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Abstract:

In this thesis five bulk ships from Kristian Gerhard Jebsen Skipsrederi AS has been monitored over time in order to discover the increase in resistance due to fouling on the hull and propeller. Each ship has reported weather and ship data twice a month. These reports have been used to discover the resistance due to fouling by correcting all other added resistances from each measurement in the given time period. When all other resistance types are corrected for, each measurement is as if the ship travelled in calm weather. Then these results can be compared. The resistance types that are corrected for in this thesis are:

- Added resistance in waves
- Added resistance in wind
- Added resistance due to steering
- Speed loss due to shallow water

When each measurement has been corrected for these resistance types, they are corrected to a reference speed and draft to be able to compare the results properly.

In addition, the extent of the added resistance due to yaw angle because of lift forces from the rudder has been investigated and found to be neglectable.

It has been found that the increase in resistance due to fouling is relatively linear the first two-three years. After three years the increase in resistance gets exponential.

Keyword:

Added resistance in waves, wind and steering
Speed and draft corrections
Fouling on ship hull

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M.Sc. thesis 2010

for

Mads Aas-Hansen

Monitoring of hull condition of ships

In order to optimize the docking intervals of merchant ships, it is important to get reliable data for how the fuel consumption is evolving over time, since an average increase of fuel consumption is usually a clear sign of increasing hull and propeller fouling. The main difficulty is that the data for fuel consumption that might be collected from the ships will be strongly affected by changes in loading conditions, route and weather conditions. Thus, in order to see the underlying trend caused by hull condition, it is necessary to develop a reliable way of correcting for operational and environmental factors.

The student shall propose a set of corrections for environmental conditions and loading condition, implement the method in a suitable computer tool, and test it on real operational data to be supplied from Kristian Gerhard Jebsens Skipsrederi. The results shall be analysed and discussed in order to evaluate the quality of the correction method. Possible improvements to the method shall be pointed out.

The candidate should in his report give a personal contribution to the solution of the problem formulated in this text. All assumptions and conclusions must be supported by mathematical models and/or references to physical effects in a logical manner.

The candidate should apply all available sources to find relevant literature and information on the actual problem.

The report should be well organised and give a clear presentation of the work and all conclusions. It is important that the text is well written and that tables and figures are used to support the verbal presentation. The report should be complete, but still as short as possible.

The final report must contain this text, an acknowledgement, summary, main body, conclusions, and suggestions for further work, symbol list, references and appendices. All figures, tables and equations must be identified by numbers. References should be given by author and year in the text, and presented alphabetically in the reference list. The report must be submitted in two paper copies unless otherwise has been agreed with the supervisor. In addition, the thesis shall be submitted electronically.

The supervisor may require that the candidate should give a written plan that describes the progress of the work after having received this text. The plan may contain a table of content for the report and also assumed use of computer resources.

From the report it should be possible to identify the work carried out by the candidate and what has been found in the available literature. It is important to give references to the original source for theories and experimental results.

The report must be signed by the candidate, include this text, appear as a paperback, and - if needed - have a separate enclosure (binder, diskette or CD-ROM) with additional material.

Supervisor : Professor Sverre Steen
Start : 18.01.2010
Deadline : 14.06.2010

Trondheim, 18.01.2010

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, Norway. This thesis is limited in time and work amount to correspond one semester.

I would like to thank my supervisor Professor Sverre Steen for very rapid and constructive support and provider of useful information during the work of this Master thesis. I would also like to thank my advisor Willy A. Reinertsen in Kristian Gerhard Jebsen Skipsrederi AS for showing genuine interest for my work by inviting me to the headquarter of the company and arrange for me to travel with one of the ships used in calculations in this thesis. He has benevolently answered all of my questions as best he can and provided all his available information regarding this thesis.

Trondheim, June 10 2010

Mads Aas-Hansen

List of symbols and abbreviations

A	[m^2]	Area of the rudder
Ac		Admiralty coefficient
A_M	[m^2]	Middle ship section area under water
A_P	[m^2]	Projected area of the superstructure in the longitudinal direction
		Propeller disc area (in calculation of rudder resistance)
b	[m]	Half span of the foil
B	[m]	Beam of the ship
C_{airp}	[-]	Resistance coefficient of the superstructure
C_B	[-]	Block coefficient
C_L	[-]	Lift coefficient
C_D	[-]	Drag coefficient
C_{D0}	[-]	Surface friction coefficient of the rudder
C_{F0}	[-]	Frictional resistance coeff. for contractually specified water and salt content
C_F	[-]	Frictional resistance for actual water temperature and salt content
C_q	[-]	Resistance coefficient of the rudder
C_{WL}	[-]	Waterline coefficient
C_B	[-]	Block coefficient
D	[N]	Drag force
DPI		Direct pressure integration
DWL		Design waterline
F	[N]	Centripetal force
F_N	[-]	Froude number
$\overline{F}_n$	[N]	Force per unit length normal to the hull
g	[m/s^2]	Acceleration of gravity
H	[m]	Water depth
$H_{1/3}$, H_s	[m]	Significant wave height
H_V	[m]	Wave height estimated from visual observation
ITTC		International Towing Tank Conference
k_0	[rad/s]	Wave number
KGJS		Kristian Gerhard Jebsen Skipsrederi AS
L	[m]	Ship length
	[N]	Lift force on the foil
L_{pp}	[m]	Length between perpendiculars
L_1	[m]	The part of the water line that experience the incoming waves
M, m	[kg]	Ship mass
P	[kW]	Engine power
$Q_{Prop.eff}$	[-]	Propeller efficiency
r_{44}	[m]	Roll radius of gyration
r_{55}	[m]	Pitch radius of gyration
r_{66}	[m]	Yaw radius of gyration
R	[N]	Resistance
R_{AA}	[N]	Air resistance

