma and Beukelman (1972) snd W. Beukelman (1972) derived a formula for added resistance in waves. The method is based on strip-theory approximation and shows that

$$R_{AW} = \frac{k}{2\omega_e}\int_L \left(B_{33}^{(2D)} + U\frac{\mathrm{d}}{\mathrm{d}x}A_{33}^{(2D)}\right) V_{za}^2(x)\mathrm{d}x \tag{2.20}$$

The integration is along the length of the ship and V_{za} is the amplitude of the relative vertical velocity between the ship and the waves. The formula shows that the added resistance depends strongly on the relative vertical motion between the ship and the waves. According to Faltinsen (1990) it is also questionable in the small wavelength range for blunt ship forms.

2.4.2 Wind resistance

Wind and air resistance can be calculated from the following formula (Molland, 2011):

$$R_A = \frac{1}{2}\rho_A C_D A_P V_A^2 \tag{2.21}$$

R_A wind resistance + air resistance

ρ_A air density $1.23 kg/m^3$

C_D drag coefficient for the ship

A_P projected area perpendicular to the relative velocity of the wind to the ship

V_A relative wind velocity

This method of calculating the wind resistance also includes the air resistance. The air drag on the ship when it sails in an area with no wind. However, the air resistance is included in the calm water resistance and should therefore be subtracted from this formula in order to obtain the wind resistance:

$$R_W = R_A - R_{AA} = \frac{1}{2}\rho_A C_D A_P V_A^2 - \frac{1}{2}\rho_A C_{D0} A_{P0} V_S^2 = \frac{1}{2}\rho_A \left(C_D A_P V_A^2 - C_{D0} A_{P0} V_S^2\right) \tag{2.22}$$

R_{AA} air resistance

C_{D0} drag coefficient for the ship in head wind

A_{P0} projected area of the ship as seen from the front

V_S ship speed

2.4.3 Fouling Resistance

Resistance increase due to fouling on the hull and propeller can be significant. Effects of marine fouling cam be responsible for 30 to 40 % increases in fuel consumption (Carlton (2007)). Data from KGJS show that the reduction in fuel consumption after hull and propeller cleaning can be over 30%. The effect of roughness can be considered as an addition to the frictional component of resistance of the hull. Carlton says the the roughness of the hull can be considered to be the sum of permanent roughness and temporary roughness. Where the permanent roughness refers to amount of unevenness in the steel plates and the temporary roughness is that caused by marine fouling. Total increase in roughness (including fouling) leads typically to increases in C_F of about 2%-2% according to Molland et al. (2011).

If fouling can be modeled as an increase in the frictional resistance C_F the power increase due to fouling should be proportional to the ship speed cubed. Data from KGJS show that the increase in resistance due to fouling does not seem to be proportional to the ship speed cubed and that is one of the reasons for this thesis.

Townsin (1985).

$$\Delta C_F = \left\{ 44 \left[\left(\frac{k_S}{L} \right)^{1/3} - 10 Re^{-1/3} \right] + 0.125 \right\} \cdot 10^{-3} \tag{2.23}$$

Chapter 3

Case Study

Two merchant vessels provided by KGJS were analyzed in this thesis. The 159,000 DWT class crude oil carrier SKS Satilla and the 120,000 DWT class product carrier SKS Doda. Model test reports and sea trial reports were provided for both vessels. For SKS Satilla the line drawings and body plan were also provided.

3.1 Ship Properties

Table 3.1: Ship specifications

	SKS Satilla	SKS Doda
Length Overall [m]	274.26	250.00
Length between perpendiculars [m]	264.00	239.00
Breath Moulded [m]	48.00	45.00
Depth Moulded [m]	23.10	21.50
Draught Moulded (design) [m]	16.00	15.20
Deadweight	159,000	120,000

3.2 Calculation method

The calculations were done by writing a scipt in Matlab. The script is attached in the appendix.

Data from noon reports (figure **??**) provided by KGJS in Excel format were imported (figure **??**). The data used in the calculations were main engine consumption in tons per day, GPS speed, draft, wind direction, wind speed and sea state. Log speed, speed through water were provided in the noon reports, but they appeared to be very inaccurate so the GPS speed was used instead. The calculations were done in the following way:

1. Load data from noon reports (excel format)
2. Select drafts close to design draft or ballast draft
3. Calculate added resistance in waves
4. Calculate added resistance in wind
5. Calculate propulsion point (propeller efficiency)
6. Calculate added power in waves and wind
7. Calculate calm water power corrected for draft
8. Calculate added power due to fouling
9. Calculate margins

3.3 Calm Water Resistance Extrapolation

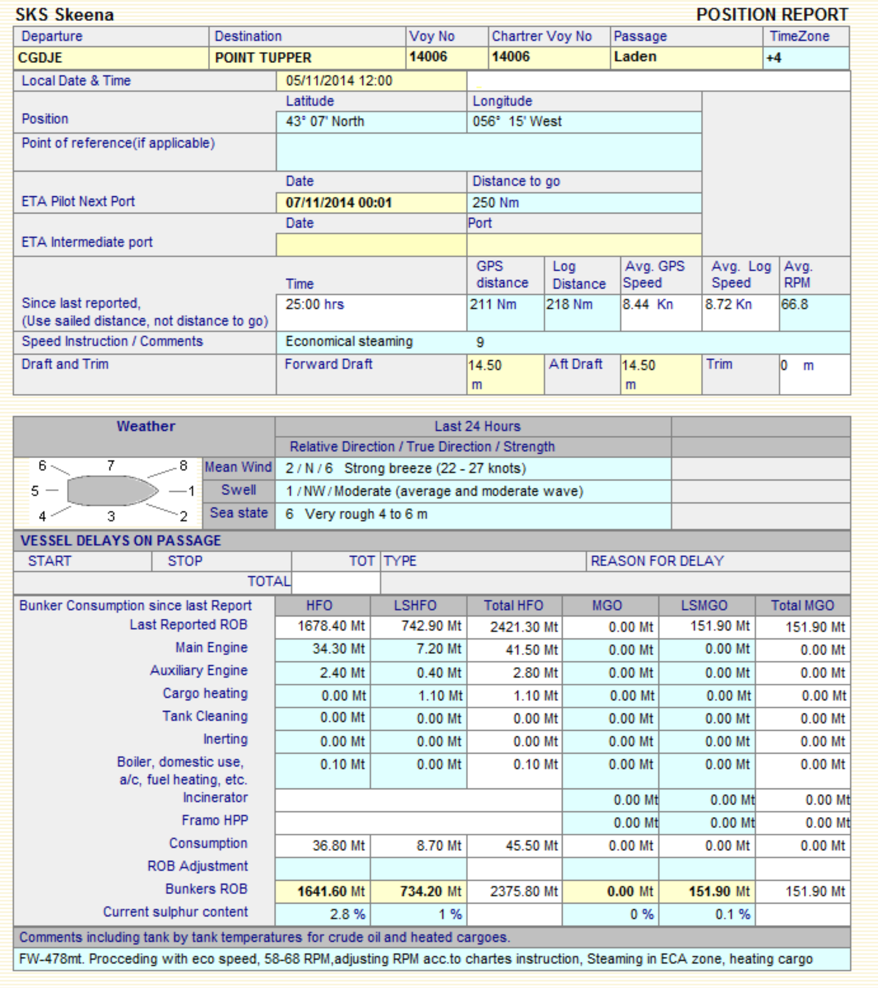
The speed-power performance in calm water from model tests and sea trial was calculated by the ship builder, Hyundai Heavy Industries. The noon reports show that the ships often sail at lower speeds than the shipbuilder has provided performance prediction for. The speed-power curves for idealized conditions were therefore extrapolated for lower speeds in the following way:

The total resistance coefficient is in the model test report calculated as

$$C_T = (1+k)C_F + \Delta C_F + C_R + C_{AA} \tag{3.1}$$

where

- k: form factor
- C_F: frictional resistance coefficient
- ΔC_F: roughness allowance
- C_R: residual resistance coefficient
- C_{AA}: correlation coefficient



SKS Skeena **POSITION REPORT**

Departure	Destination	Voy No	Chartrer Voy No	Passage	TimeZone
CGDJE	**POINT TUPPER**	**14006**	**14006**	**Laden**	**+4**

Local Date & Time	05/11/2014 12:00					
	Latitude	Longitude				
Position	43° 07' North	056° 15' West				
Point of reference(if applicable)						
	Date	Distance to go				
ETA Pilot Next Port	**07/11/2014 00:01**	250 Nm				
	Date	Port				
ETA Intermediate port						
	Time	GPS distance	Log Distance	Avg. GPS Speed	Avg. Log Speed	Avg. RPM
Since last reported, (Use sailed distance, not distance to go)	25:00 hrs	211 Nm	218 Nm	8.44 Kn	8.72 Kn	66.8
Speed Instruction / Comments	Economical steaming	9				
Draft and Trim	Forward Draft	14.50 m	Aft Draft	14.50 m	Trim	0 m

Weather	Last 24 Hours	
	Relative Direction / True Direction / Strength	
Mean Wind	2 / N / 6 Strong breeze (22 - 27 knots)	
Swell	1 / NW / Moderate (average and moderate wave)	
Sea state	6 Very rough 4 to 6 m	

VESSEL DELAYS ON PASSAGE

START	STOP	TOT	TYPE	REASON FOR DELAY
	TOTAL			

Bunker Consumption since last Report	HFO	LSHFO	Total HFO	MGO	LSMGO	Total MGO
Last Reported ROB	1678.40 Mt	742.90 Mt	2421.30 Mt	0.00 Mt	151.90 Mt	151.90 Mt
Main Engine	34.30 Mt	7.20 Mt	41.50 Mt	0.00 Mt	0.00 Mt	0.00 Mt
Auxiliary Engine	2.40 Mt	0.40 Mt	2.80 Mt	0.00 Mt	0.00 Mt	0.00 Mt
Cargo heating	0.00 Mt	1.10 Mt	1.10 Mt	0.00 Mt	0.00 Mt	0.00 Mt
Tank Cleaning	0.00 Mt	0.00 Mt	0.00 Mt	0.00 Mt	0.00 Mt	0.00 Mt
Inerting	0.00 Mt	0.00 Mt	0.00 Mt	0.00 Mt	0.00 Mt	0.00 Mt
Boiler, domestic use, a/c, fuel heating, etc.	0.10 Mt	0.00 Mt	0.10 Mt	0.00 Mt	0.00 Mt	0.00 Mt
Incinerator				0.00 Mt	0.00 Mt	0.00 Mt
Framo HPP				0.00 Mt	0.00 Mt	0.00 Mt
Consumption	36.80 Mt	8.70 Mt	45.50 Mt	0.00 Mt	0.00 Mt	0.00 Mt
ROB Adjustment						
Bunkers ROB	**1641.60** Mt	**734.20** Mt	2375.80 Mt	**0.00** Mt	**151.90** Mt	151.90 Mt
Current sulphur content	2.8 %	1 %		0 %	0.1 %	

Comments including tank by tank temperatures for crude oil and heated cargoes.

FW-478mt. Procceding with eco speed, 58-68 RPM,adjusting RPM acc.to chartes instruction, Steaming in ECA zone, heating cargo

Figure 3.1: Position report example for SKS Skeena. Speed, fuel consumption, weather, draft, trim and position is reported.

The correlation coefficient C_{AA} and the roughness allowance coefficient ΔC_F are constant for all speeds. The frictional resistance coefficient C_F and the residual resistance coefficient C_R changes with ship speed. If C_F and C_R are calculated for other speeds the total resistance can also be calculated for different speeds.

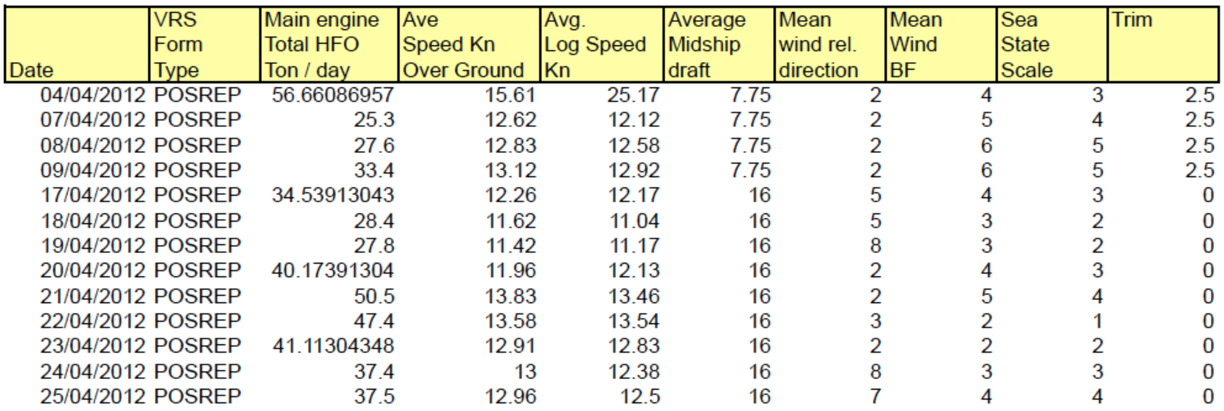
The frictional resistance coefficient can be estimated by the ITTC 1957 friction line

$$C_F = \frac{0.075}{(\log R_N - 2)^2} \tag{3.2}$$

where

- R_N: Reynolds number

The residual resistance coefficient is assumed to approach zero as the speed goes to zero. The



Date	VRS Form Type	Main engine Total HFO Ton / day	Ave Speed Kn Over Ground	Avg. Log Speed Kn	Average Midship draft	Mean wind rel. direction	Mean Wind BF	Sea State Scale	Trim
04/04/2012	POSREP	56.66086957	15.61	25.17	7.75	2	4	3	2.5
07/04/2012	POSREP	25.3	12.62	12.12	7.75	2	5	4	2.5
08/04/2012	POSREP	27.6	12.83	12.58	7.75	2	6	5	2.5
09/04/2012	POSREP	33.4	13.12	12.92	7.75	2	6	5	2.5
17/04/2012	POSREP	34.53913043	12.26	12.17	16	5	4	3	0
18/04/2012	POSREP	28.4	11.62	11.04	16	5	3	2	0
19/04/2012	POSREP	27.8	11.42	11.17	16	8	3	2	0
20/04/2012	POSREP	40.17391304	11.96	12.13	16	2	4	3	0
21/04/2012	POSREP	50.5	13.83	13.46	16	2	5	4	0
22/04/2012	POSREP	47.4	13.58	13.54	16	3	2	1	0
23/04/2012	POSREP	41.11304348	12.91	12.83	16	2	2	2	0
24/04/2012	POSREP	37.4	13	12.38	16	8	3	3	0
25/04/2012	POSREP	37.5	12.96	12.5	16	7	4	4	0

Figure 3.2: Data collected from noon reports organized in a spreadsheet.

curve has been linearly interpolated for lower speeds under the assumption that C_R goes to $zero$ as F_N goes to zero. This is shown in Figure 3.3.

The total resistance coefficient C_T can then be calculated by equation 3.1 and the total ship resistance can be found using the definition of C_T

$$R_T = \frac{\rho}{2} V^2 S C_T \tag{3.3}$$

where

- S: total wetted surface
- V: ship speed $[\frac{m}{s}]$

The effective power is $P_E = R_T V_S$ and the brake power is

$$P_B = \frac{P_E}{\eta_D \eta_M} C_P \tag{3.4}$$

- P_B Brake power
- P_E Effective power
- η_D Propulsion efficiency
- η_M Transmission efficiency
- C_P Trial correction for shaft power

Figure 3.4 shows the extrapolated speed-power relationship in calm water. The power requirement was also calculated for SKS Satilla in loaded condition using Hollenbach´s method. This gave similar results as the simplified method mentioned above. The simplified method was

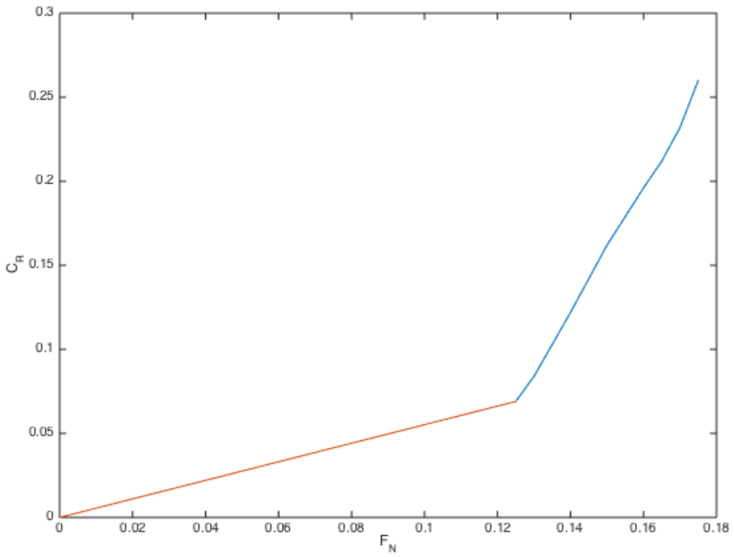


Figure 3.3: C_R from model test linearly interpolated for lower Froude numbers. Blue line is values from model tests and red line is extrapolated values.

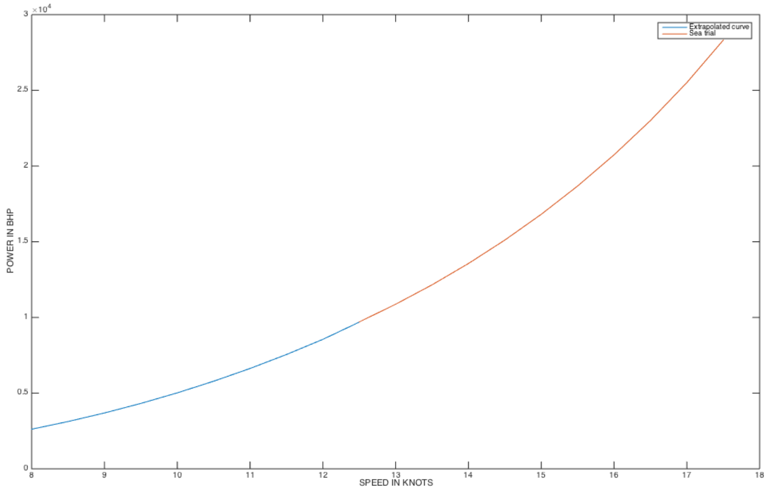


Figure 3.4: Speed power curve from sea trial extrapolated for lower velocities. The red curve is the predicted power from the sea trial, the blue curve is the extrapolated part.

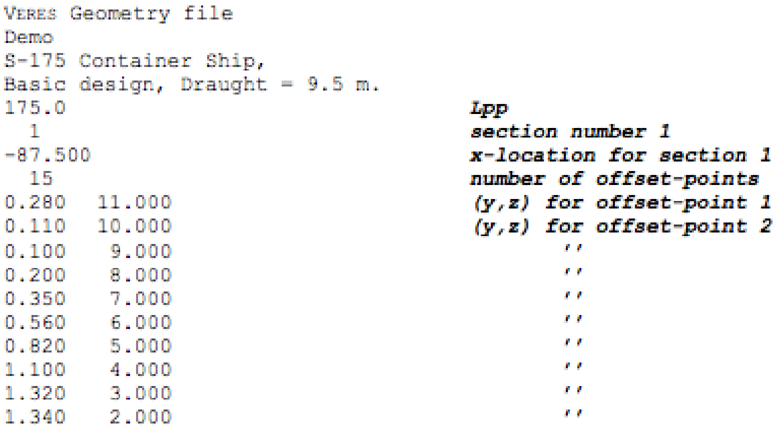
therefore used for both ships in both loaded and ballast condition.

3.4 ShipX

ShipX was used to calculate the added resistance in waves. The basic idea behind ShipX is to make a platform that integrates all kinds of hydrodynamic analysis into an integrated design tool. The plug-in Veres (Vessel Response) in ShipX can calculate ship motions and global loads.