R_{wind}	[N]	Added resistance due to wind
R_{AW}	[N]	Added resistance in waves
R_{AW}'	[-]	Dimensionless added resistance, $R_{AW}' = \frac{R_{AW}}{\rho g \zeta_A^2 \left(\frac{B^2}{L}\right)}$
R_F	[N]	Frictional resistance
$R_{Fouling}$	[N]	Added resistance due to fouling
R_{Draft}	[N]	Added resistance due to draft
R_{Rudder}	[N]	Added resistance due to rudder angle
R_{T0}	[N]	Total resistance at contractually specified water temp. and salt content
R_T	[N]	Ship resistance
R_{yaw}	[N]	Added resistance due to yaw angle on the ship
RAO		Response amplitude operator
T	[N]	Propeller thrust
	[m]	Draft of the ship
T_p	[s]	Peak period
U_A	[m/s]	Axial velocity induced by the propeller
V	[m/s]	Wind velocity (air resistance calculation)
		Ship speed
		Horizontal steady velocity parallel to the ship side
$V_{Prop.inflow}$	[m/s]	Flow velocity into the propeller (propeller resistance calculation)
V_{ave}	[m/s]	Average velocity of the fluid inflow on the rudder
V_s	[m/s]	Ship speed
w	[-]	Wake factor
y	[m]	half the beam of the foil
Δ	[m^3]	Displacement
α		Wave propagation direction with respect to the x-axis
		Rudder angle
β		Yaw angle
ζ_A	[m]	Wave amplitude of incident wave
ζ_r	[m]	Relative motion on c
η	[m]	Motion component
Γ	[m^2/s]	Circulation round the foil
θ		Angle between the tangent of the waterline and the for- and -aft axis (x- axis)
ρ	[kg/m^3]	Density
ρ_0	[kg/m^3]	Density for the contractually specified water and salt content
ωe	[rad/s]	Encounter frequency

Summary

In this thesis five bulk ships from Kristian Gerhard Jebsen Skipsrederi AS has been monitored over time in order to discover the increase in resistance due to fouling on the hull and propeller. Each ship has reported weather and ship data twice a month from January to June 2010. These reports have been used to discover the resistance due to fouling by correcting all other added resistances from each measurement in the given time period. When all other resistance types are corrected for, each measurement is as if the ship travelled in calm weather. Then these results can be compared. The resistance types that are corrected for in this thesis are:

- Added resistance in waves
- Added resistance in wind
- Added resistance due to steering
- Speed loss due to shallow water

The added resistance in waves is calculated in Veres in the ShipX workbench with the direct pressure integration method. A simpler and more general formula for added resistance in waves by Kreitner is also tested in the calculations, but only to check if the results from this formula can be trusted. Kreitners formula is found to predict the added resistance in waves relatively accurate; however the formula strongly over predicts the result in some cases.

The added resistance in wind is done by a general formula. But the added resistance due to steering is found by formulas from (Brix, 1993). In the added resistance due to steering the resistance due to rudder angle is the only one of significance. The extent of the added resistance due to yaw angle because of lift forces from the rudder has been investigated and found to be neglectable.

When each measurement has been corrected for these resistance types, they are corrected to a reference speed and draft to be able to compare the results properly.

It has been found that the increase in resistance due to fouling is relatively linear the first two-three years. After three years the increase in resistance gets exponential.

The slope of the linear trend is found to be an increase in resistance due to fouling by approximately 0.39 BHP per day. After 1500 days, when the slope has been exponential for a while, the daily increase in BHP is 5.529 BHP/day and after 1800 days the increase of resistance is 8.469 BHP/day.

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1 Introduction

Kristian Gerhard Jebsen Skipsrederi AS (KGJS) has started to plan a way to optimize the docking interval for the ships in their fleet. The project thesis (Aas-Hansen 2009) described a suggestion for this optimization and was made as a preparation for this Master Thesis.

It is difficult to monitor the extent of speed loss and added power on a ship due to fouling accurately. This is because there are many other varying added resistance types that include in the total added resistance. The scope of this thesis is to remove by calculations all important added resistance types except fouling resistance from the ship over a period of time. When all other resistance types are corrected for, the only added resistance left should be the added resistance due to fouling on the hull and propeller. This is illustrated in Figure 1-1.