Digitalization of Ships

In order to use ShipX, the ship geometry has to be digitalized. ShipX supports several import formats, such as AutoCad DXF, AutoShip and Shipshape. Another format is supported in Veres (*.mgf). This is a simple text format, where the coordinates for each section is specified. The lines drawing for the SKS Skeena were provided by KGJS. They were digitalized using the program GraphClick. In the program you can place a coordinate system over a scanned drawing and click on the points you want to register. This was done with the body plan. The coordinates were organized in a text file according to the Veres file format in figure **??** and imported into ShipX. The geometry was verified by comparing values calculated by ShipX (block coefficient, displacement etc) with the values provided from ship documentation. KGJS could not provide the line plans for SKS Doda because the ship builder, Huyndai, would not provide them. SKS Skeena and SKS Doda are geometrically very similar, so SKS Skeena imported to ShipX was transformed to do calculations on SKS Doda. In ShipX this is done by changing the main perpendiculars,



```
VERES Geometry file
Demo
S-175 Container Ship,
Basic design, Draught = 9.5 m.
175.0                                   Lpp
  1                                     section number 1
-87.500                                 x-location for section 1
  15                                    number of offset-points
0.280   11.000                          (y,z) for offset-point 1
0.110   10.000                          (y,z) for offset-point 2
0.100    9.000                                  ''
0.200    8.000                                  ''
0.350    7.000                                  ''
0.560    6.000                                  ''
0.820    5.000                                  ''
1.100    4.000                                  ''
1.320    3.000                                  ''
1.340    2.000                                  ''
```

Figure 3.5: Example of Veres geometry file (*.mgf). From Veres User Manual

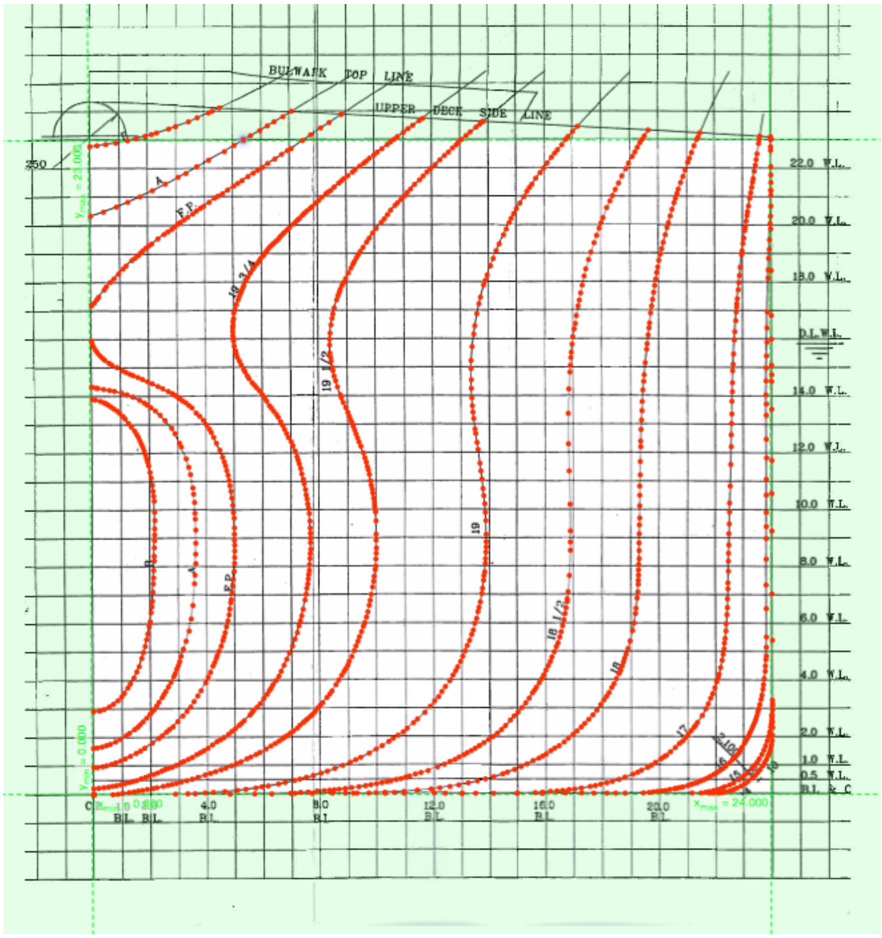


Figure 3.6: Screenshot of digitalization of body plan with GraphClick.

such as length, breadth and depth. Again the correctness of the geometry was confirmed by comparing the ShipX generated values with known values from ship documentation.

Coefficients for added resistance in waves

In ShipX it is possible to choose between direct pressure integration or Gerritsma and Beukelmans method. Gerritsma and Beukelmans method gave large negative values for waves from behind, therefore the direct pressure integration method is selected because it seems to give more realistic values for waves from behind. The results from ShipX are presented in figures as dimensionless coefficients as a function of peak period T_P as shown in figure 3.7.

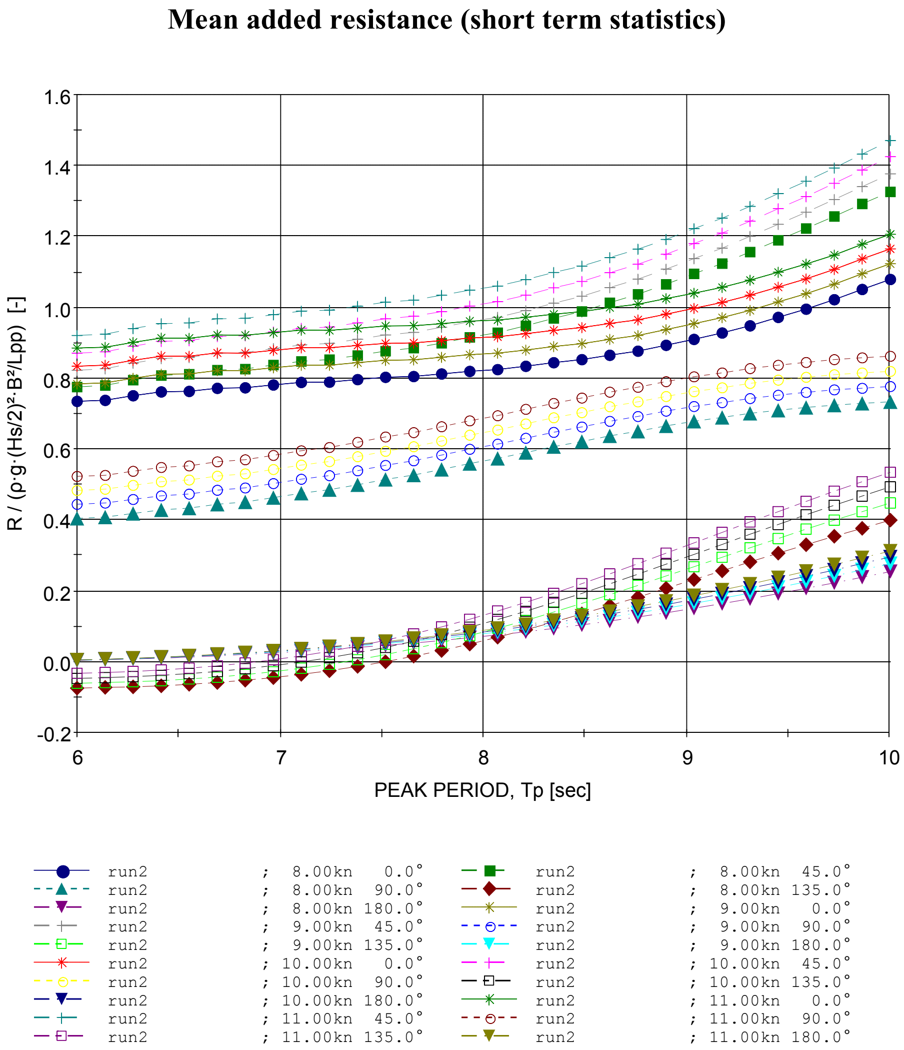


Figure 3.7: Coefficients for added resistance in waves for SKS Skeena

Table 3.2: Douglas sea scale

Sea state number	Description	Wave height [m]
0	Calm (glassy)	0
1	Calm (rippled	0-0.1
2	Smooth (wavelets)	0.1-0.5
3	Slight	0.5-1.25
4	Moderate	1.25-2.5
5	Rough	2.5-4
6	Very rough	4-6
7	High	6-9
8	Very high	9-14
9	Phenomenal	Over 14

3.5 Added resistance in wind

The relative wind direction is given in the noon reports as numbers from 1 to 8 as show in figure **??**.. The relationship between relative wind and true wind can be found found using the law of cosines

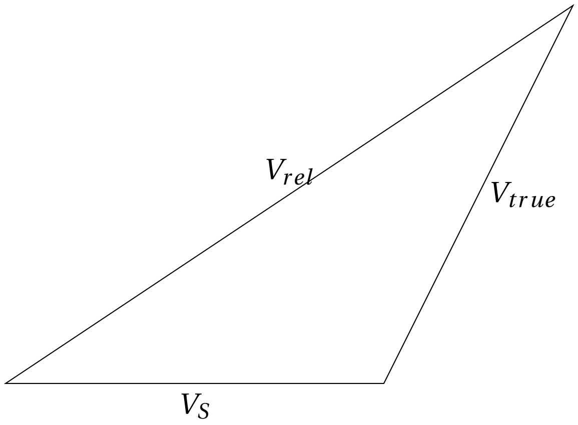
$$V_{true}^2 = V_S^2 + V_{rel}^2 - 2V_S V_{rel} \cos\beta V_{rel}^2 = V_S^2 + V_{true}^2 - 2V_S V_{true} \cos(\pi - \gamma) \tag{3.5}$$

V_{true} True wind velocity

V_{rel} Relative wind velocity

β Angle between relative wind velocity and ship direction measured from bow

γ Angle between true wind velocity and ship direction measured from bow



The wind speed in given in the Beaufort scale.

3.6 Calculation of full scale propulsion point

When the resistance increases for a ship sailing at a certain speed the propeller thrust increases and the propeller efficiency changes. The full scale propulsion point J^* can be found from the intersection between $\frac{K_T}{J^2}$ from the scaled open water test and the following term:

$$\frac{K_T}{J^2} = \frac{R_{TS} + R_{AW} + R_W}{\rho n^2 D^4 (1-t) V_S^2 (1-w_s)^2} \tag{3.6}$$

When J^* is found the propeller efficiency can be found from the full scale open water diagram where $J = J^*$ intersects the η_0 curve. The propulsive efficiency $\eta_D = \eta_0 \eta_H \eta_R$ can then be calculated. The hull efficiency η_H, the relative rotative efficiency η_R and the effective wake W_S are assumed to be equal to the values calculated in the model test.

3.7 Calculation of added power

The added resistance due to waves R_{AW} and wind R_W can be converted to added brake power using the propulsive efficiency η_D and transmission efficiency η_M:

$$P_B = \frac{RV_S}{\eta_D \eta_M} \tag{3.7}$$

3.8 Correction for draft

The speed-power predicted in the model test is for either loaded condition or ballast condition. In figure REF the curves show the calm water power for SKS Skeena in the two conditions. When the actual draft deviates from these the power can be overestimated or underestimated. This is corrected by assuming a linear relationship between the power in loaded and ballast condition.

$$P = P_{ballast} + \frac{P_{design} - P_{ballast}}{D_{design} - D_{ballast}}(D - D_{ballast}) \tag{3.8}$$

Chapter 4

Results

4.1 Total margin

The total sea margin in figure 4.1 was calculated as

$$100\% \cdot k_{total} = 100\% \cdot \frac{P_{measured} - P_{calmwater}}{P_{calmwater}} \tag{4.1}$$

The trend line is a third degree fitting of the measured values for the two ships in loaded condition. It is seen that the margin decreases with speed. The dashed line shows a 15% sea margin as suggested by the shipbuilder Hyundai for both ships. Data for the ships in ballast condition in figure 4.2 shows a similar trend.

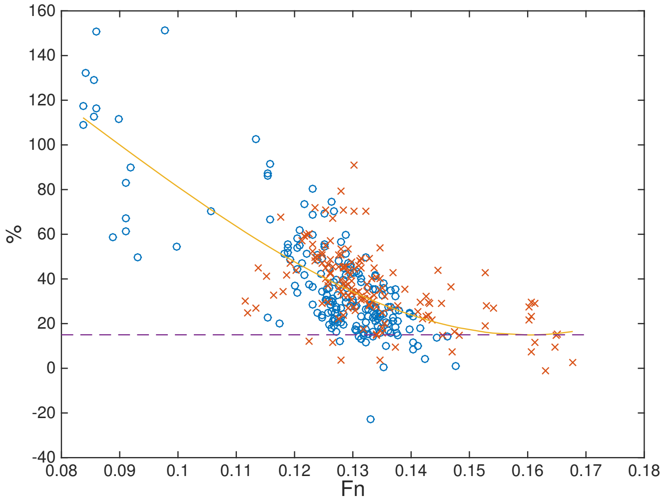


Figure 4.1: Total margin for two tankers in design condition.

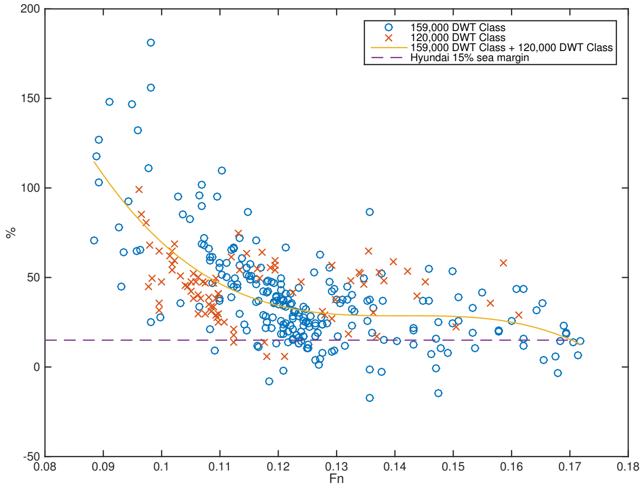


Figure 4.2: Total margin for two tankers in ballast condition.

4.2 Wave margin

Figures 4.3 and 4.4 show the wave margin calculated for respectively design in ballast condition for the two ships. Both figures show that the wave margin tends to decrease with speed. The large differences in these margins are due to the different sea states as illustrated in figure 4.5.

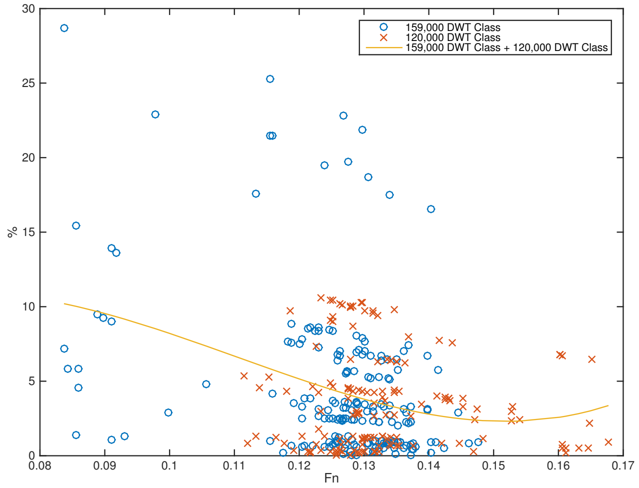


Figure 4.3: Wave margin for two tankers in design condition.

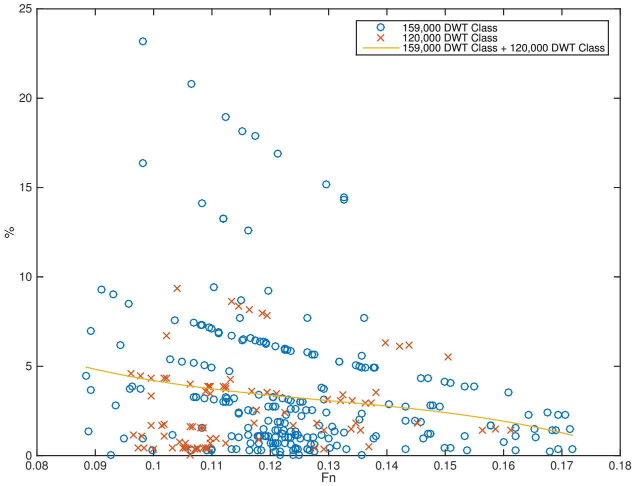


Figure 4.4: Wave margin for two tankers in ballast condition.

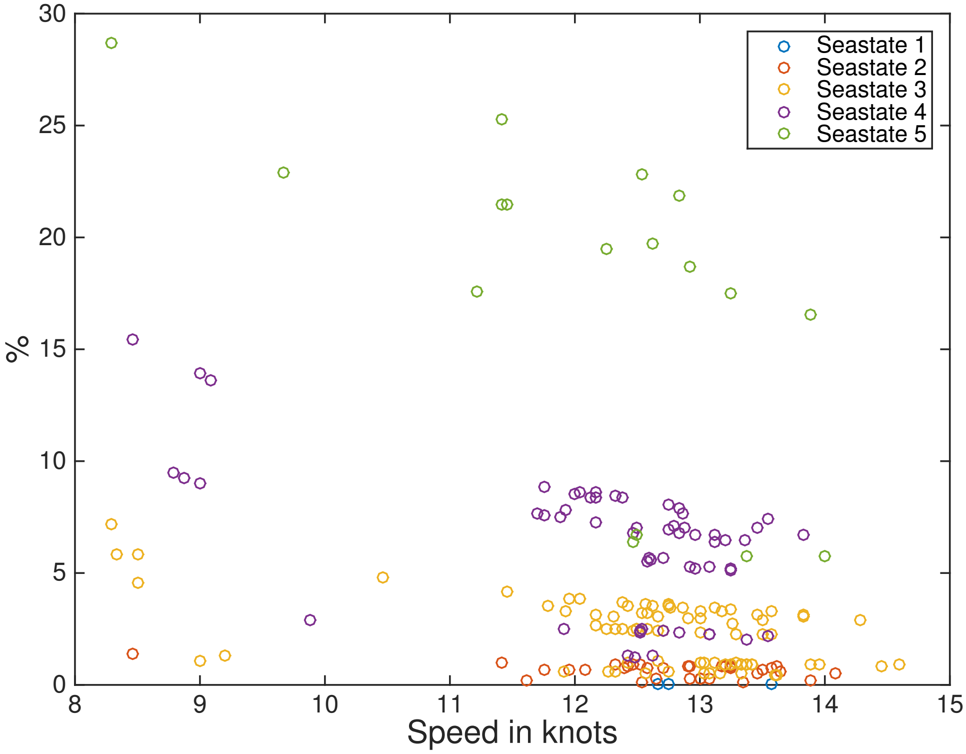


Figure 4.5: Wave margin for different seastates. 159,000 DWT class loaded condition

4.3 Fouling margin

Figures 4.6 and 4.7 show the calm water power corrected for draft and the measured power corrected for waves, wind and roughness. If all of the components contributing to added power in service are accounted for the values will be equal for the two. In this case the fouling has been calculated as roughness with equation 2.23. For the lower Froude numbers the calculated added power is underestimated or the calm water prediction is overestimated. When the added power due to fouling on the hull and propeller is calculated this way the fouling margin is almost constant, as shown in figure 4.8. This is due to the fact that roughness is added to the friction resistance which is proportional to the ship speed cubed. The calm water power prediction is also proportional to the ship speed cubed and therefore the margin is close to constant.

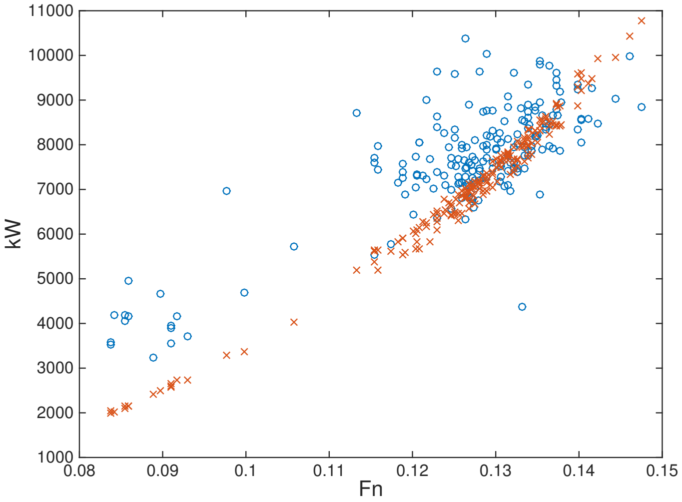


Figure 4.6: Calm water power and measured power corrected for waves, wind and roughness in loaded condition.