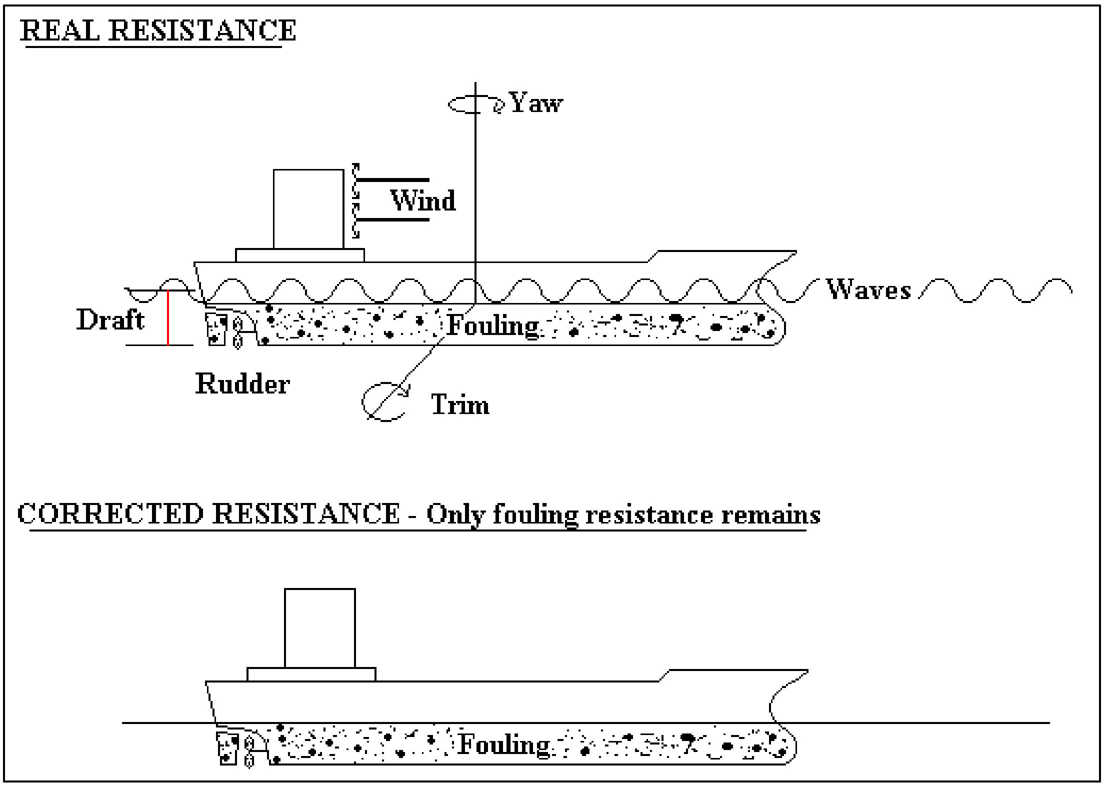


Figure 1-1: Illustration of the ship before and after the added resistance corrections has been made

This correction is to be done two times per month for five ships between January and June 2010. After a while it will ideally be possible to discover a trend in increased resistance which is due to fouling on the hull and propeller. This increasing resistance will ideally correlate with the growth rate of the fouling, and the most economical docking interval can be found.

2 Background

Fouling is an important part of the added resistance of a ship. Especially for ships that has sailed for a while without hull maintenance. A problem is that it is difficult to monitor the extent and the increase of the fouling over time. And how much of the total added resistance is the fouling at a given time. Numbers from Marintek, which is given by Willy A. Reinertsen in KGJS, states that the possible added resistance due to the different types of fouling can be enormous (Table 2-1).

Fouling increases the added resistance on a ship because it increases the surface roughness of the wetted part of the hull. This makes the friction between the water and the hull larger, and therefore increases the resistance. Different types of fouling sets on the surface over time and makes the hull rough.

Fouling Type	**Percentage of added fuel consumption**
Slime	5 to 15
Weed & Grass, scattered	10 to 20
Weed & grass, heavy	20 to 40
Barnacles, scattered 5 %	20 to 40
Barnacles, scattered 50 %	50 to 100

Table 2-1: Increasing fuel consumption with increasing fouling (Willy A. Reinertsen)

Dry docking and hull maintenance is very expensive. Both because the dry dock price itself, and the lost income due to the ship downtime. The ship owners are very interested in when it will be most profitable to send the ship to maintenance because of the extra fuel expenditures due to increased resistance. Will it be more profitable to let divers clean and polish the hull and propeller, which is cheaper but less thorough, or is it better to send the ship to dry docking for maintenance, which is more expensive but of course more thorough with new paint and possible sand blasting etc.

Until now KGJS has decided when it is time for hull maintenance on the basis of the increased fuel consumption. They have not been able to consider if some of the extra fuel consumption is due to bad weather. The loading conditions have not been taken into consideration either, even though it has a large impact on the total resistance.

The requirement for weather data from the ships has not been thoroughly prioritized over the years. This has lead to that the ship crew has not filled out the old weather forms properly. Therefore old weather data cannot be trusted to be accurate. I have proposed a new weather and sea condition form in this thesis which is shown and explained in chapter 6.1. The form also requires logging of engine data and trim and draft of the ship. The form has been taken in use from the beginning of 2010. I have also been on board on of the ships and explained the importance of an accurately fulfilled form to the crew.

3 The scope of the thesis

In this chapter a description of the calculation process and the means and goals of the thesis will be presented.

3.1 The ships

The ships that are used in this thesis are five equal bulk vessels from Kristian Gerhard Jebsen Skipsrederi. The reason that five equal ships are being used in the corrections is to get more representative results. If only one ship would have been included, the uncertainty of the results would have been much higher. With five ships it is a more solid basis for comparison.

The ships that are included in the thesis are:

- Emu Arrow
- Merlin Arrow
- Penguin Arrow
- Plover Arrow
- Weaver Arrow

Figure 2-1 shows the general arrangement of the ships represented by Toucan Arrow. Toucan Arrow herself is not a part of the calculations but is a sister ship and is therefore a physically similar ship.

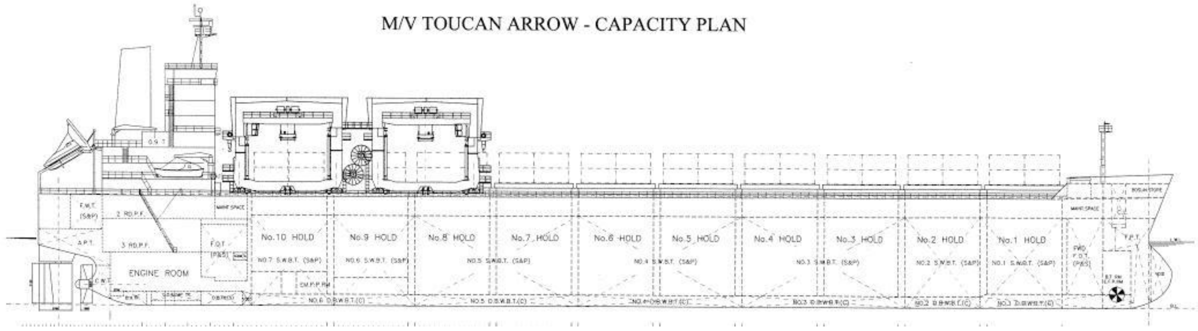


Figure 3-1: M/V Toucan Arrow - Capacity Plan (KGJS)

3.1.1 Ship specifications

The table below shows the ships principal particulars.

Length O.A.	199.7	m
Length Between PP	192	m
Breath mld	32.2	m
Depth mld	19.3	m
Draught mld. (Design)	11.8	m
Draught mld. (Scantling)	13.5	m
DWT at Design Draft	41462.7	mt
DWT at Scantling Draft	55918	mt

Table 3-1: The ships principal particulars

3.2 The corrections

There are many different resistance types that are included in the total resistance of a ship. Some are easier to find an approximation for by calculation than others. One of the most difficult one is the fouling resistance. This is because we do not know exactly how large the friction becomes as the fouling sets on the hull. It is also very difficult to estimate how fast the fouling grows, because it depends on many factors like how much time the ship spends in port, in which climate the ship travels and how rough the hull surface is. In this thesis the goal is to find a mean growth rate of the fouling by removing other known added resistance types.

The most important resistance types which are taken into account in this thesis are:

- Added wave resistance
- Air and wind resistance
- Added resistance due to draft
- Added resistance due to steering and yawing
- Speed loss due to shallow water

The added resistance due to trim is also discussed in the thesis, but it is not taken into account in the resistance calculations. In general the ships travel without trim, but when the ship has a trim angle the result of the resistance calculation may be different.

The added resistance due to fouling on the hull will be the total resistance of the ship minus the sum of all other resistances:

$$\Delta R_{Fouling} = R_{Measured} - \left(R_{Calm\ water} + \Delta R_{AW} + \Delta R_{Wind} + \Delta R_{Draft} + \Delta R_{ruddder} + \Delta R_{yaw}\right)$$

There are different options for displaying the additional resistance that comes due to fouling on the hull over time. This means that there are also different approaches in the calculation process.

In the project thesis (Aas-Hansen 2009) it was proposed to display the increased fouling over time at a constant shaft power as a decreasing speed over time. This is shown in the figure below.

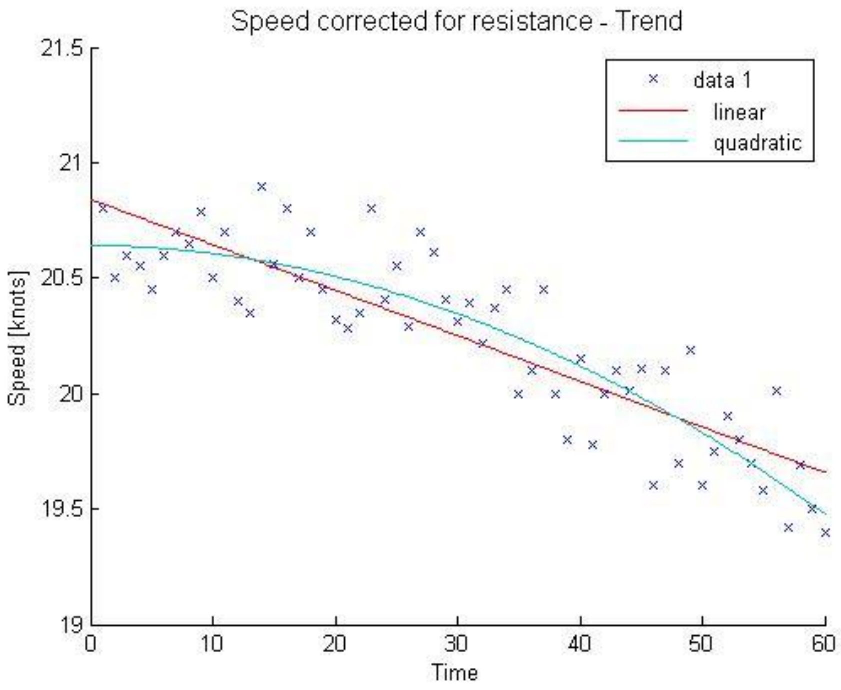


Figure 3-2: Suggestion from the project thesis for presentation of final results

The goal was here to show by results that the speed of the ship decreased over time as a result of fouling on the hull and the propeller. This would have been a good way of stating the result, but the ship owning company is more interested in the increased fuel consumption over time. This is because the ship will travel at a constant speed regardless of how the condition of the hull is, since the ship must follow a time schedule. Besides, it would have been too much to ask for a constant shaft power from the crew. Changing speed or shaft power and get the ship stabilized at the new level, which is important, would probably take at least half an hour. Therefore the displaying of the results has been changed compared to the sketch in the project thesis.

The approach I will follow in this thesis is to display the increasing use of engine power to a corrected constant speed and draft over time. Given in the ship resistance documents is the engine power prediction in calm water at design and ballast waterline.