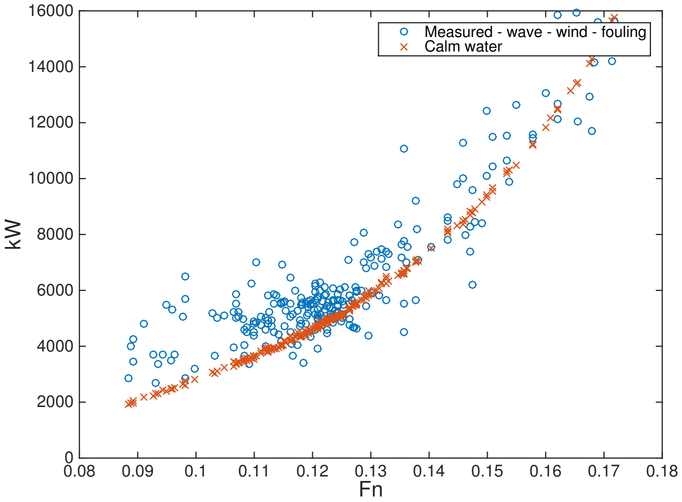


Figure 4.7: Calm water power and measured power corrected for waves, wind and roughness in ballast condition.

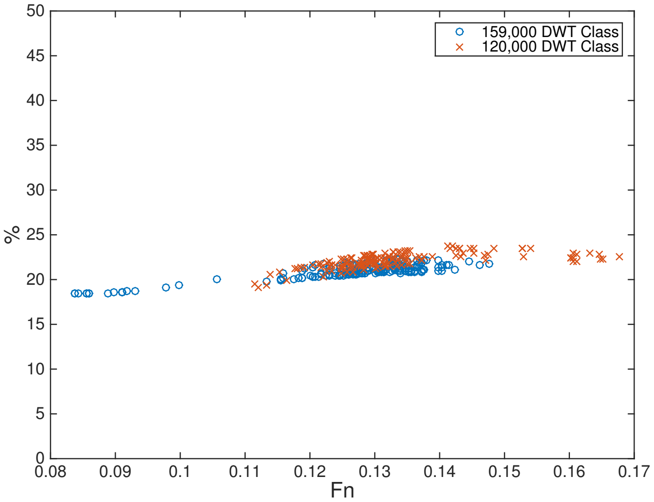


Figure 4.8: Fouling/roughness margin in loaded condition.

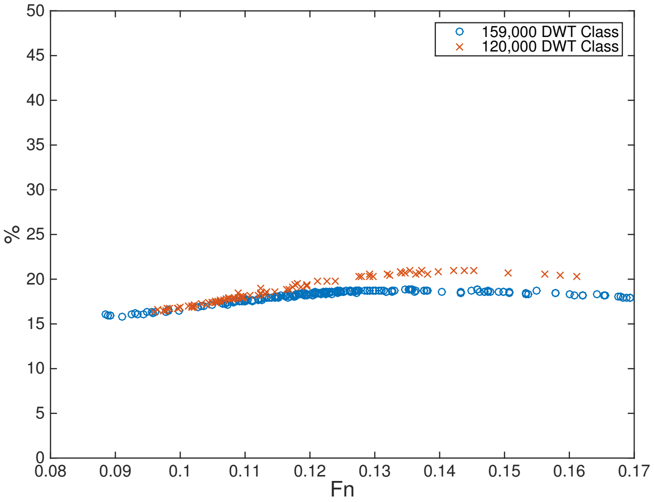


Figure 4.9: Fouling/roughness margin in ballast condition.

4.4 Rest margin

The power that remains unaccounted for after subtracting the calm water power, the wave power, the wind power and the fouling power from the measured power is shown in figures 4.10 and 4.11. The trend line shows that the rest margin is large for the lower Froude numbers and decreases to values close to zero for higher Froude numbers.

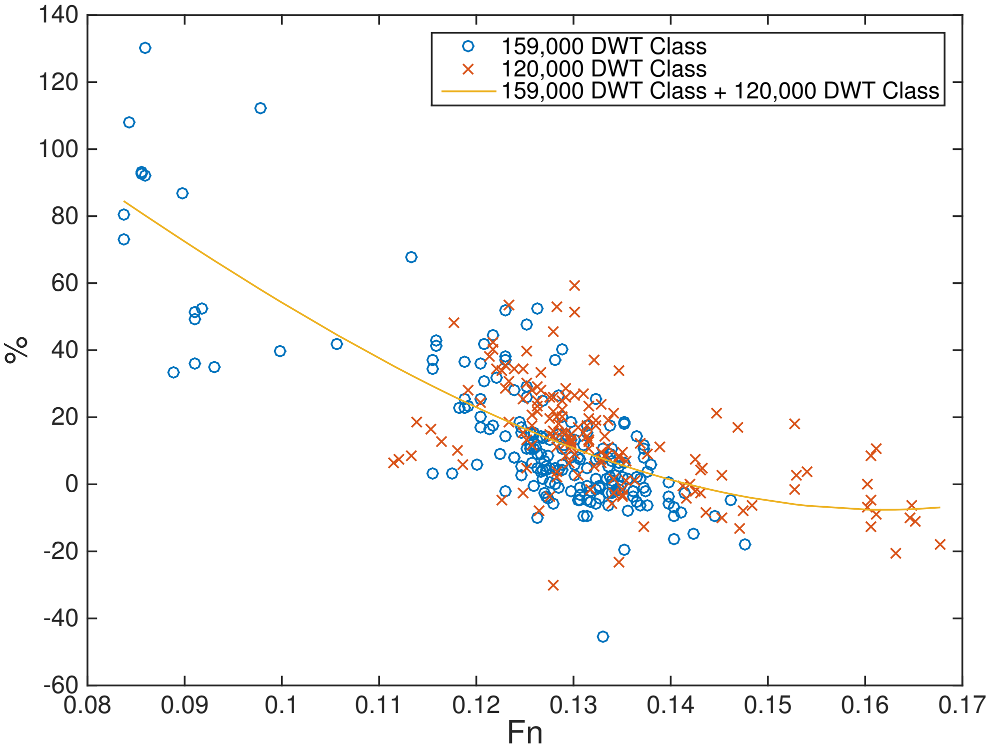


Figure 4.10: Rest margin in loaded condition.

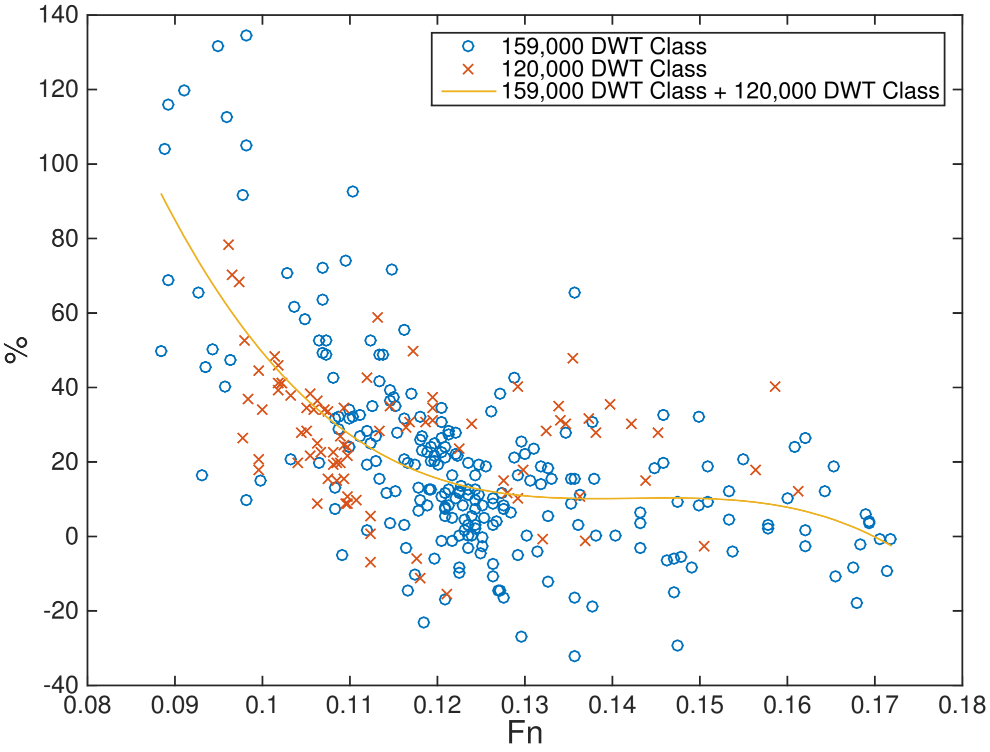


Figure 4.11: Rest margin in ballast condition.

4.5 Comparison with calculations based on current methods of predicting such margins

Stasiak (2004) identified that the wave margin is inversely proportional to the ship speed. This also seems to be the case in the calculations in this thesis. He proposed formulas to calculate the wave margin for head sea conditions. According to Stasiak they did not aspire to be complete and directly applicable as they were based on too scarce material and were an upper estimation of the margin. Figure 4.12 shows Stasiak´s model compared to the wave margin calculated for the 159,000 DWT ship investigated in this thesis. Stasiak´s model is limited to Fn between 0.12 and 0.30. Stasiak´s model gives significantly larger values, but the slope seems to agree with the calculated values.

In figures 4.13 and 4.14 the wave margin and wind margin has been combined to compare the calculated values in this work with values calculated with the approximate formulas by Townsin and Kwon described in chapter 2.3. The calculated values in this thesis are calculated using direct pressure integration for added resistance in waves and wind coefficients from tables by

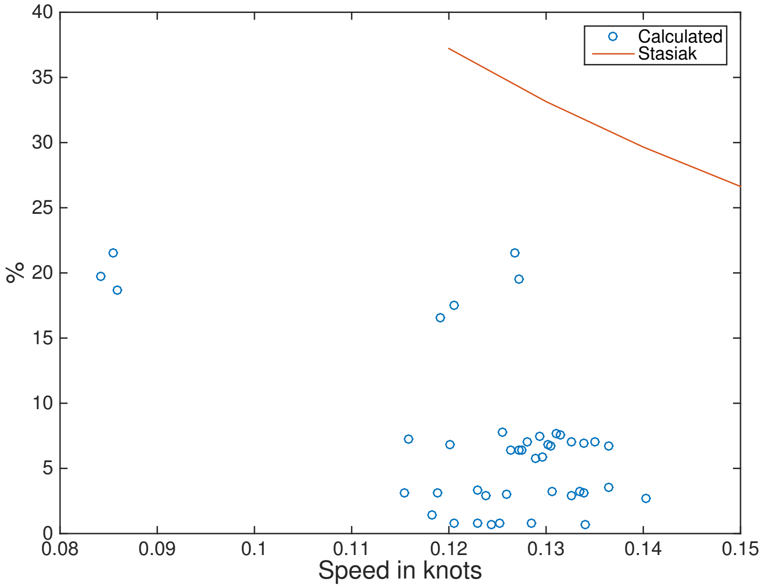


Figure 4.12: Comparison between calculated combined wave margins and Stasiak model. 159k DWT Draft: 14 m to 16 m

Brix (1993). The method by Townsin and Kwon are formulas for speed loss converted to calculate power increase with equation 2.15. The two methods follow the same trend, but are not equal in magnitude. The Townsin and Kwon method uses only the Beaufort number while the calculated values use Beaufort for the wind speed and the Douglas sea scale for the wave height.

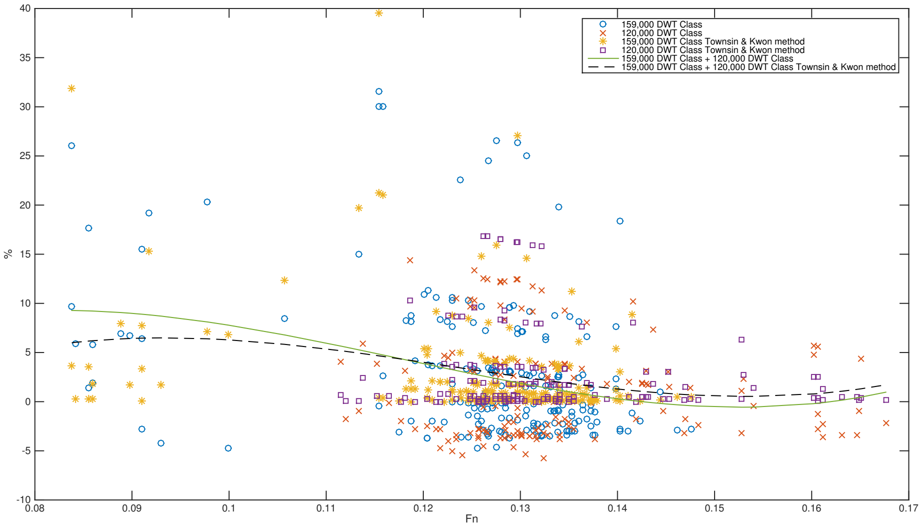


Figure 4.13: Combined wave and wind margins for two tankers in design condition.

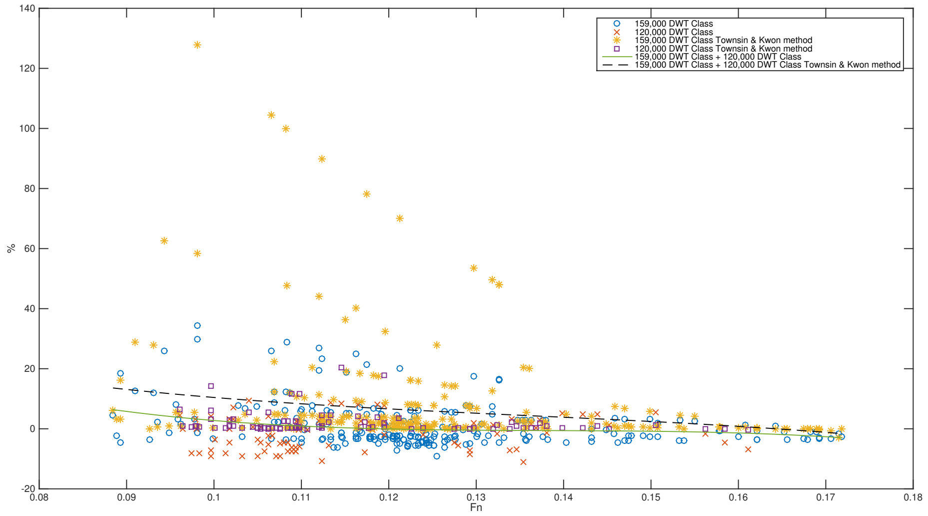


Figure 4.14: Combined wave and wind margins for two tankers in ballast condition.

4.6 Approximate formulas

Approximate formulas have been developed based on the calculations. The formulas have been made dimensionless with the Froude number as the variable. Data from both ships investigated in this thesis have been used. For the total sea margin the following formula is proposed for both loaded and ballast condition (figures 4.15 and 4.16)

$$100\% \cdot k_{SM} = \frac{12.227}{Fn} - 59.526 \tag{4.2}$$

It is based on data in the speed range where model test data was available $Fn = 0.125 - 0.170$ so that the uncertainty of the extrapolation of the calm water speed-power curve is not a factor. All the approximate formulas are for this range of Froude numbers. For lower Froude numbers it is more inaccurate.

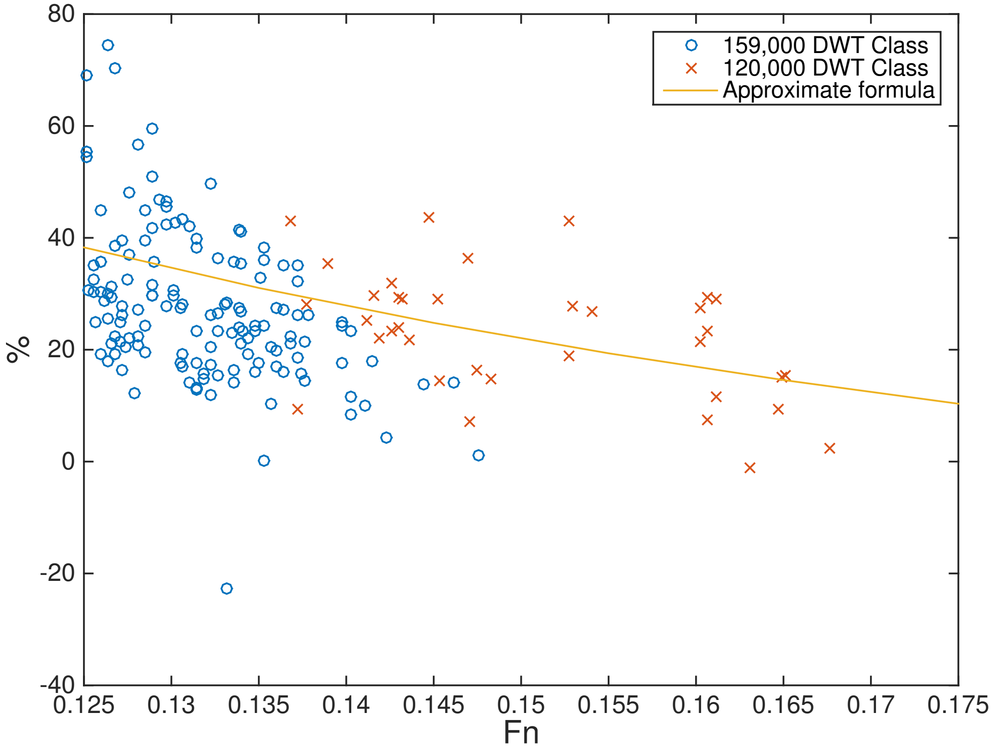


Figure 4.15: Total margin in design condition and approximate formula.

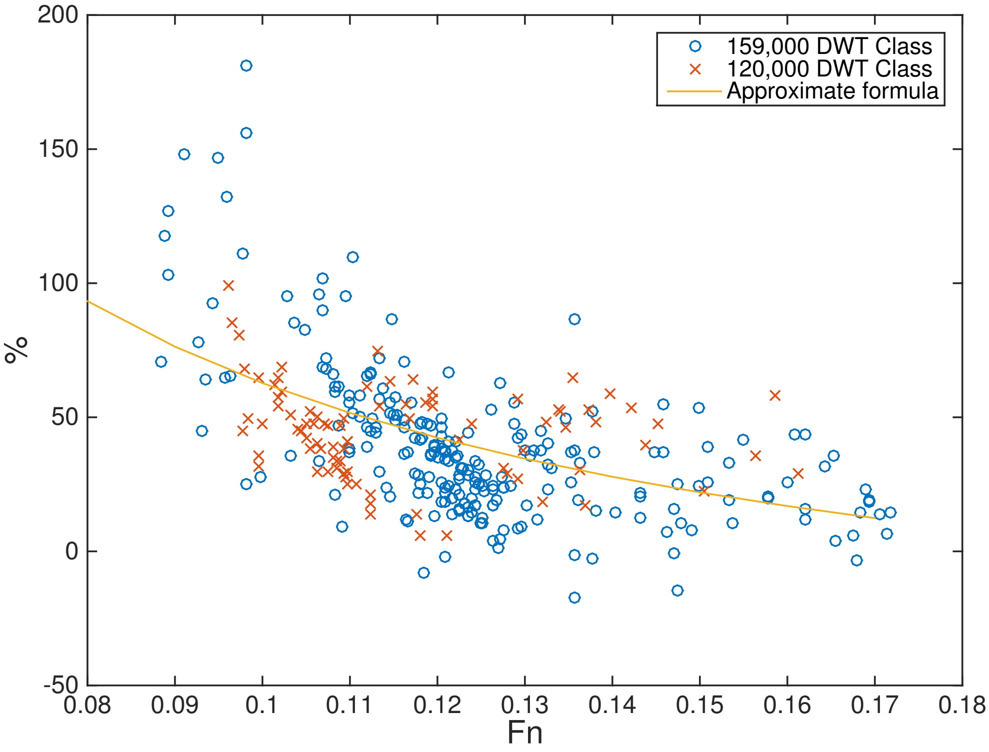


Figure 4.16: Total margin in ballast condition and approximate formula.