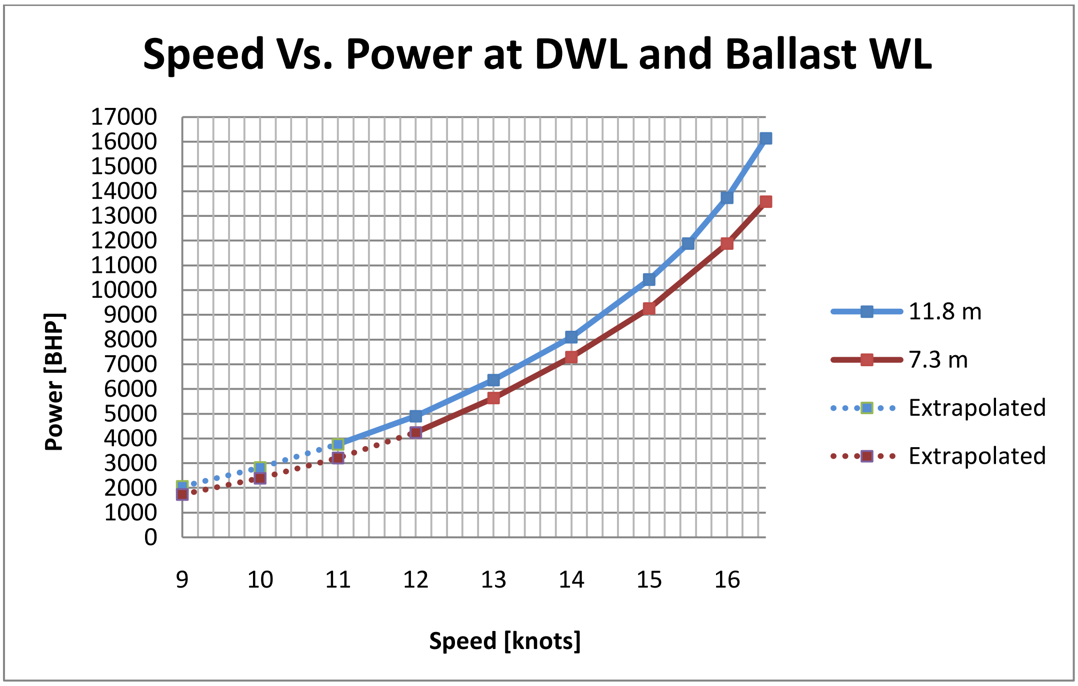


Figure 3-3: Speed versus power at DWL and Ballast Waterline

Figure 3-3 shows the ideal power usage at different ship velocities. The use of power at any given time is given from a shaft power meter. This is filled in a form given to the ships (Figure 6-1). The power value provided by the ship crew is corrected for the different resistance types like waves, wind etc. to estimate what the power usage would have been if the ship had traveled in calm weather. After correcting for the different resistance types the result is then corrected to the reference draft of T = 11.8m (DWL). When the ship is corrected to the reference draft, correction to reference speed can be done by following the speed vs. power curve for the actual draft which is given in the sea trial results. This will then be done for every collected ship form. Over time the increase of power at this constant speed and draft will be visible. The resistance in ideal conditions at design water line and ballast water line, and the steps in the correction are shown in the sketch below.

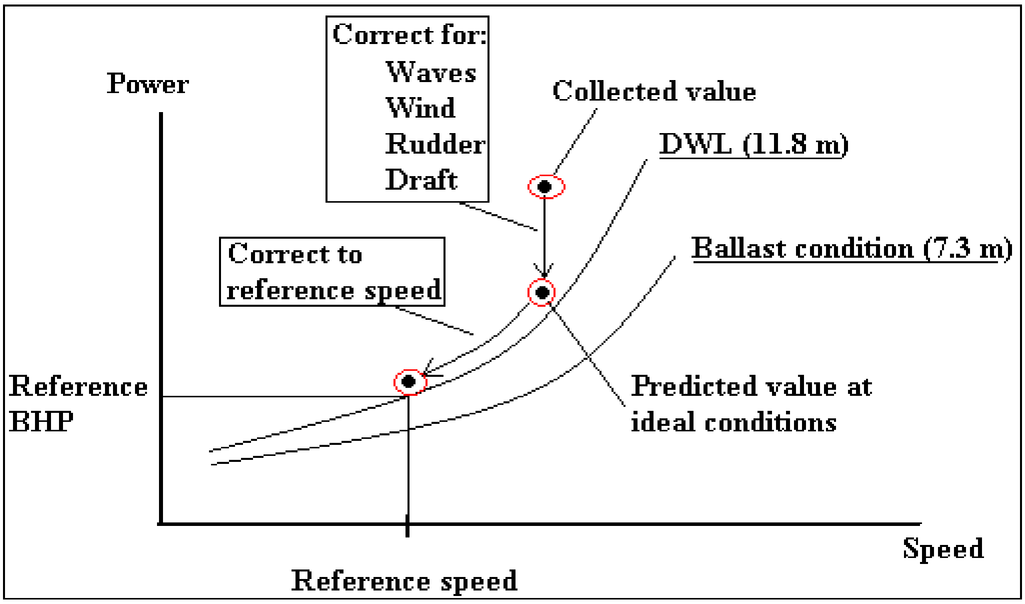


Figure 3-4: Illustration of the correction process

4 Theory

In this chapter the theory behind the calculations will be presented. The choice of method for calculating the added resistance in waves will be explained, and the method used in this thesis will be described. The calculation method for wind resistance will, along with the method used for correcting for added resistance due to steering and yawing and shallow water, also be described.

4.1 Wave resistance

In the design process of a ship, the resistance is historically calculated mostly in calm water. Added resistance in waves has not been taken much into consideration in the hull design; the solution has been to add an extra power margin to the calm water power need.

Added resistance in waves is a result of a change in point of equilibrium between the total ship resistance and propeller thrust. The total resistance will increase and the propeller thrust will decrease when the ship encounters waves. As a result, the ship cannot sustain the same forward speed as in calm water.

In the calculation of added resistance in regular waves it is common to separate the waves in two main groups, small and large wavelengths (Faltinsen & Minsaas, Added Resistance in Waves - Paper no. 8). The added resistance from small wavelengths ($\lambda/L < 0.5$) in head sea is mainly due to the reflection of waves in the bow. The added resistance from large wavelengths (wavelengths close to the ship length) is from the vertical motion between the ship and the waves.

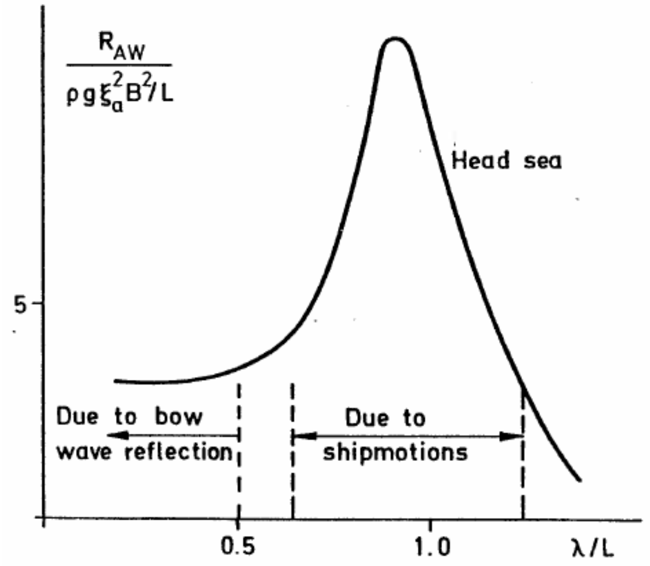


Figure 4-1: Added wave resistance due to bow reflection range and ship motion range (Faltinsen & Minsaas, Added Resistance in Waves - Paper no. 8)

A simple formula for correcting for added wave resistance is presented in ITTC report 7.5-04-01-01.2 and is given by Kreitner. This is a relative inaccurate approximation; however, it will give an estimate of the correct added wave resistance, especially for wave heights under 2 meters:

$$dR_0 = 0.64 H_v^2 \cdot C_B \cdot \frac{B^2}{L} \cdot g \cdot \rho_{TRIAL} \tag{4.1}$$

$$dR = dR_0[0.667 + 0.333\cos(\alpha)]$$

Where

α = Wave heading angle relative to the bow (0 degrees is head seas)
H_V = Wave height estimated from visual observation
C_B = Block coefficient
B = Breadth
L = Length
ρ = Density

The block coefficients for the ships at a given draft are given in Appendix 12.

This formula will not be used as a main wave resistance calculation. However, the results from this formula will be compared with the results from the main added resistance calculations.

4.1.1 Choice of calculation method

The methods that are available for calculation in Veres post processor program for added resistance in waves are Gerritsma & Beukelmans method and the direct pressure integration method. According to Sverre Steen and Dariusz Fathi the Gerritsma & Beukelmans method becomes inaccurate when the waves hit the ship with an angle and the method generally underestimates the added wave resistance. They therefore recommend the direct pressure integration method. From tests of both methods in Veres it appears that the Gerritsma & Beukelmans method gives negative resistance in following seas. These results are shown in the figure below.

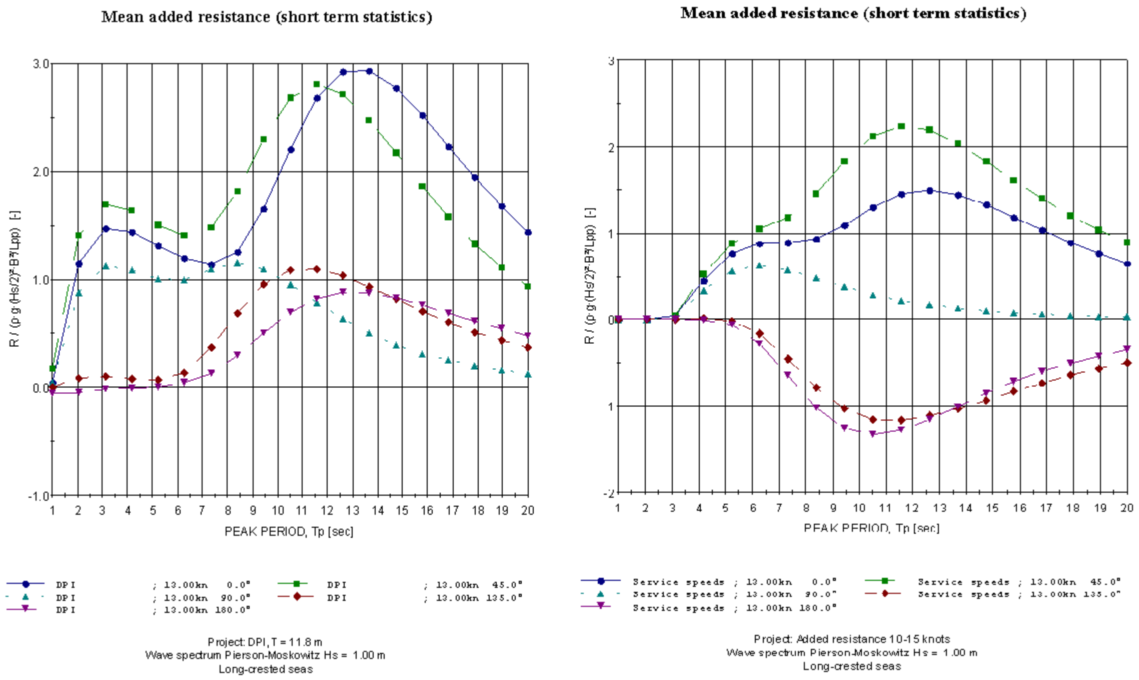


Figure 4-2: Added resistance at 13 knots and DWL. DPI to the left and G & B to the right.

From Figure 4-2 it becomes known, in this case, that the two methods differ quite much. For head seas the added wave resistance coefficient with direct pressure integration is much larger than the coefficient with Gerritsma & Beukelmans method. This is also the case with waves from a 45 degree angle. With waves from a 90 degree angle the direct pressure integration method gives a value almost twice as high as for the Gerritsma & Beukelmans method. In following seas we can see that the direct pressure integration method gives a positive value while Gerritsma & Beukelmans method gives a negative value.