The wave margin for loaded condition and an approximate formula is shown in figure 4.17

$$100\% \cdot k_{wave} = \frac{1.298}{Fn} - 5.119 \tag{4.3}$$

Ballast condition is shown in figure 4.18 and the following approximate formula is proposed

$$100\% \cdot k_{wave} = \frac{0.676}{Fn} - 2.645 \tag{4.4}$$

An approximation of the fouling margin can be obtained by using the equation for roughness by Townsin from chapter 2.4.3.

$$100\% \cdot k_{roughness} = \frac{\Delta C_F}{C_T} \tag{4.5}$$

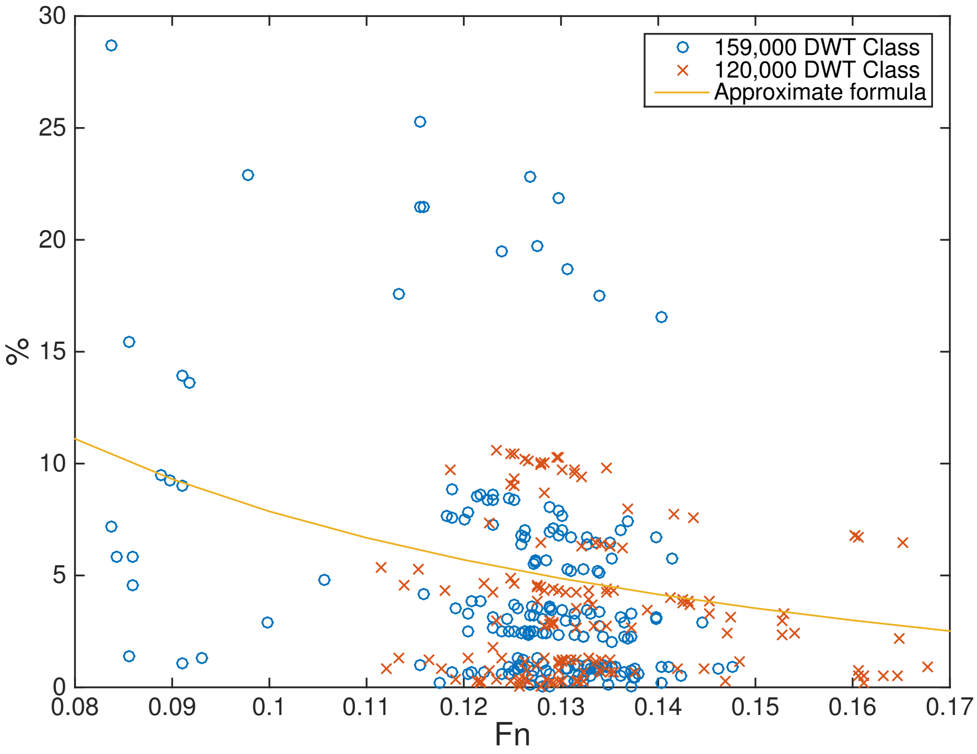


Figure 4.17: Wave margin in design condition and approximate formula.

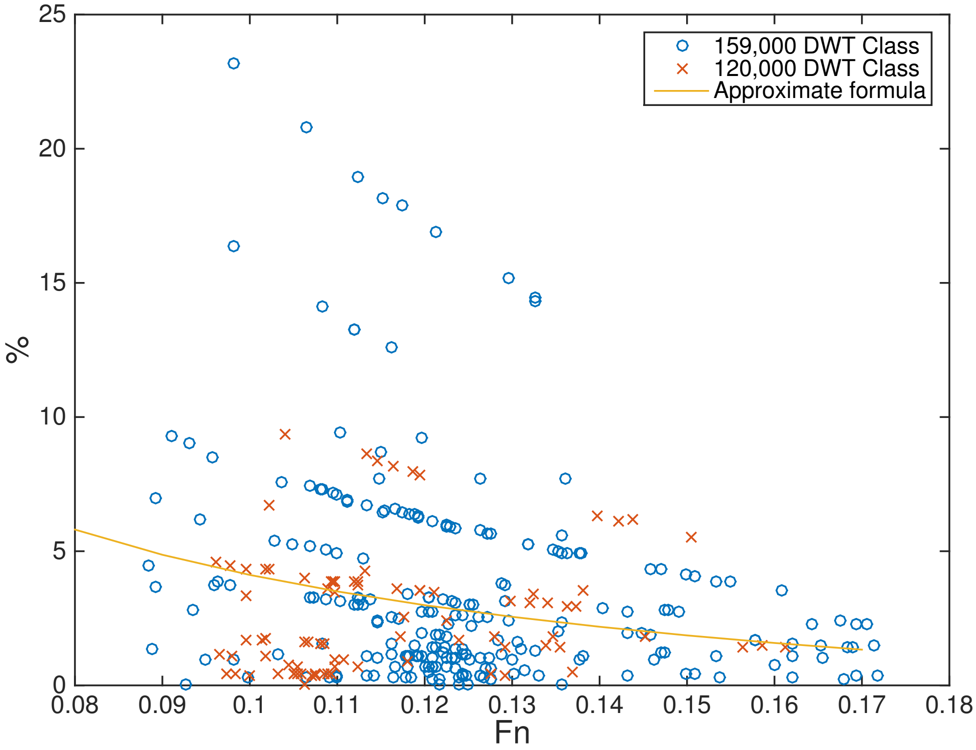


Figure 4.18: Wave margin in ballast condition and approximate formula.

Chapter 5

Discussion

5.1 Limitations

The calculations in this thesis are based on data from noon reports for two different ships owned by KGJS. There are some uncertainty in the data that has affected the calculations:

Weather data from the noon reports are instantaneous values, but are in this work treated as average values for 24 hours. This gives significant uncertainty in wind speed, direction and wave height.

Fuel consumption measurements require correct calibration of flowmeter, use of correct density, no fuel in the pocket and no leaks from the fuel loop.

The measurement of log speed, the ship speed through water, is inaccurate. The GPS speed is therefore used as the ship speed. Currents are therefore not taken into account in the calculations.

According to KGJS the time zone and time since the last report are critical parameters. If the time since last report is not correct, the fuel consumption and the average gps speed will be wrong.

The ships often sail at a slower speed than the speeds Hyundai have predicted the calm water resistance for. The extrapolation of this relationship to cover all normal service speeds is simple and may not be correct.

5.2 Discussion

The calculations of total sea margin show that the margin is speed dependent and decreases with speed. The 15% sea margin that Hyundai use in their power prediction is fairly accurate for the design speed, but deviates significantly for lower speeds. The total margin is very large for the lower speeds. This could be due to the fact that the calm water power prediction from model tests did not cover the lower speeds and the simplified extrapolation may have underestimated the power requirement.

The wave margin decreases with speed. This was also shown by Stasiak (2004).

The added power due to wind seems to be negligible on average. This is because the wind gives negative resistance when the wind blows from behind or more than 90 degrees from the bow. The wind may have other effects than the drag force, such as rudder angle to keep the ship on course.

The fouling margin modeled as roughness seems to be overestimated for the lower speeds. The rest margin show that the calculations of added power in wind, waves and due to roughness does not cover the total power increase in service, especially for the lower speeds. Model test results for these lower speeds would decrease the uncertainty of the calculations.

Chapter 6

Conclusion

The calculations of sea margin in this thesis show that the power prediction for ships can not be predicted accurately by adding a fixed percentage on top of the calm water prediction. The margin is speed dependent.

The speed-power prediction in calm water should include all speeds that the ship is likely to operate in. Including slow steaming speed.

Alternative formulations for calculating sea margin, wave margin and fouling margin are proposed. They are not directly applicable for the calculation of such margins because:

- The calm water speed-power relations did not include the speed range that the ships sailed in most of the time. The extrapolation of the speed-power relation was made with the simple assumption (simplification) that the residual resistance approaches zero as the Froude number approaches zero. Since the calm water resistance is the denominator in all margin calculations it is critical that it is accurate.
- The data from the noon reports are uncertain. Especially since instantaneous weather data is used as the average over 24 hours.
- The calculation of the full scale propulsion point should include all resistance components. Only the calm water resistance, the wave resistance and the wind resistance was included.

The formulations does show some clear tendencies:

- The total sea margin is inversely proportional to the ship speed
- The wave margin is inversely proportional to the ship speed

The rest margin is significant for the lower speeds, which indicates that the fouling margin (roughness) calculated is underestimated for these speeds. This reason for this could be that the speed power relation in calm water is underestimated in the extrapolated speed range. The model tests should be carried out for all speeds that the ship is likely to operate in.

Bibliography

Aertssen, G. (1969). Service performance and trials at sea. app.v performance committee, 12th ittc.

Arribas, P. (2007). Some methods to obtain the added resistance of a ship advancing in waves. *Ocean Engineering*, 34:946.

Brix, J. E. (1993). *Manoeuvring Technical Manual.* Seehafen-Verlag.

Carlton, J. (2007). *Marine Propellers and Propulsion.* Butterworth-Heinemann.

Faltinsen, O. M. (1990). *Sea loads on ships and offshore structures.* Cambridge University Press.

Faltinsen, O. M., Minsaas, K. J., Liapis, N., and Skjørdal, S. O. (1980). Prediction of resistance and propulsion of a ship in a seaway. In *Proc. Thirteenth Symp. On Naval Hydrodynamics*, pages 505–529, Tokyo, Japan.

ITTC (2008). Recommended procedures and guidelines: Testing and extrapolation methods, propulsion, performance, predicting powering margins 7.5-02-03-01.5.

Kwon, Y. J. (2008). Speed loss due to added resistance in wind and waves. *The Naval Architect*, pages 14–16.

Molland, A. F., Turnock, S. R., and Hudson, D. A. (2011). *Ship Resistance and Propulsion: Practical Estimation of Propulsive Power.* Cambridge University Press, 2011.

Nabergoj, R. and Prpic-Orsic, J. (2007). A comparison of different methods for added resistance prediction. pages 149–152. 22nd International Workshop on Water Waves and Floating Bodies.

Pettersen, B. (2007). *Marin teknikk 3 - Hydrodynamikk.* Norwegian University of Science and Technology, Trondheim.

snd W. Beukelman, J. G. (1972). Analysis of the resistance increase in waves of a fast cargo ship. volume 19, pages 289–292.

Stasiak, J. (2004). Service margin - solution of the problem or a problem waiting for a solution? *Polish Maritime research*, Special Issue:29.

Townsin, R. (1985). The ittc line - its genesis and correlation allowance. *The Naval Arcitect*.

Townsin, R. and Kwon, Y. (1983). Approximate formulae for the speed loss due to added resistance in wind and waves. volume 125, pages 191–209.

Appendix A

Margins for SKS Skeena

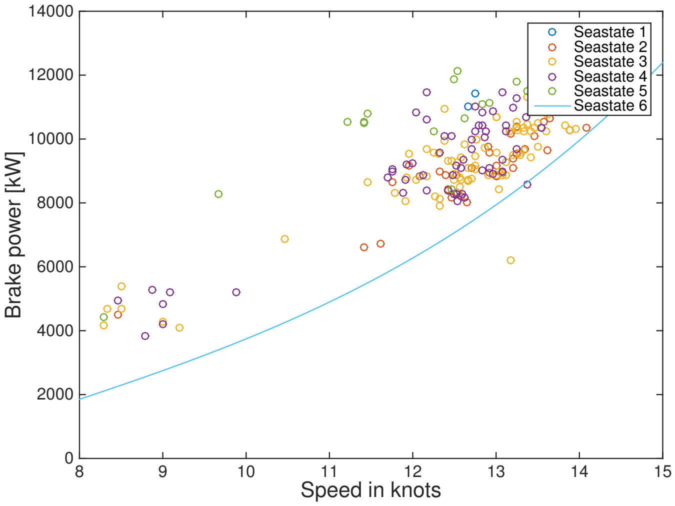


Figure A.1: Measured main engine power for different sea states. 159,000 DWT Class in loaded condition

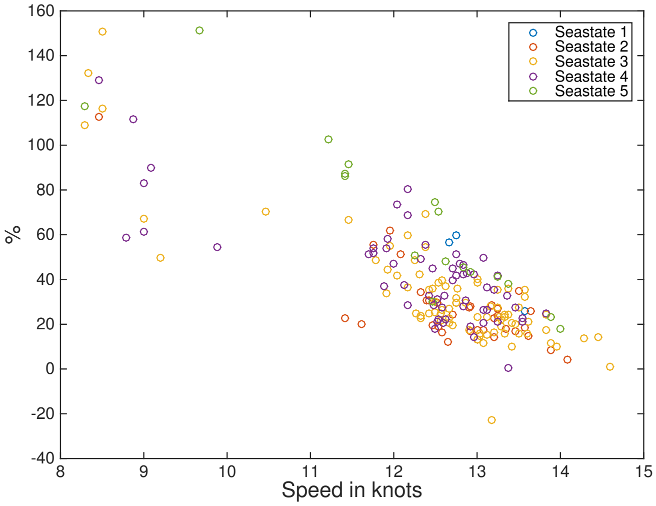


Figure A.2: Total sea margin. 159,000 DWT Class in loaded condition

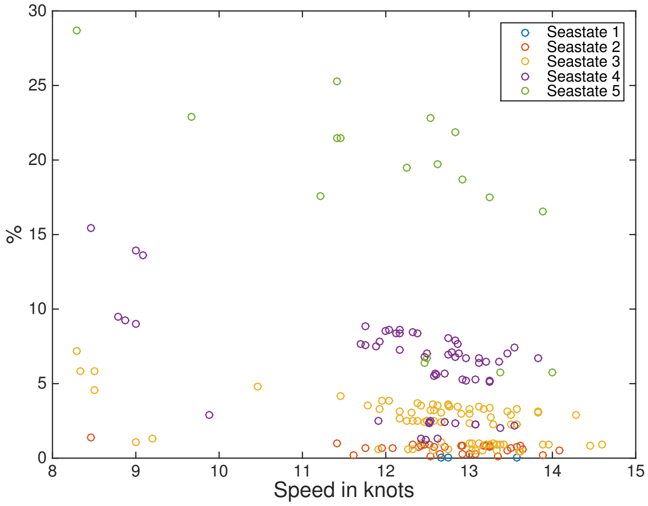


Figure A.3: Wave margin. 159,000 DWT Class in loaded condition

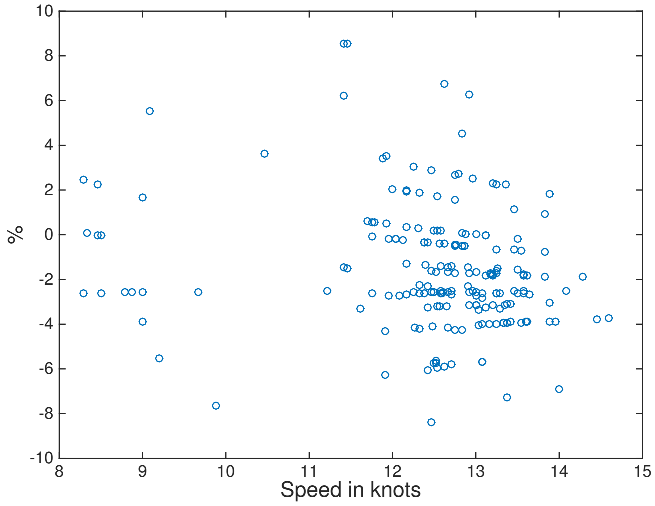


Figure A.4: Wind margin. 159,000 DWT Class in loaded condition

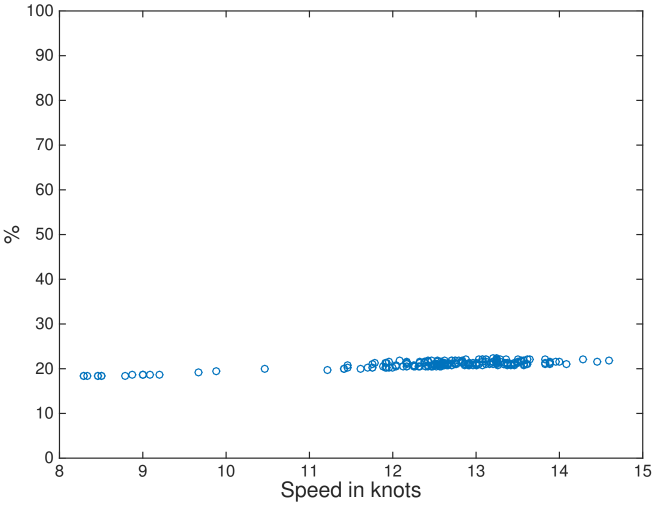


Figure A.5: Roughness/fouling margin. 159,000 DWT Class in loaded condition

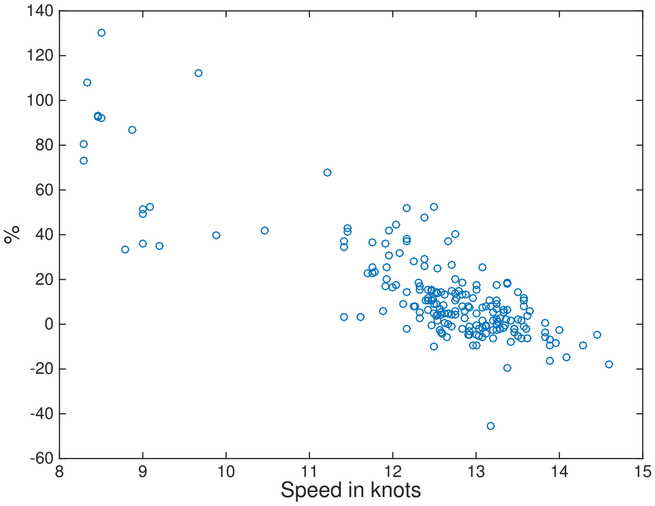


Figure A.6: Rest margin. 159,000 DWT Class in loaded condition

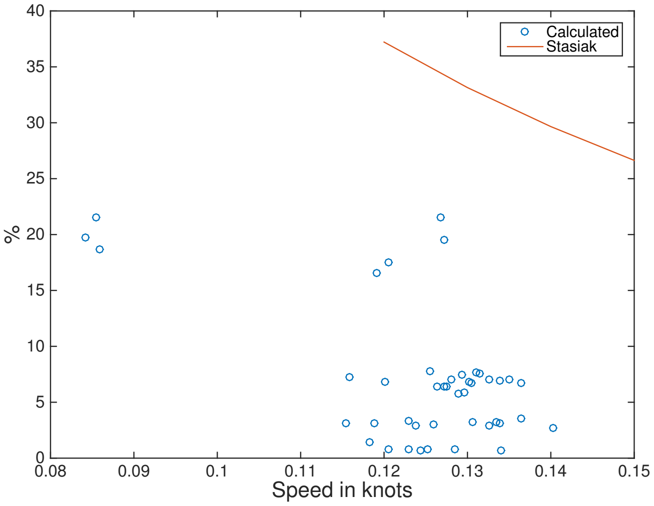


Figure A.7: Wave margin for head sea compared with Stasiak model. 159,000 DWT Class in loaded condition

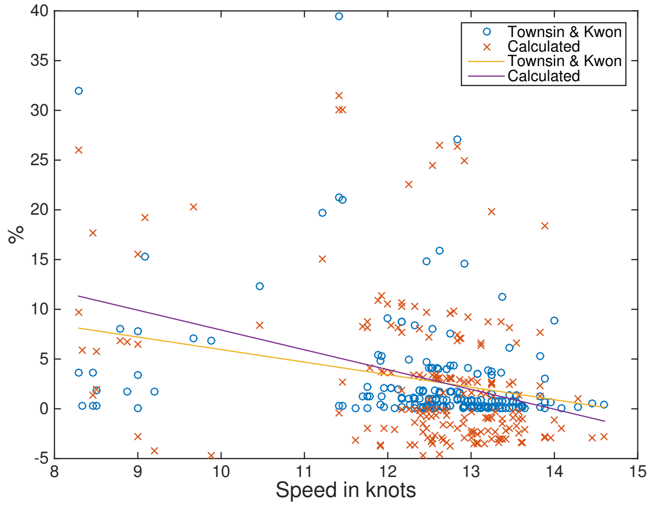


Figure A.8: Combined wave and wind margins compared with Townsin and Kwon model. 159,000 DWT Class in loaded condition

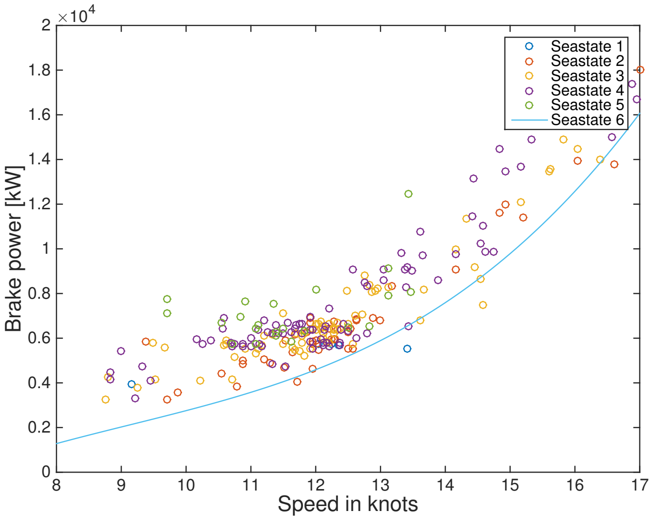


Figure A.9: Measured main engine power for different sea states. 159,000 DWT Class in ballast condition

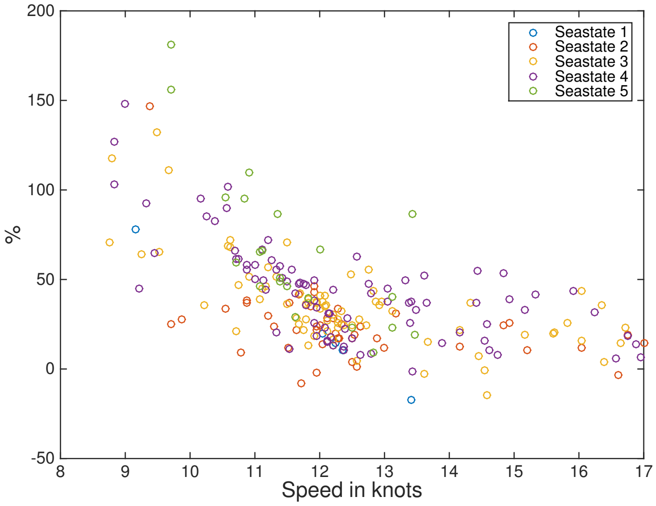


Figure A.10: Total sea margin. 159,000 DWT Class in ballast condition

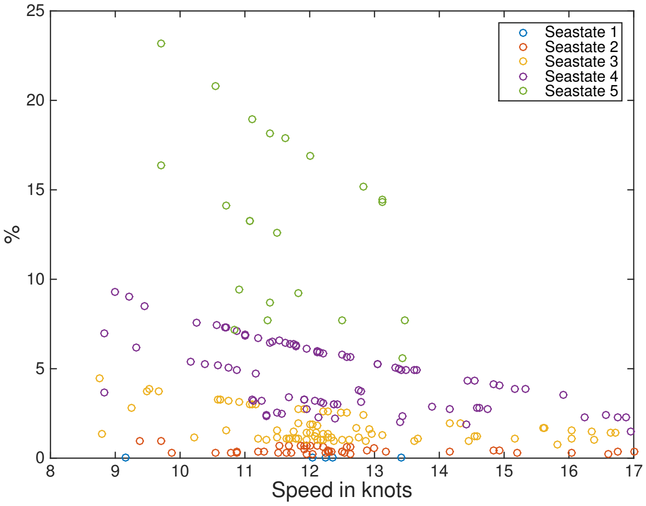


Figure A.11: Wave margin. 159,000 DWT Class in ballast condition

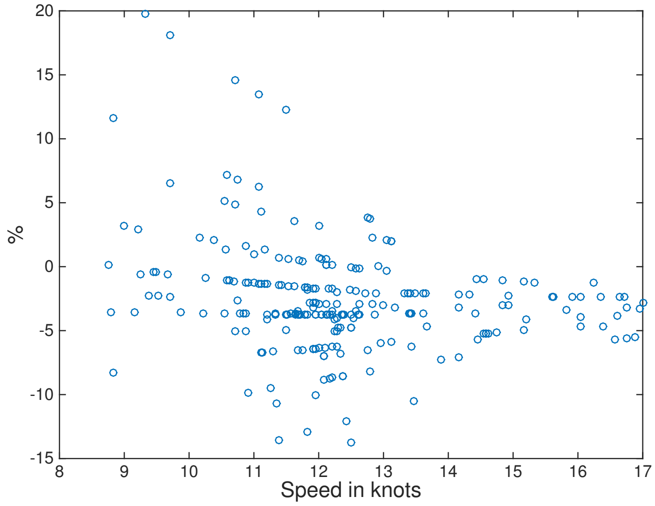


Figure A.12: Wind margin. 159,000 DWT Class in ballast condition

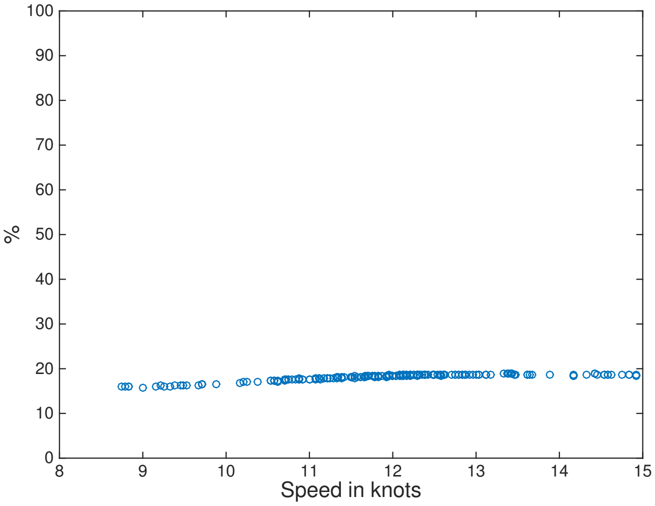


Figure A.13: Roughness/fouling margin. 159,000 DWT Class in ballast condition

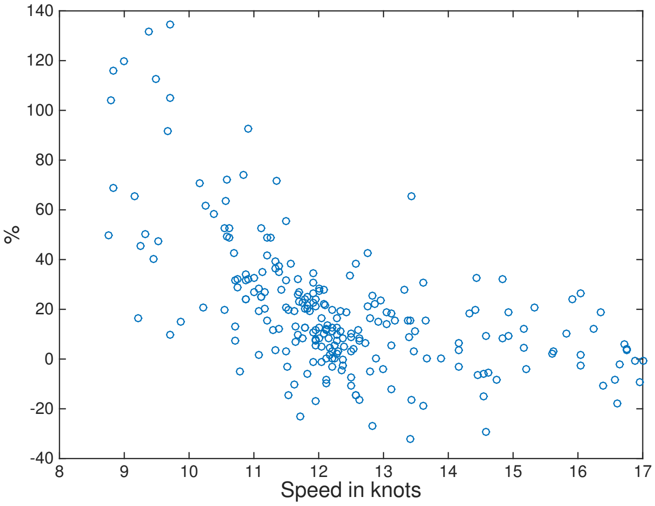


Figure A.14: Rest margin. 159,000 DWT Class in ballast condition

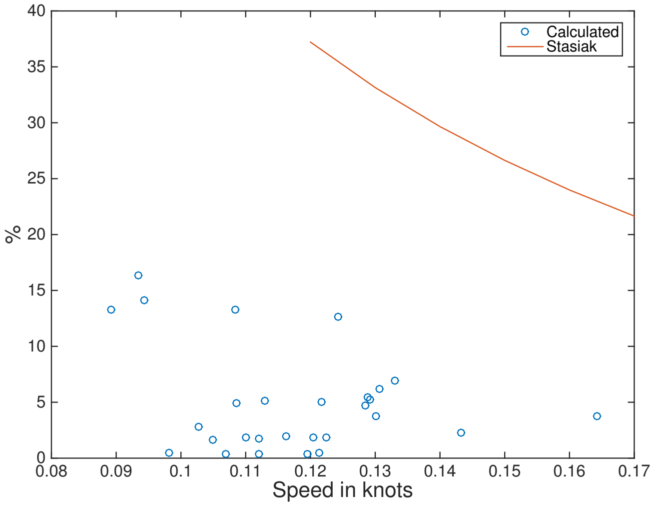


Figure A.15: Wave margin for head sea compared with Stasiak model. 159,000 DWT Class in ballast condition

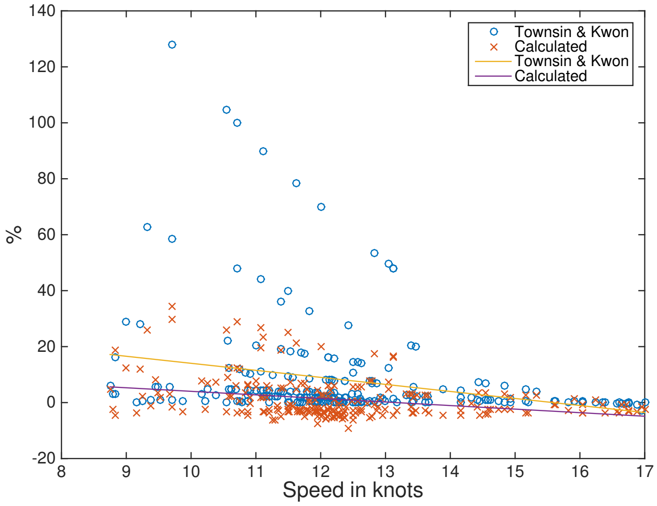


Figure A.16: Combined wave and wind margins compared with Townsin and Kwon model. 159,000 DWT Class in ballast condition

Appendix B

Margins for SKS Doda

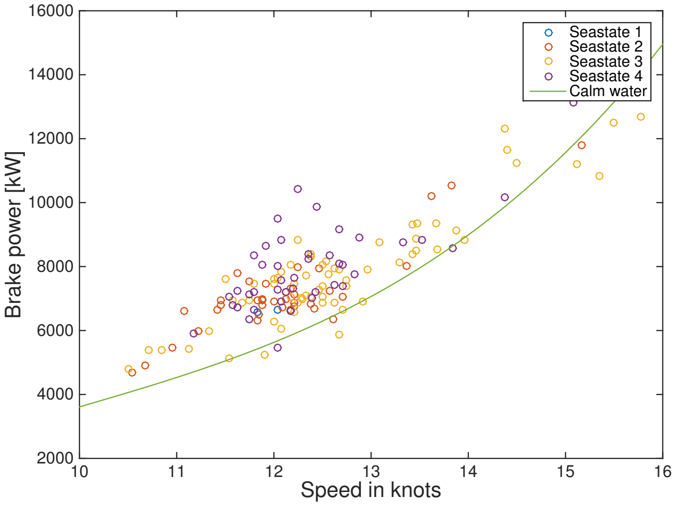


Figure B.1: Measured main engine power for different sea states. 120,000 DWT Class in loaded condition

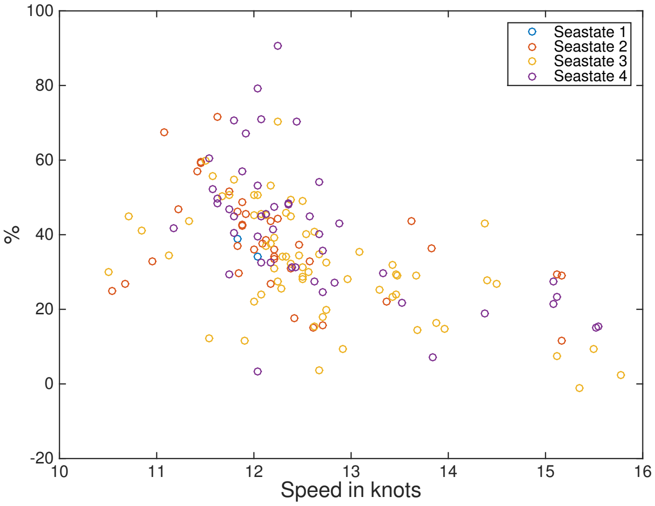


Figure B.2: Total sea margin. 120,000 DWT Class in loaded condition

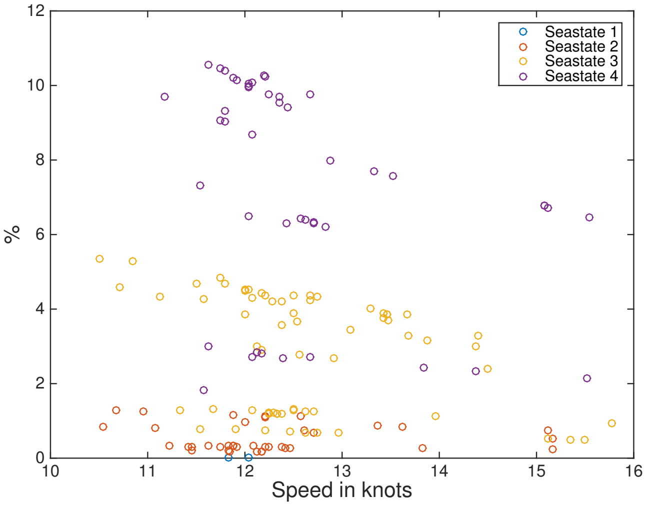


Figure B.3: Wave margin. 120,000 DWT Class in loaded condition

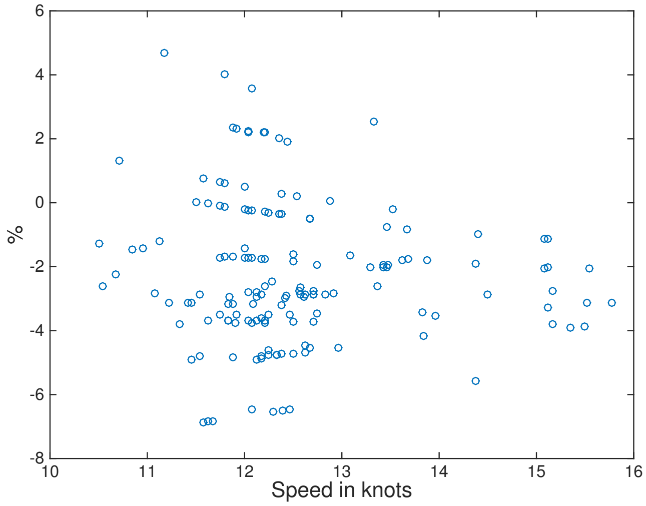


Figure B.4: Wind margin. 120,000 DWT Class in loaded condition

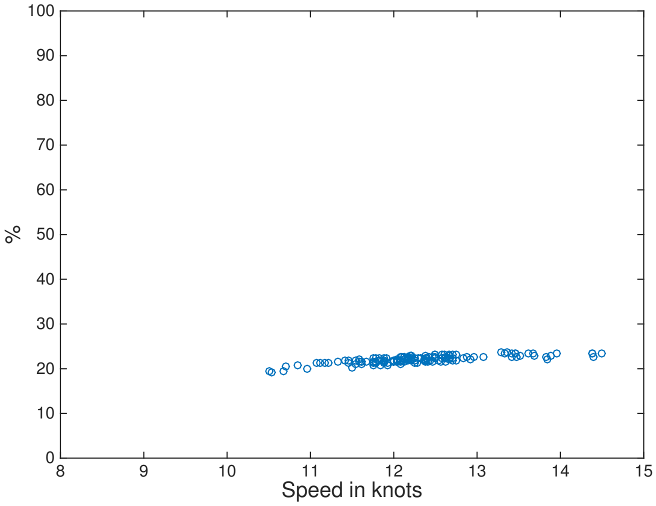


Figure B.5: Roughness/fouling margin. 120,000 DWT Class in loaded condition

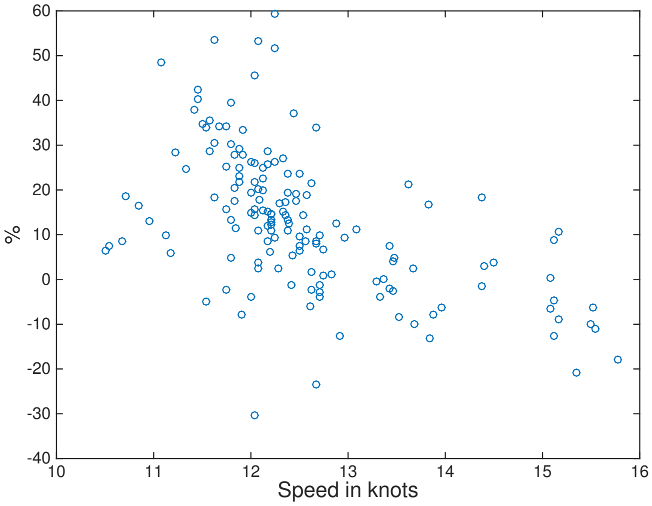


Figure B.6: Rest margin. 120,000 DWT Class in loaded condition

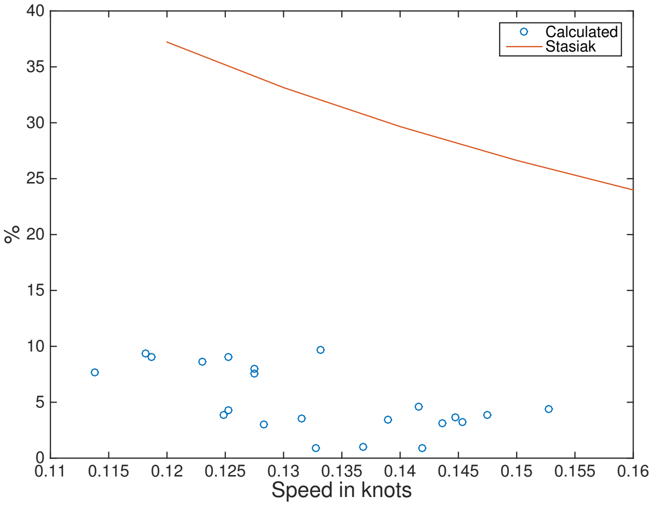


Figure B.7: Wave margin for head sea compared with Stasiak model. 120,000 DWT Class in loaded condition

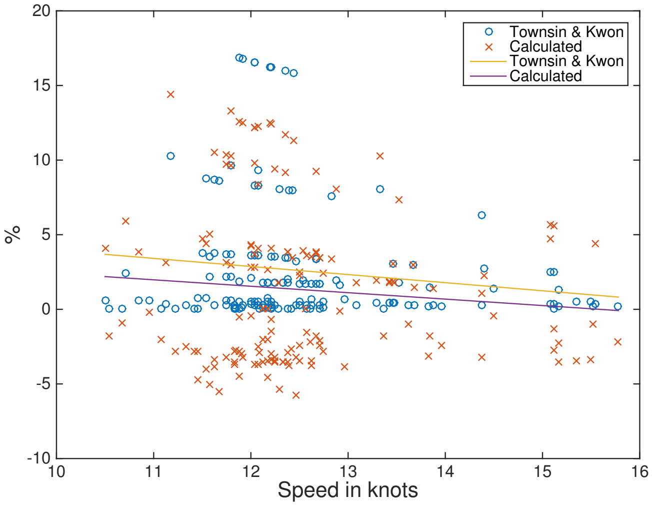


Figure B.8: Combined wave and wind margins compared with Townsin and Kwon model. 120,000 DWT Class in loaded condition

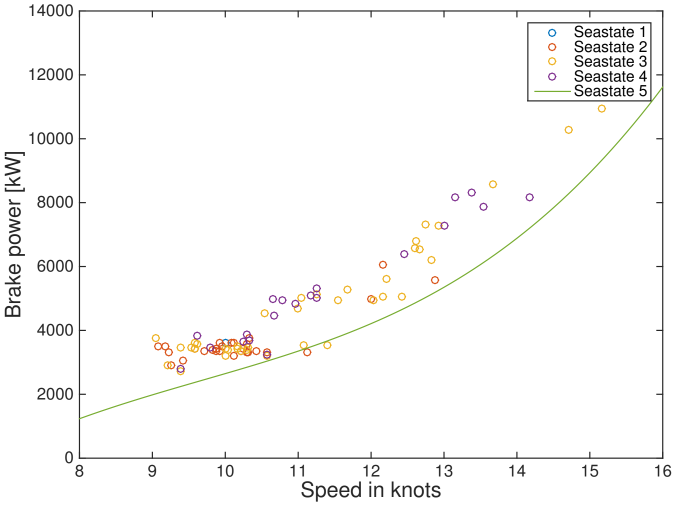


Figure B.9: Measured main engine power for different sea states. 120,000 DWT Class in ballast condition