These results correspond with the statements given by Steen and Fahti, and on the basis of this the calculation method used in this thesis is the direct pressure integration method. This method is described in chapter 4.1.2.

4.1.2 Direct Pressure Integration method

The direct pressure integration method is presented in (Faltinsen, Minsaas, Liapis, & Skjørdal, 1980). The basis of the method is the Bernoulli's equation. They have also discussed another version of the method proposed by Boese in 1970. However, this method neglects the influence of sway, roll, yaw and any flow which is asymmetric with respect to the x-z-plane. On the x-z-plane x is in the longitudinal direction of the ship while z is in the vertical direction. The neglecting in Boeses method means that the method only can be used for head and following seas.

In the direct pressure integration method there is two cases for added resistance in waves; one case for the ship motion range and one case for the small wavelengths. In the formula for the ship motion range the resistance for bow reflections is neglected and only resistance due to ship motions is considered.

$$
\begin{aligned}
\bar{F}_1 = \int_C & \left\{-\frac{\rho g}{2}\overline{\zeta_r^2}\right\} n_1 ds - \omega_e^2 M \overline{\eta_3 \eta_5} + \omega_e^2 M \overline{(\eta_2 - z_G \eta_4)\eta_6} \\
& + \rho \int_{S_B} \left\{ \overline{(\eta_2 + x\eta_3 - z\eta_4)\frac{\delta}{\delta y}\left(\frac{\delta \phi^{(1)}}{\delta t} + U\frac{\delta \phi^{(1)}}{\delta x}\right)|_m} \right. \\
& + \overline{(\eta_3 + x\eta_6 - z\eta_4)\frac{\delta}{\delta z}\left(\frac{\delta \phi^{(1)}}{\delta t} + U\frac{\delta \phi^{(1)}}{\delta x}\right)|_m} \\
& \left. + \overline{\frac{1}{2}\left(\left(\frac{\delta \phi^{(1)}}{\delta x}\right)^2 + \left(\frac{\delta \phi^{(1)}}{\delta y}\right)^2 + \left(\frac{\delta \phi^{(1)}}{\delta z}\right)^2\right)} \right\} n_1 ds
\end{aligned}
$$

ζ_r is the relative wave amplitude along the waterline curve, c. Ship sides are assumed vertical, and the ship must be slender and the bow should be blunt. The first part is the most important in the formula when the added resistance is at its maximum, and therefore the relative vertical motions are very important.

The other case is for the small wavelengths and is based on asymptotic theory. This case only considers the added resistance due to bow reflecting of the waves. The ship sides are assumed vertical and the wavelength is small compared to the draft of the ship. Due to the small wavelength assumptions the wave excitation forces will be small. This implies that the influence of the wave induced motions of the ship can be neglected. The following formula is very sensitive to these assumptions, and tends to underestimate the added resistance if the ship sides are not vertical. As long as the ship sides are vertical and the bow is blunt the formula predicts the added resistance quite accurate(Steen & Faltinsen, 1998).

$$\bar{F}_1 = \int_{L_1} \bar{F}_n \sin(\theta)\, dl \tag{4.2}$$

$$\bar{F}_n = \frac{1}{2}\rho g \zeta_a^2 \left(\left[\frac{1}{2}\frac{k_1}{k_0} - \frac{1}{2}cos^2(\theta + \alpha)\right] + \frac{1}{2}\frac{k_2}{k_0}\sin(\theta + \alpha)\right)$$

$$k_1 = \frac{[\omega_e - Vk_0\cos(\theta + \alpha)]^2}{g}$$

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

The formula can be reduced in head seas:

$$\frac{\bar{F}_1}{\zeta_a^2} = \frac{1}{2}\rho g\left(1 + \frac{2\omega_0 U}{g}\right)\int_{L_1} sin^2\theta n_1 dl \tag{4.3}$$

Where

$\bar{F}_n$ = force per unit length normal to the hull
ζ = wave amplitude
θ = Angle between the tangent of the waterline and the fore-and-aft axis (x-axis)
α = wave propagation direction with respect to the x-axis
L_1 = the part of the waterline that experience the incoming waves
ω_e = circular frequency of encounter

V = horizontal steady velocity parallel to the ship side
K_0 = wave number

4.2 Wind and air resistance

Air resistance is resistance due to air flow around the superstructure of the ship. It depends on the ship speed and the velocity and direction of the wind and of course the shape and size of the superstructure.

4.2.1 Calculation method

To find the total air resistance of the ship, corrections for the wind speed and direction relative to the ship can be made. However, in this thesis the added resistance corrections are meant to correct the added resistance of the ship to a state that is as if the ship sailed in calm weather. This is to be able to compare the results with the sea trials. The sea trials are done in calm weather when the ship was new, and is the reference ideal resistance for the ship. If added resistance due to relative wind speed and direction is subtracted alone, it will mean that the corrections are done to correct the ship to a state in vacuum. This is not the idea.

The air resistance is the resistance that occurs only because of the speed of the ship. This means the resistance due to air in calm weather. The wind resistance is the resistance that is due to wind speed and direction relative to the ship. To correct the added wind resistance only, the air resistance due to ship speed is added after the added resistance due to relative wind speed and direction is subtracted.