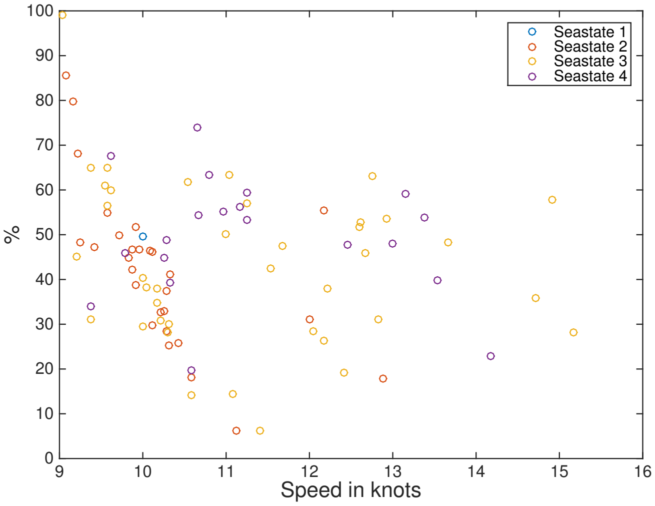


Figure B.10: Total sea margin. 120,000 DWT Class in ballast condition

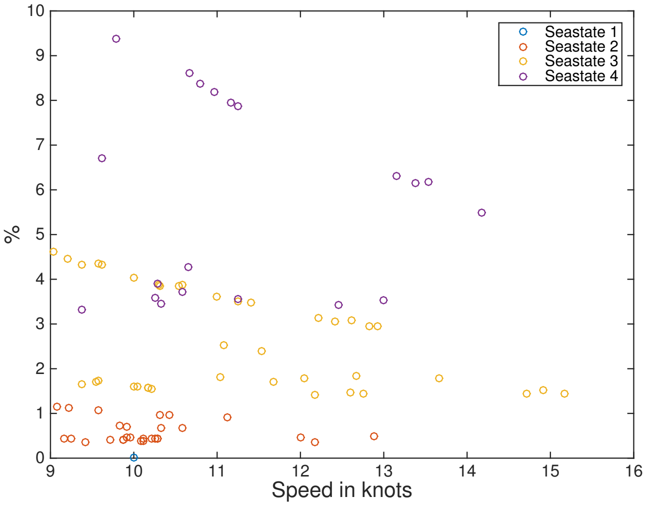


Figure B.11: Wave margin. 120,000 DWT Class in ballast condition

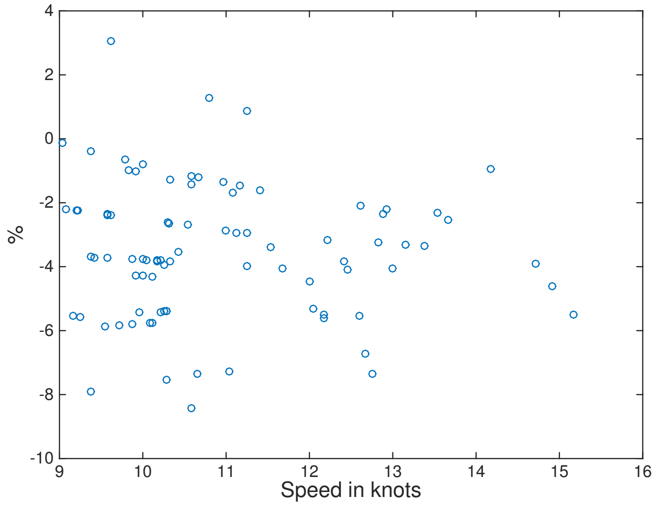


Figure B.12: Wind margin. 120,000 DWT Class in ballast condition

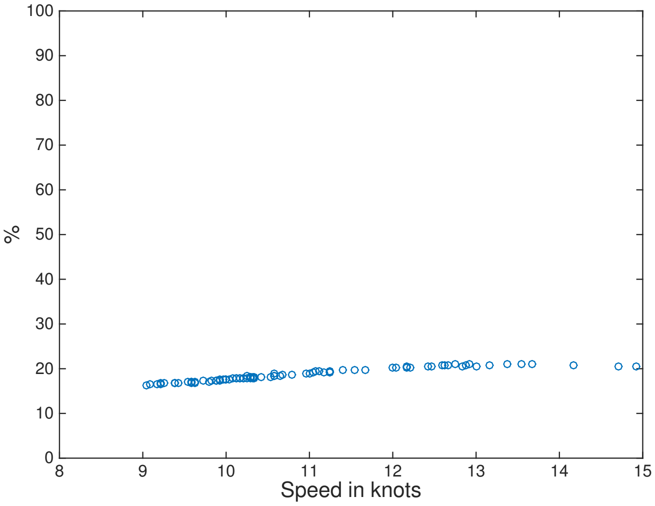


Figure B.13: Roughness/fouling margin. 120,000 DWT Class in ballast condition

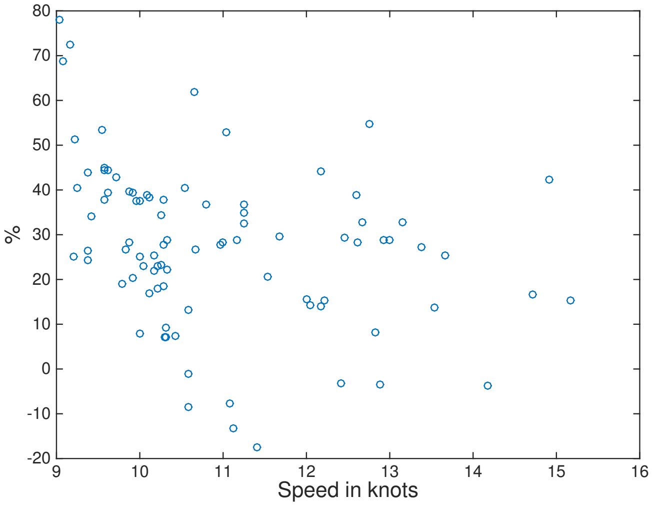


Figure B.14: Rest margin. 120,000 DWT Class in ballast condition

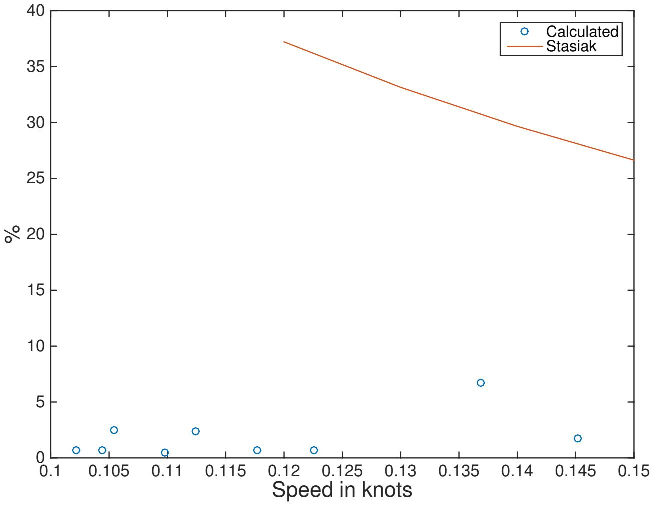


Figure B.15: Wave margin for head sea compared with Stasiak model. 120,000 DWT Class in ballast condition

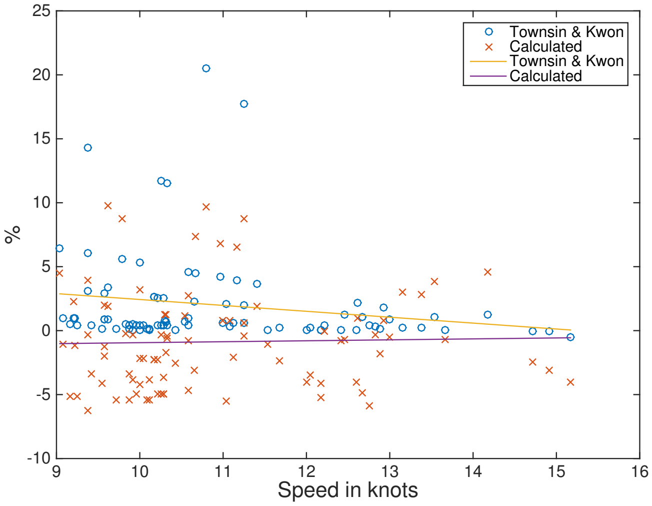
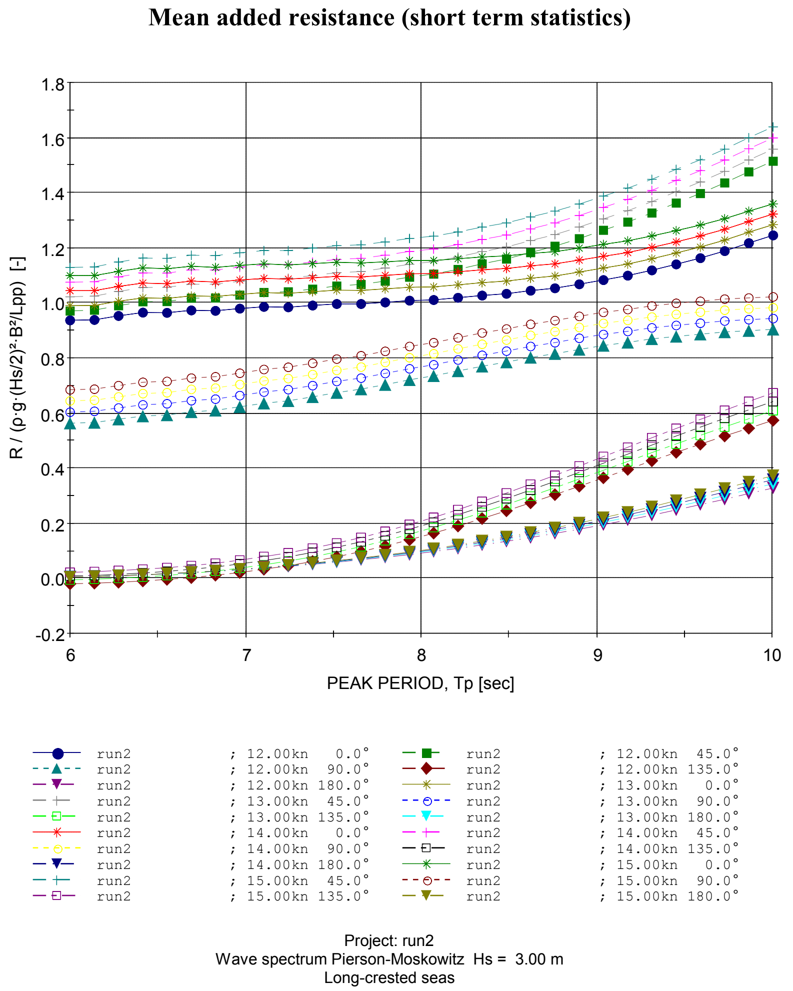


Figure B.16: Combined wave and wind margins compared with Townsin and Kwon model. 120,000 DWT Class in ballast condition

Appendix C

Coefficients for added resistance in waves from ShipX

ShipX		
	ENCL.	A.139
SHORT TERM STATISTICS	REPORT	
	DATE	16.05.15
	REF.	

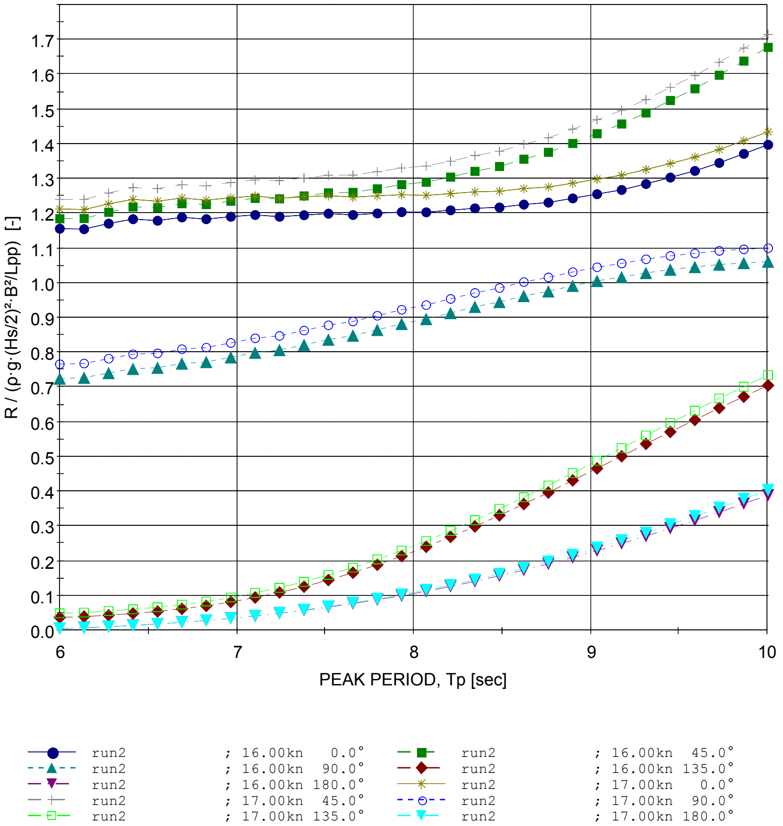


ShipX - 16.05.15 - 15:32:19 - Licensed to: NTNU (NTNU)

Figure C.1: Coefficients for added resistance in waves for 159,000 DWT Class in loaded condition

ShipX	SHORT TERM STATISTICS	ENCL. A.140
		REPORT
		DATE 16.05.15
		REF.

Mean added resistance (short term statistics)



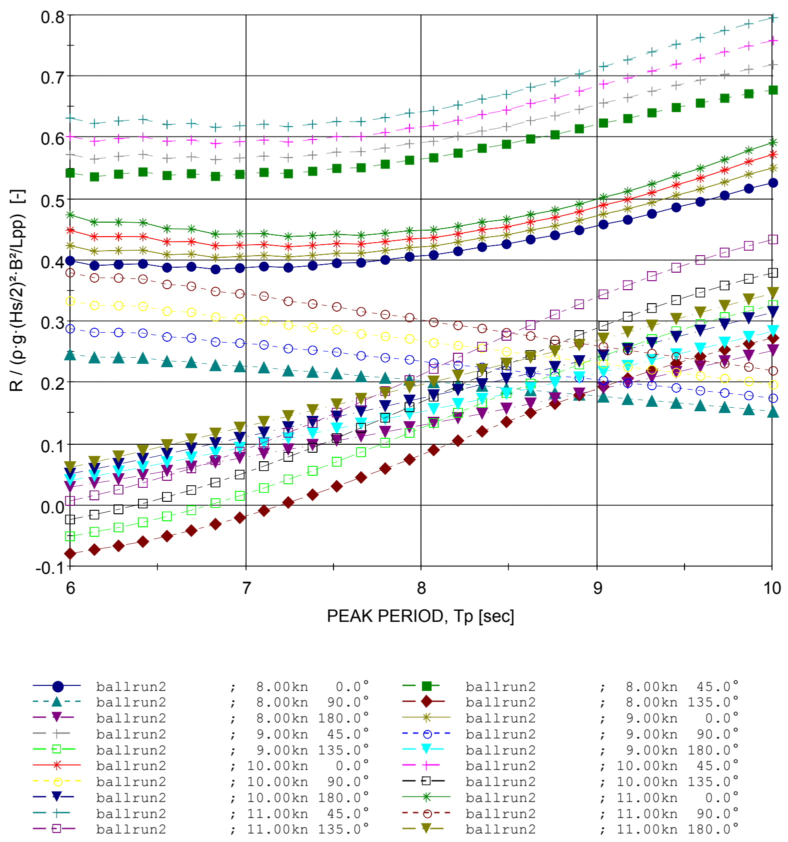
Project: run2
Wave spectrum Pierson-Moskowitz Hs = 3.00 m
Long-crested seas

ShipX - 16.05.15 - 15:32:19 - Licensed to: NTNU (NTNU)

Figure C.2: Coefficients for added resistance in waves for 159,000 DWT Class in loaded condition

ShipX	SHORT TERM STATISTICS	ENCL. A.144
		REPORT
		DATE 16.05.15
		REF.

Mean added resistance (short term statistics)



Project: ballrun2
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 16.05.15 - 15:36:30 - Licensed to: NTNU (NTNU)

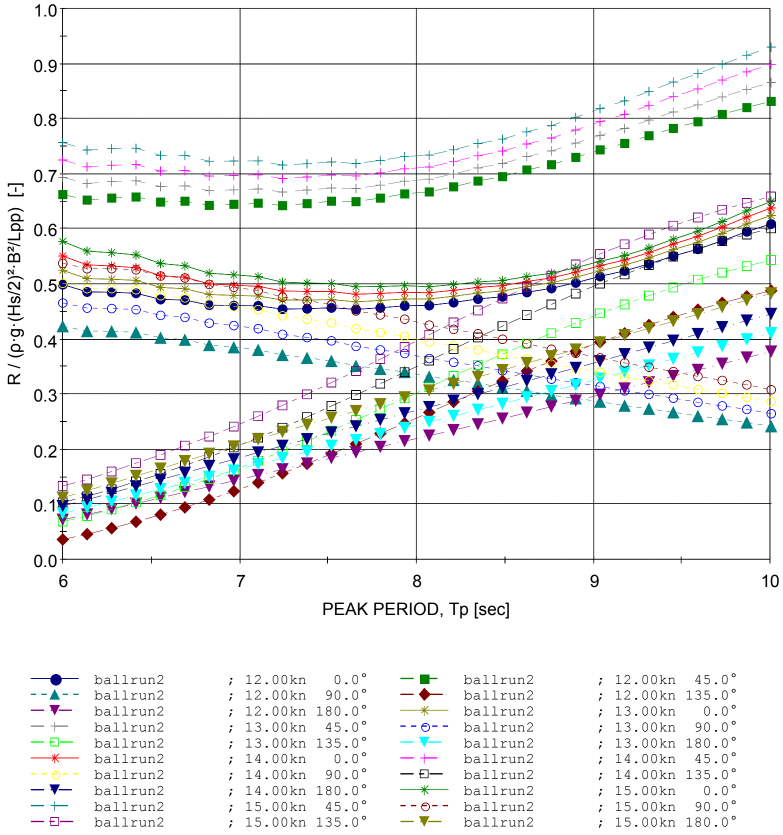
Figure C.3: Coefficients for added resistance in waves for 159,000 DWT Class in ballast condition

ShipX

SHORT TERM STATISTICS

ENCL. A.145
REPORT
DATE 16.05.15
REF.

Mean added resistance (short term statistics)



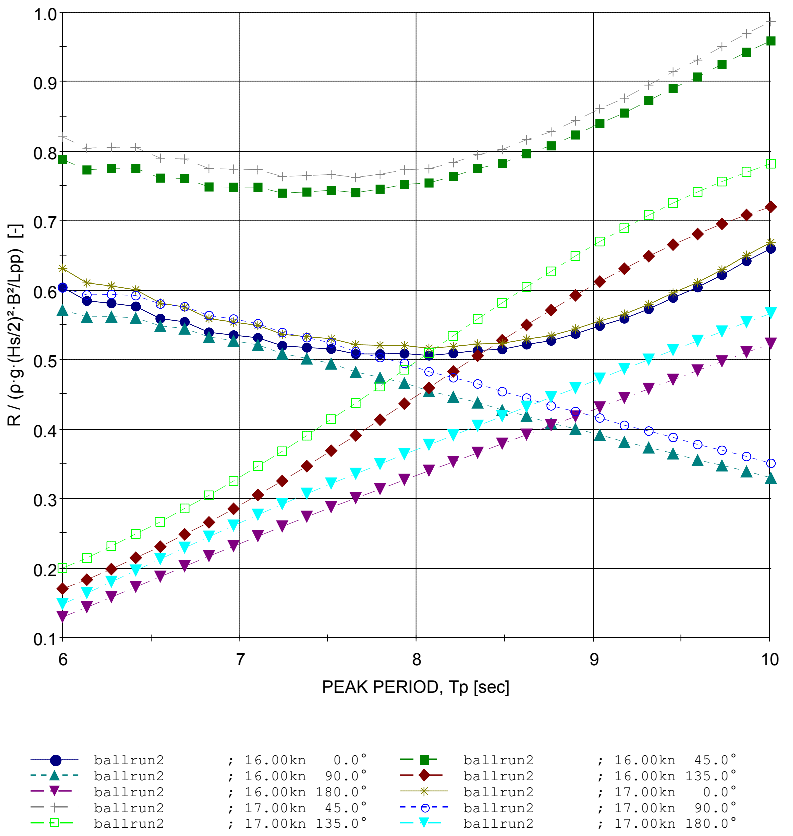
Project: ballrun2
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 16.05.15 - 15:36:31 - Licensed to: NTNU (NTNU)

Figure C.4: Coefficients for added resistance in waves for 159,000 DWT Class in ballast condition

ShipX	SHORT TERM STATISTICS	ENCL. A.146
		REPORT
		DATE 16.05.15
		REF.

Mean added resistance (short term statistics)



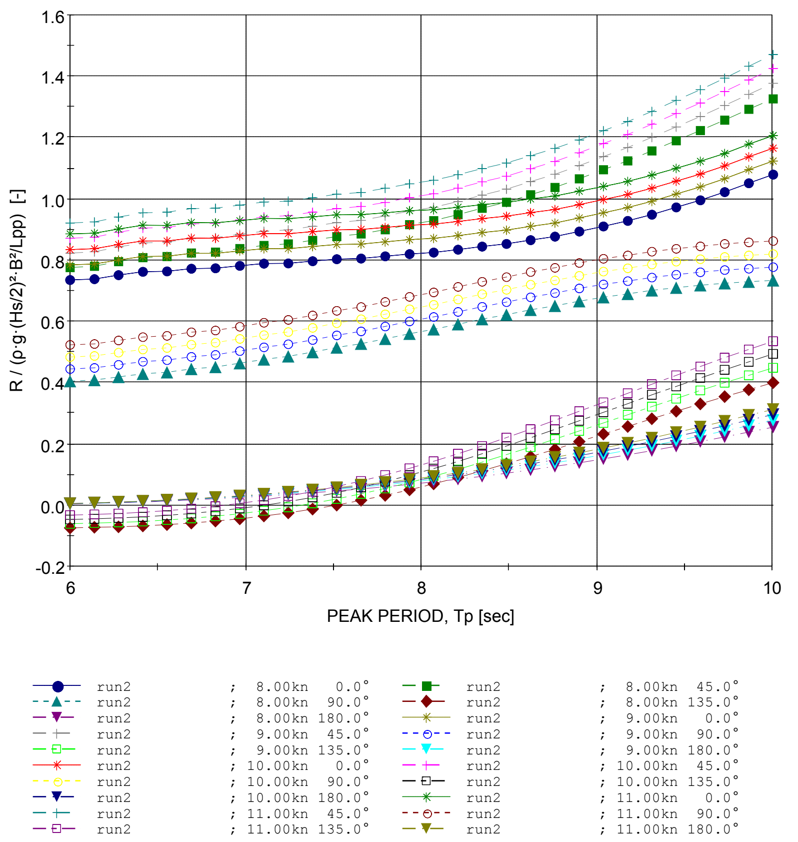
Project: ballrun2
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 16.05.15 - 15:36:31 - Licensed to: NTNU (NTNU)

Figure C.5: Coefficients for added resistance in waves for 159,000 DWT Class in ballast condition

ShipX	SHORT TERM STATISTICS	ENCL. A.150
		REPORT
		DATE 16.05.15
		REF.

Mean added resistance (short term statistics)



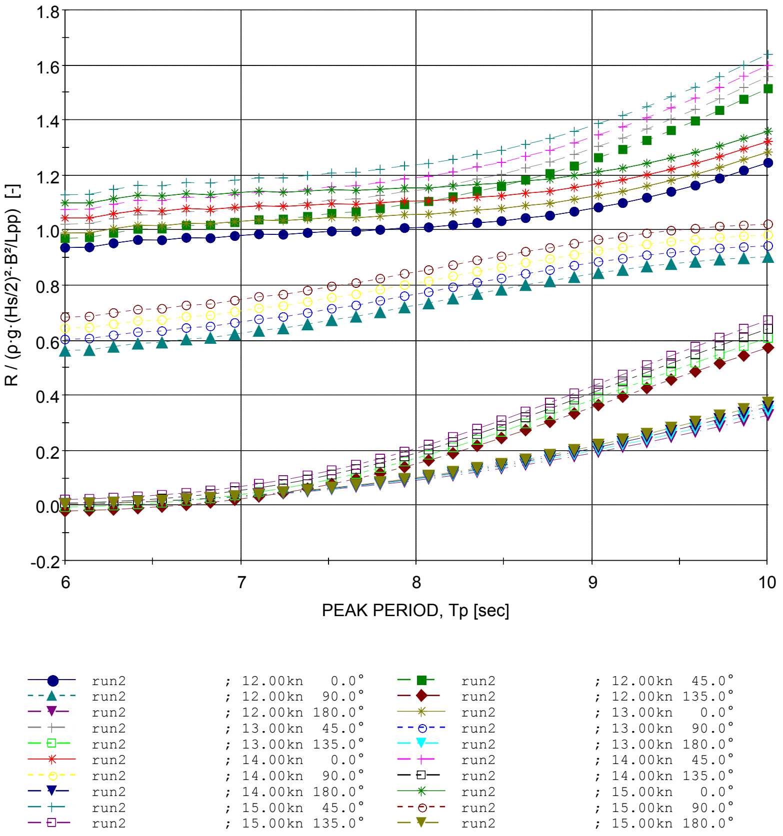
Project: run2
Wave spectrum Pierson-Moskowitz Hs = 3.00 m
Long-crested seas

ShipX - 16.05.15 - 15:39:51 - Licensed to: NTNU (NTNU)

Figure C.6: Coefficients for added resistance in waves for 120,000 DWT Class in design condition

ShipX SHORT TERM STATISTICS	ENCL. A.151
	REPORT
	DATE 16.05.15
	REF.

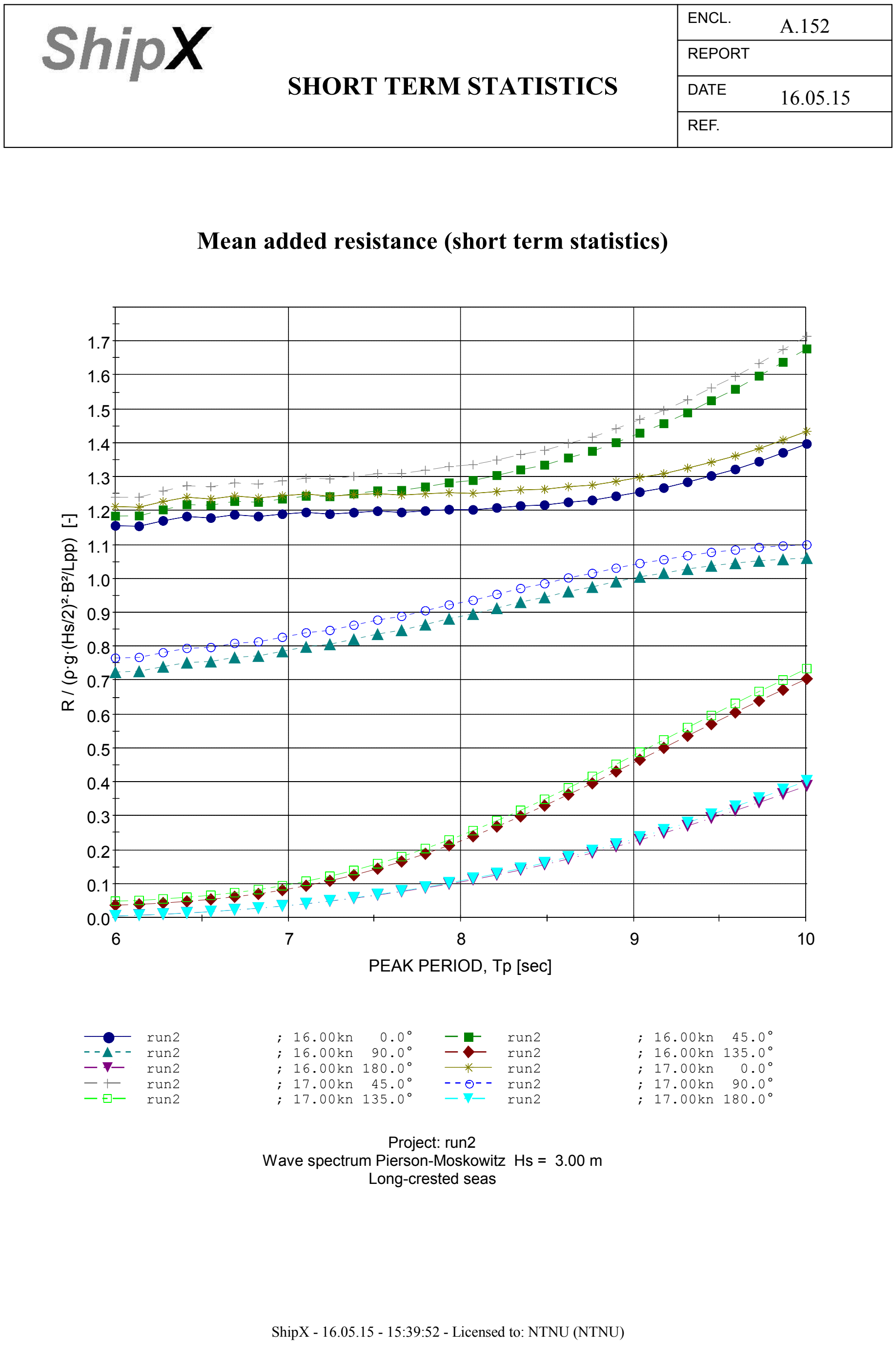
Mean added resistance (short term statistics)



Project: run2
Wave spectrum Pierson-Moskowitz Hs = 3.00 m
Long-crested seas

ShipX - 16.05.15 - 15:39:52 - Licensed to: NTNU (NTNU)

Figure C.7: Coefficients for added resistance in waves for 120,000 DWT Class in design condition



ShipX

SHORT TERM STATISTICS

ENCL.	A.152
REPORT	
DATE	16.05.15
REF.	

Mean added resistance (short term statistics)

● run2 ; 16.00kn 0.0°
■ run2 ; 16.00kn 45.0°
▲ run2 ; 16.00kn 90.0°
◆ run2 ; 16.00kn 135.0°
▼ run2 ; 16.00kn 180.0°
✳ run2 ; 17.00kn 0.0°
+ run2 ; 17.00kn 45.0°
○ run2 ; 17.00kn 90.0°
□ run2 ; 17.00kn 135.0°
▼ run2 ; 17.00kn 180.0°

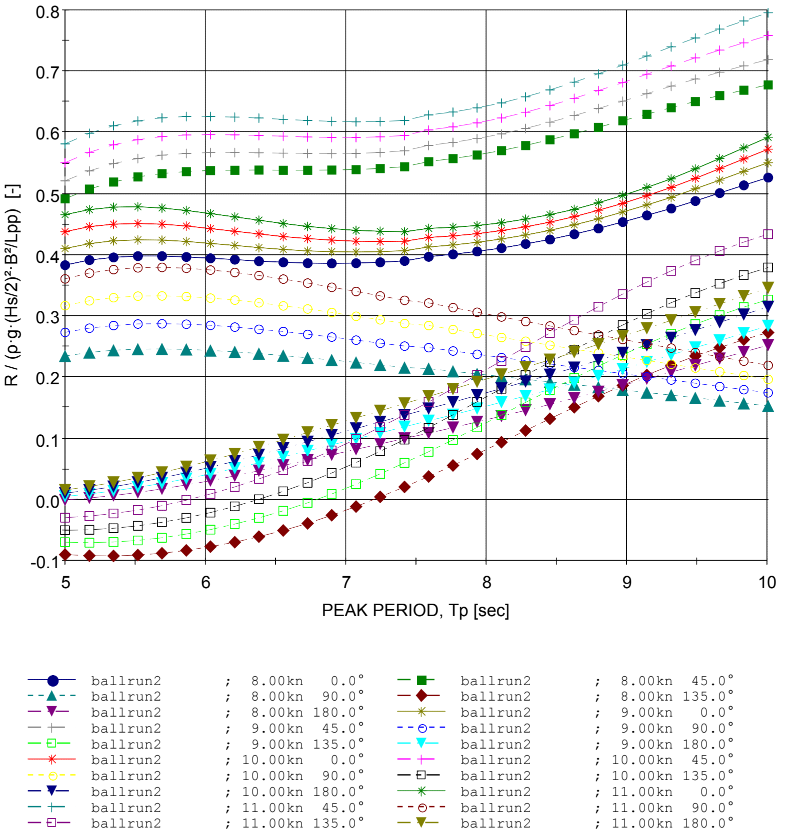
Project: run2
Wave spectrum Pierson-Moskowitz Hs = 3.00 m
Long-crested seas

ShipX - 16.05.15 - 15:39:52 - Licensed to: NTNU (NTNU)

Figure C.8: Coefficients for added resistance in waves for 120,000 DWT Class in design condition

ShipX	SHORT TERM STATISTICS	ENCL.	A.153
		REPORT	
		DATE	16.05.15
		REF.	

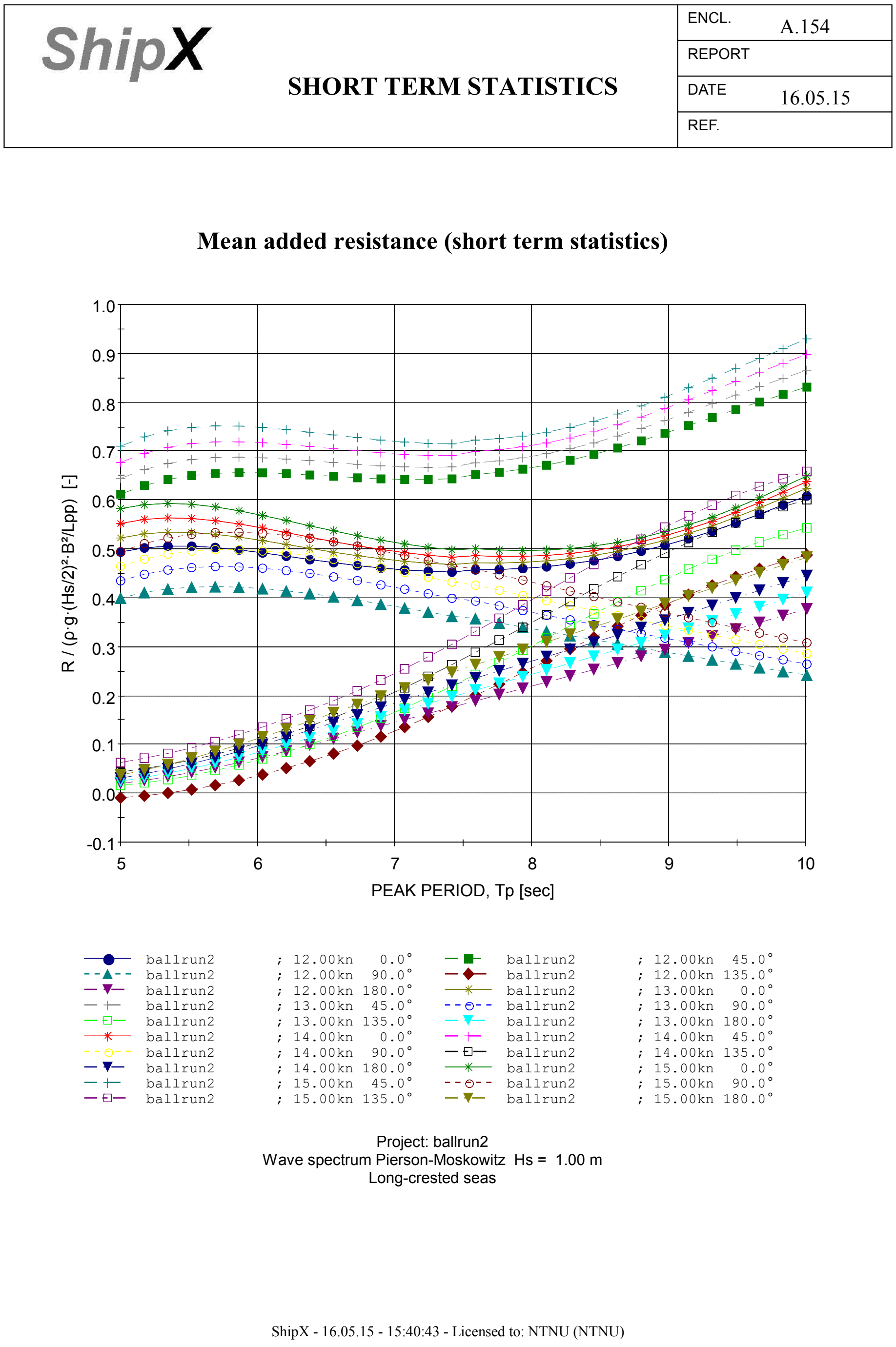
Mean added resistance (short term statistics)



Project: ballrun2
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 16.05.15 - 15:40:43 - Licensed to: NTNU (NTNU)

Figure C.9: Coefficients for added resistance in waves for 120,000 DWT Class in ballast condition



ShipX

SHORT TERM STATISTICS

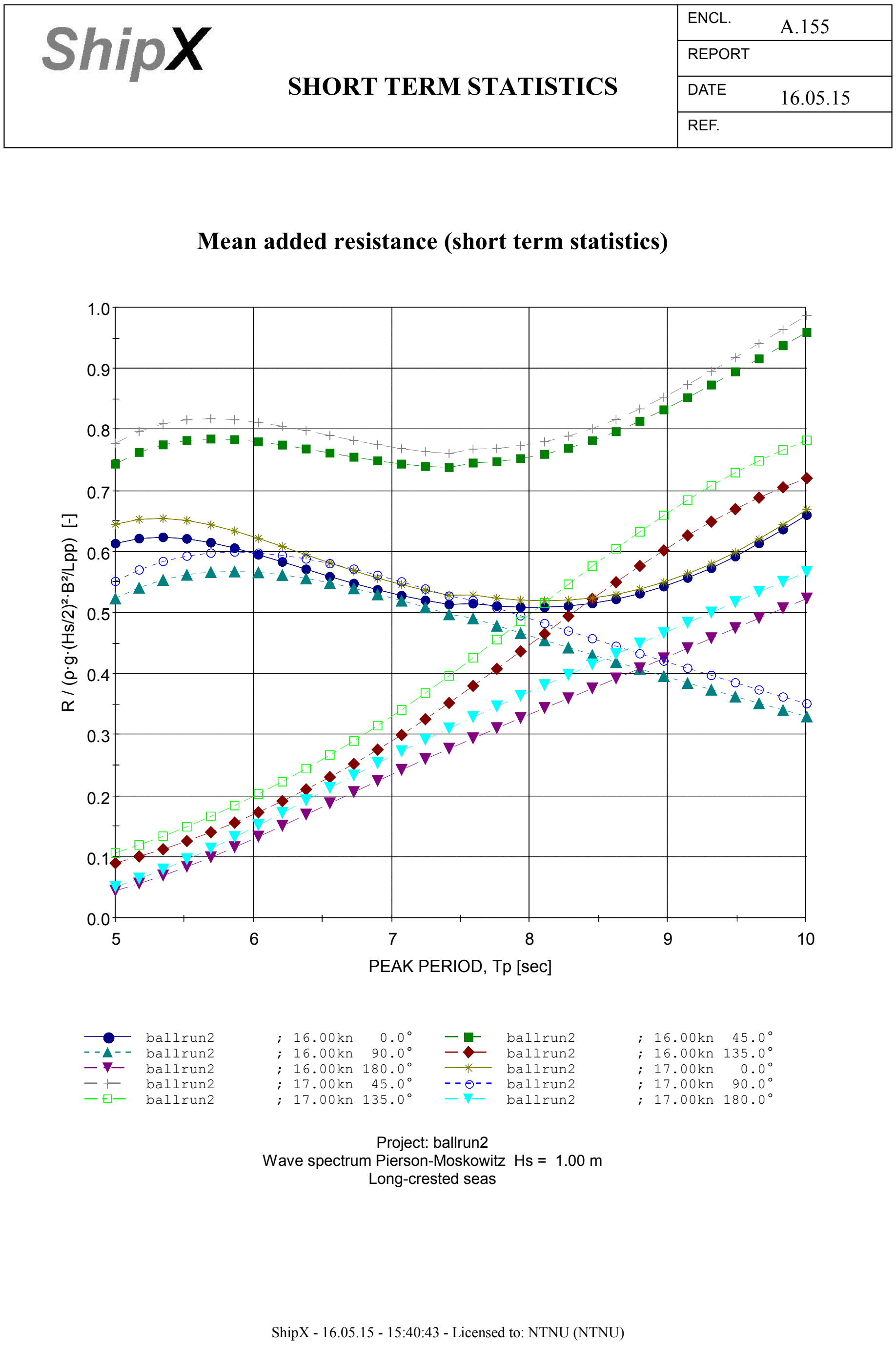
ENCL.	A.154
REPORT	
DATE	16.05.15
REF.	

Mean added resistance (short term statistics)

Project: ballrun2
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 16.05.15 - 15:40:43 - Licensed to: NTNU (NTNU)

Figure C.10: Coefficients for added resistance in waves for 120,000 DWT Class in ballast condition



ShipX

SHORT TERM STATISTICS

ENCL.	A.155
REPORT	
DATE	16.05.15
REF.	

Mean added resistance (short term statistics)

```
—●— ballrun2    ; 16.00kn   0.0°    —■— ballrun2    ; 16.00kn  45.0°
--▲-- ballrun2  ; 16.00kn  90.0°    —◆— ballrun2    ; 16.00kn 135.0°
—▼— ballrun2    ; 16.00kn 180.0°    —✳— ballrun2    ; 17.00kn   0.0°
—+— ballrun2    ; 17.00kn  45.0°    --○-- ballrun2  ; 17.00kn  90.0°
—□— ballrun2    ; 17.00kn 135.0°    —▽— ballrun2    ; 17.00kn 180.0°
```

Project: ballrun2
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 16.05.15 - 15:40:43 - Licensed to: NTNU (NTNU)

Figure C.11: Coefficients for added resistance in waves for 120,000 DWT Class in ballast condition

Appendix D

Coefficients for wind resistance

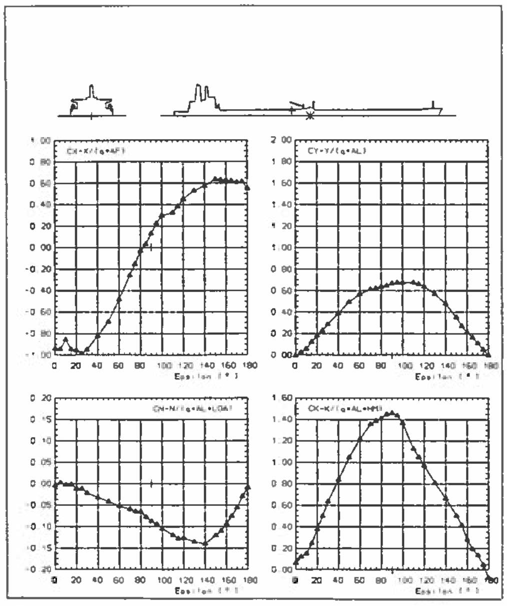


Fig. I.7: Tanker, loaded; L_{pp} = 336,00 m; L_{oa} = 351,40 m; B = 55,40 m; T = 23,50 m; AL = 3401,47 m²; AF = 1131,79 m²; SL rel. to main section = −24,45; SH rel. to above water line = 6,83 m

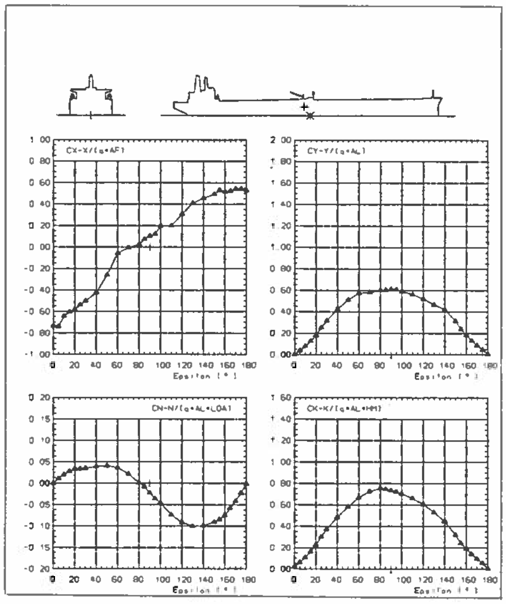


Fig. I.8: Tanker, ballast; L_{pp} = 336,00 m; L_{oa} = 351,40 m; B = 55,40 m; T_1 = 8,25 m; T_2 = 13,00 m; AL = 7839,63 m²; AF = 1803,93 m²; SL rel. to main section = 8,32 m; SH rel. to above water line = 12,34 m

Figure D.1: Coefficients for wind resistance. Figure from Brix (1993)

Appendix E

Matlab code

```
clear all
close all
% Loaded condition

% Skip
rho=1025;
rho_air = 1.23;
g=9.81;

B = 48;
Lpp = 264;
Ap = 830;
D=8.2;
nabla=165626;

etaD = [0.722 0.722 0.722 0.722 0.722 0.727 0.735 0.738 0.733 0.722 0.716];
etaH = [1.210 1.210 1.210 1.210 1.210 1.209 1.211 1.209 1.205 1.197 1.195];
etaR = [1.018 1.018 1.018 1.018 1.018 1.023 1.030 1.035 1.036 1.036 1.035];
t =    [0.223 0.223 0.223 0.223 0.223 0.220 0.214 0.211 0.216 0.224 0.226];
ws =   [0.358 0.358 0.358 0.358 0.358 0.355 0.351 0.348 0.349 0.352 0.352];
etam = .99;
etadm = etaD.*.95; %trial correction
cx0 = 0.95; % air resitance coefficient
cx = [.95 .75 0 -.55 -.55 -.55 0 .75]; % Wind coefficients for directions 1-8 from noon rep
bhptokw=0.7353;
tontokw=.7353/.0031;

deg0 = [0.9000    0.9444    0.9889    1.0333    1.0778    1.1222    1.1667    1.2111
```

```
1.2556    1.3000];
deg45 = [1.1000    1.1389    1.1778    1.2167    1.2556    1.2944    1.3333
1.3722    1.4111    1.4500];
deg90 = [0.7000    0.7389    0.7778    0.8167    0.8556    0.8944    0.9333
0.9722    1.0111    1.0500];
deg135 = [0.2250    0.2556    0.2861    0.3167    0.3472    0.3778    0.4083
0.4389    0.4694    0.5000];
deg180 = [0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2];

wave_factor = {deg0 deg45 deg90 deg135 deg180}; % For directions head to stern 45 degree i

% Propulsion
            J = [0:.05:.8];
            Kt= [3.54 3.383 3.213 3.032 2.843 2.647 2.444 2.235 2.022 1.803 1.580 1.35 1.1
            Kq = [3.738 3.609 3.463 3.304 3.135 2.957 2.773 2.583 2.388 2.188 1.982 1.768 
            eta0 = J.*Kt./(2*pi.*Kq);
            eta0fit = polyfit(J,eta0,6);

            ktfit = polyfit(J,Kt,2);
            J2 = J(9:length(J));
            Kt2 = Kt(9:length(J));
            ktj2 = Kt2./(J2.^2);
            ktj2fit = polyfit(ktj2,J2,3);

% Reading weather and consumption info from noon reports
num = xlsread('Skeena posreps.xls');

ton_day = num(:,3);
gps_speed = num(:,4);
log_speed = num(:,5);
draft = num(:,6);
dir = num(:,7);
bf = num(:,8);
seastate = num(:,9);
trim = num(:,10);

% Deleting wrong reports (fuel consumption less than 7 ton/day)
i=0;
for j=1:length(ton_day)
    i=i+1;
    if (ton_day(i)<7)
        ton_day(i)=[];
        gps_speed(i)=[];
        draft(i)=[];
        dir(i)=[];
```

```
        bf(i)=[];
        seastate(i)=[];
        i=i-1;
    end
end

% Extrapolating speed-power relation for lower speeds ballast
Cr = [.274 .315 .358 .401 .449 .502 .562 .629 .705 .787 .868];
fn_test = [.138:0.005:.188];

fn = [0:0.005:.138];
a = 0.274/0.138;
Cr_int = fn.*a;

Ukn = [13.5:.5:18.5];
Ums = 0.5144.*Ukn;
lwl = 260.42;
my = 1.1883*10^-6;
Ct = [2.405 2.438 2.473 2.509 2.550 2.596 2.649 2.711 2.780 2.857 2.932];
Rn = Ums.*lwl./my;

Cf = 10^3*0.075./(log10(Rn)-2).^2;

Ukn2 = [8:.5:13];
Ums2 = 0.5144.*Ukn2;
Rn2 = Ums2.*lwl./my;
Cf2 = 10^3*0.075./(log10(Rn2)-2).^2;

fn2 = Ums2./sqrt(9.81.*lwl);
Cr2 = fn2.*a;
caa = 0.093;
deltacf = 0.234;
form = 1.230;
Ct2 = form.*Cf2 + deltacf + Cr2 + caa;

S = 13203.7;
Vkn = [8:0.5:18.5];
V = Vkn.*0.5144;
CT = [Ct2 Ct];
RT = 0.5*1025.*V.^2.*S.*CT./1000;

etad = .783;
mecfac = 1.042;
Pe = RT.*V;
Pd = Pe./etad;
```

```
PB = Pd./mecfac;

BHP = PB./(735.3); % Estimated speed-power relationship for lower speeds

power_with15sm = [10453 11886 13511 15320 17362 19637 22181 25041 28248 31827 35828];
speed = [13.5 14 14.5 15 15.5 16 16.5 17 17.5 18 18.5];

power = power_with15sm/1.15;

polyball = polyfit([Vkn(1:12) speed], [BHP(1:12) power].*bhptokw,3);

% Extrapolating speed-power relation for lower speeds

Cr = [0.069 0.084 0.103 0.122 0.142 0.162 0.179 0.196 0.212 0.232 0.260];
fn_test = [.125:0.005:.175];

fn = [0:0.005:.125];
a = 0.069/0.125;
Cr_int = fn.*a;

Ukn = [12.5:.5:17.5];
Ums = 0.5144.*Ukn;
lwl = 269.3;
my = 1.1883*10^-6;
Ct = [2.155 2.161 2.171 2.183 2.195 2.208 2.218 2.228 2.238 2.251 2.2744];
Rn = Ums.*lwl./my;

Cf = 10^3*0.075./(log10(Rn)-2).^2;

Ukn2 = [8:.5:12];
Ums2 = 0.5144.*Ukn2;
Rn2 = Ums2.*lwl./my;
Cf2 = 10^3*0.075./(log10(Rn2)-2).^2;

fn2 = Ums2./sqrt(9.81.*lwl);
Cr2 = fn2.*a;
caa = 0.045;
deltacf = 0.224;
form = 1.235;
Ct2 = form.*Cf2 + deltacf + Cr2 + caa;

S = 18265;
Vkn = [8:0.5:17.5];
V = Vkn.*0.5144;
CT = [Ct2 Ct];
```

```
RT = 0.5*1025.*V.^2.*S.*CT./1000;

etad = .722;
mecfac = 1.042; % etaM/Cp (trial correction)
Pe = RT.*V;
Pd = Pe./etad;
PB = Pd./mecfac;

BHP = PB./(735.3); % Estimated speed-power relationship for lower speeds

power_with15sm = [11157 12504 13976 15597 17377 19335 21485 23851 26456 29340 32563];
speed = [12.5 13 13.5 14 14.5 15 15.5 16 16.5 17 17.5];

power = power_with15sm/1.15;

poly = polyfit([Vkn(1:10) speed], [BHP(1:10) power].*bhptokw,3);

angle = [0 45 90 135 180 135 90 45].*(pi/180);

% Calculating true direction and wind speed[8:1:1
for i=1:length(bf)
    vs =gps_speed(i)*0.5144;
    vrel = 0.836*bf(i)^(3/2);
    vtrue = sqrt(vs^2 + vrel^2 -2*vs*vrel*cos(angle(dir(i))));
    truedir = pi- acos((vs^2+vtrue^2-vrel^2)/(2*vs*vtrue));
    true_angle(i) = truedir;
    true_wind(i) = vtrue;
    testval(i)=(vs^2+vtrue^2-vrel^2)/(2*vs*vtrue);
end
v_rel = 0.836*bf.^(3/2);

true_dir_round = round((true_angle*180/pi)/45)*45;
for i=1:length(true_dir_round)
    for j=1:length(angle)
        if true_dir_round(i) == angle(j)*180/pi
            true_dir(i)=j;
        end
    end
end

% Selecting data for drafts 14m-16m (Loaded condition 16m)

iddraft=[];
idhead=[];
id1 = [];
```

```
id2 = [];
id3 = [];
id4 = [];
id5 = [];
for i=1:length(ton_day)
    if 14<=draft(i) & draft(i)<=16
        iddraft = [iddraft i];
    end
end

% Selecting weather direction
idhead=[];
id45=[];
id90=[];
id135=[];
id180=[];

for i=1:length(iddraft)
    if dir(iddraft(i))==1
        idhead = [idhead iddraft(i)];
    elseif dir(iddraft(i))==2 || dir(iddraft(i)) == 8
        id45 = [id45 iddraft(i)];
    elseif dir(iddraft(i))==3 || dir(iddraft(i)) == 7
        id90 = [id90 iddraft(i)];
    elseif dir(iddraft(i))==4 || dir(iddraft(i)) == 6
        id135 = [id135 iddraft(i)];
    elseif dir(iddraft(i))==5
        id180 = [id180 iddraft(i)];
    end
end

iddir = {idhead id45 id90 id135 id180};

% Selecting sea state
for j=1:5
id1 = [];
id2 = [];
id3 = [];
id4 = [];
id5 = [];
id6 = [];
for i=1:length(iddir{j})
    if seastate(iddir{j}(i))==1
        id1 = [id1 iddir{j}(i)];
        elseif seastate(iddir{j}(i))==2
```

```
        id2 = [id2 iddir{j}(i)];
        elseif seastate(iddir{j}(i))==3
        id3 = [id3 iddir{j}(i)];
        elseif seastate(iddir{j}(i))==4
        id4 = [id4 iddir{j}(i)];
        elseif seastate(iddir{j}(i))==5
        id5 = [id5 iddir{j}(i)];
        elseif seastate(iddir{j}(i))==6
        id6 = [id6 iddir{j}(i)];
    end
end
idsea{j} = {id1 id2 id3 id4 id5 id6};
end

% Calculating added wave resistance
seascale = [.1 .5 1 1.5 2.5 4];
Raw = rho*g*B^2/(Lpp*4).*seascale.^2; % for BF 1-6, must be multiplied by wave coefficient

% Added resistance due to wind
Rw = 0.5*rho_air*Ap ; %must be multiplied by relative wind speed squared in m/s and wind co
% Air resistance
Rair =0.5*rho_air*Ap; % must be multiplied by ship speed squared

kw_wave_vec = [];
kw_wind_vec = [];
kw_calm_vec = [];
service_vec =  [];
kw_vec = [];
speed_vec = [];
kw_day_vec =[];
id_vec = [];
kwon_vec=[];
dr_vec=[];
for i=1:5 % go through each direction
    for j=1:6 % go through each sea state
        for k=1:length(idsea{i}{j}) % go through each report

            % Added resistance in waves, wind and calm water
            Rawtemp = Raw(seastate(idsea{i}{j}(k)))*wave_factor{i}(round(gps_speed(idsea{i}
            Rwtemp = Rw*(v_rel(idsea{i}{j}(k))^2*cx(dir(idsea{i}{j}(k)))-cx0*(gps_speed(ids
            Rtstemp = 1000.*(polyval(polyball,gps_speed(idsea{i}{j}(k)))+((polyval(poly,gps

            % Calculation of propulsion point
            ktj2temp = (Rtstemp+Rawtemp+Rwtemp)/(rho*(1-t(ceil(round(gps_speed(idsea{i}{j}
            jstar = polyval(ktj2fit,ktj2temp);
```

```
            etatemp = polyval(eta0fit,jstar);
            etadtemp = etaH(ceil(round(gps_speed(idsea{i}{j}(k))/.5)*.5)-7)*etaR(ceil(rounc

            % Conversion from resistance to brake power in kW
            kw_aw{i}{j}(k) = Rawtemp*.5144*gps_speed(idsea{i}{j}(k))/(etadtemp*etam*1000);
            kw_wave_vec = [kw_wave_vec kw_aw{i}{j}(k)];

            kw_wind{i}{j}(k) = Rwtemp*.5144*gps_speed(idsea{i}{j}(k))/(etadtemp*etam*1000);
            kw_wind_vec = [kw_wind_vec kw_wind{i}{j}(k)];

            kw_calm{i}{j}(k) = Rtstemp*.5144*gps_speed(idsea{i}{j}(k))/(etadtemp*etam*1000)
            kw_calm_vec = [kw_calm_vec kw_calm{i}{j}(k)];

            service{i}{j}(k) = ton_day(idsea{i}{j}(k)).*tontokw - kw_aw{i}{j}(k) - kw_wind{
            service_vec = [service_vec service{i}{j}(k)];

            kw{i}{j}(k) = ton_day(idsea{i}{j}(k)).*tontokw - kw_aw{i}{j}(k) - kw_wind{i}{j}
            kw_day_vec = [kw_day_vec ton_day(idsea{i}{j}(k)).*tontokw];
            kw_vec = [kw_vec kw{i}{j}(k)];
            speed_vec = [speed_vec gps_speed(idsea{i}{j}(k))];
            id_vec = [id_vec idsea{i}{j}(k)];

            % Townsin-Kwon
            my1=1.7-.003*(bf(idsea{i}{j}(k))-4)^2;
            my2=.9-.006*(bf(idsea{i}{j}(k))-6)^2;
            my3=.4-.003*(bf(idsea{i}{j}(k))-8)^2;
            my = [1 my1 my2 my2 my3 my2 my2 my1];
            fntemp=.5144*gps_speed(idsea{i}{j}(k))/sqrt(g*Lpp);
            alpha=2.6-13.1*fntemp-15.1*fntemp^2;
            kwon_vec=[kwon_vec ((1/(1-.01*(alpha*.5*my(dir(idsea{i}{j}(k)))*(.5*bf(idsea{i}

            % Townsin roughness
            RN = .5144*gps_speed(idsea{i}{j}(k))*Lpp/(1.1883*10^-6);
            ahr=1000*10^-6;
            deltacf=44*((ahr/Lpp)^(1/3)-10*RN^(-1/3))+.125;
            deltaRf=.5*rho*(.5144*gps_speed(idsea{i}{j}(k)))^2*S*deltacf/1000;
            deltaPf=deltaRf*.5144*gps_speed(idsea{i}{j}(k))/(etadtemp*etam*1000);
            dr_vec = [dr_vec deltaPf];

        end
    end
end
% Write to text file
y = [speed_vec; kw_day_vec; kw_wave_vec; kw_wind_vec; service_vec; kw_calm_vec; kwon_vec; c
fid=fopen('sd.txt','w');
```

```
fprintf(fid,'%f %f %f %f %f %f %f %f\n',y);
fclose(fid);

% Townsin roughness
figure
plot(speed_vec,dr_vec,'o',speed_vec,service_vec,'x')
xlabel('Speed in knots')
ylabel('kW')
legend('Power due to fouling modelled as hull roughness','Calculated power due to fouling')

% Stasiak: Wave margin as function of Froude number
kw_aw2=[kw_aw{1}{1} kw_aw{1}{2} kw_aw{1}{3} kw_aw{1}{4} kw_aw{1}{5}];
kw_calm2=[kw_calm{1}{1} kw_calm{1}{2} kw_calm{1}{3} kw_calm{1}{4} kw_calm{1}{5}];
figure
plot(0.5144.*gps_speed(idhead)./sqrt((g*Lpp)),100.*kw_aw2./kw_calm2,'o',[.12:.01:.15],100.*
legend('Calculated','Stasiak')
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('%', 'FontSize', 18);

% Townsin-Kwon
polykwon=polyfit(speed_vec,100.*kwon_vec,1);
polyww=polyfit(speed_vec,100.*(kw_wave_vec+kw_wind_vec)./kw_calm_vec,1);
figure
plot(speed_vec,100.*kwon_vec,'o',speed_vec,100.*(kw_wave_vec+kw_wind_vec)./kw_calm_vec,'x',
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('%', 'FontSize', 18);
legend('Townsin & Kwon','Calculated','Townsin & Kwon','Calculated')

% Main engine consumption measured, converted to kW, for different
% seastates
sea1=[];
sea2=[];
sea3=[];
sea4=[];
sea5=[];
sea6=[];
for i=1:length(id_vec)
    if seastate(id_vec(i))==1
        sea1=[sea1 i];
    elseif seastate(id_vec(i))==2
        sea2=[sea2 i];
    elseif seastate(id_vec(i))==3
        sea3=[sea3 i];
```

```
    elseif seastate(id_vec(i))==4
        sea4=[sea4 i];
    elseif seastate(id_vec(i))==5
        sea5=[sea5 i];
    elseif seastate(id_vec(i))==6
        sea6=[sea6 i];
    end
end
figure
plot(speed_vec(sea1),kw_day_vec(sea1),'o',speed_vec(sea2),kw_day_vec(sea2),'o',speed_vec(se
legend('Seastate 1','Seastate 2','Seastate 3','Seastate 4','Seastate 5','Seastate 6')
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('Brake power [kW]', 'FontSize', 18);

% Total margin for different seastates
figure
plot(speed_vec(sea1),100.*(kw_day_vec(sea1)-kw_calm_vec(sea1))./kw_calm_vec(sea1),'o',speec
legend('Seastate 1','Seastate 2','Seastate 3','Seastate 4','Seastate 5','Seastate 6')
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('%', 'FontSize', 18);

% Wave margin
figure
plot(speed_vec(sea1),100.*kw_wave_vec(sea1)./kw_calm_vec(sea1),'o',speed_vec(sea2),100.*kw_
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('%', 'FontSize', 18);
legend('Seastate 1','Seastate 2','Seastate 3','Seastate 4','Seastate 5','Calm water predict

% Wind margin
figure
plot(speed_vec,100.*kw_wind_vec./kw_calm_vec,'o')
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('%', 'FontSize', 18);

% Roughness margin
figure
plot(speed_vec,100.*dr_vec./kw_calm_vec,'o')
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('%', 'FontSize', 18);
axis([8 15 0 100])
```

```
% Rest margin
figure
plot(speed_vec,100.*(service_vec-dr_vec)./kw_calm_vec,'o')
set(gca,'FontSize',14)
xlabel('Speed in knots', 'FontSize', 18);
ylabel('%', 'FontSize', 18);
```