The formula for the air and wind resistance which is used in this thesis is presented in (Minsaas & Steen, Ship Resistance, 2008):

$$R_{AA} = C_{airp} \cdot \frac{\rho_{air}}{2} \cdot V^2 \cdot A_p \tag{4.4}$$

Where

C_{airp} = resistance coefficient for the superstructure at given wind direction
A_p = projected area of the superstructure in the longitudinal direction
V = wind velocity

To find only the wind resistance and let the air resistance remain, the added resistance wind relative to the ship is found and then subtracted by the air resistance of the ship due to the ship speed. The formula becomes:

$$R_{Wind} = \left(C_{airp} \cdot V_{Wind}^2 - C_0 V_{ship}^2\right) \frac{\rho_{air} \cdot A_p}{2} \tag{4.5}$$

Where

C_0 = Wind resistance coefficient at a wind angle of zero degrees
V_{Wind} = Wind speed
V_{Ship} = Ship speed

When correcting for the relative wind, V is the relative wind velocity and the C_{airp} is given from the relative wind direction angle from the ship direction. C_{airp} and C_0 are found in Figure 5-14. When correcting for air only, the wind speed is equal to the speed relative to the ground (not the speed though water) and the resistance coefficient is constant from wind direction angle equal to zero.

4.2.2 Coefficients

The resistance coefficient for the superstructure changes with the direction of the wind relative to the ship. For wind directions between 90 and 270 degrees the wind resistance coefficient will be negative. This means that the resistance for wind angles between 90 and 270 degrees will be negative.

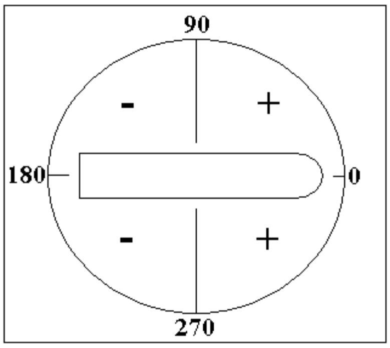


Figure 4-3: Sign on the wind coefficient relative to the wind direction

The wind coefficients for the ships is found by ShipX Speed and Powering and is shown among the other results from ShipX in chapter 5.4.

4.3 Resistance due to steering and yawing

When the ship travels with a rudder angle the extra drag force of the rudder contributes to the total added resistance. And the lift from the rudder when it has an angle lead to a yaw angle on the ship since the ship will counteract the lift from the rudder. When the ship travels with a yaw angle, it will create a pressure difference between the ship sides. This will again lead to an extra resistance.

4.3.1 Resistance due to rudder angle

The total resistance due to the rudder consists of the drag of the rudder itself plus the extra drag that the rudder creates when it is turned. In the corrections in this thesis only the additional drag due to rudder angle is calculated. This is because the corrections are being made to recreate calm water with zero extra rudder drag, not remove the drag due to the rudder itself.

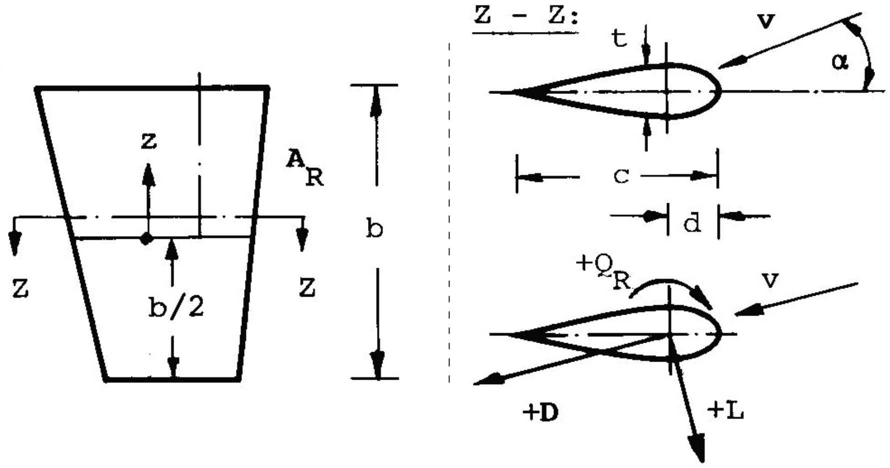


Figure 4-4: Rudder characteristics (Brix, 1993)

The drag force on the rudder is given by (Brix, 1993):

$$D = \frac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot V_{ave}^2 \tag{4.6}$$

Where

ρ = Density of the water
C_D = Rudder drag coefficient
A = Rudder area
V_{ave} = Average rudder inflow speed

The added resistance from rudder due to rudder angle will look similar to the figure below.

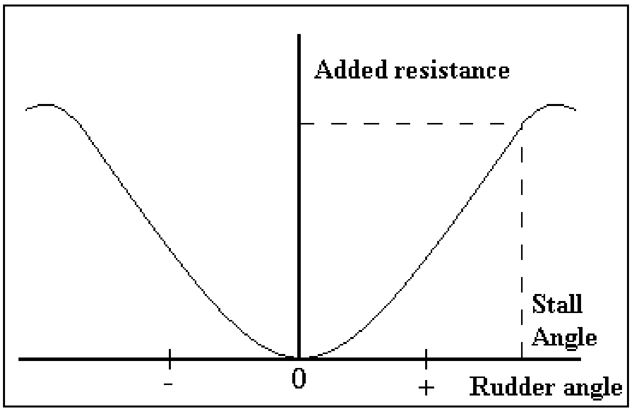


Figure 4-5: Illustration of the increasing added resistance with increasing rudder angle

In practice, there will be a slight difference between resistance in positive and negative angle. The zero resistance point might therefore not be exactly in the zero angle point. This is because of the uneven flow from the propeller. Due to the ship hull the propeller inflow velocity varies over the propeller disc, and therefore the flow after the propeller disc will vary. However, in this thesis, it is calculated with an average rudder inflow speed, which makes the added resistance due to positive angle the same as for the negative angle.

If the angle of the rudder relative to the incoming fluid is less than the stall angle, the following equation can be used to find the drag coefficient. The stall angle is the angle where the lift force is at its maximum.

The drag coefficient of the rudder is given by (Brix, 1993):

$$C_D = 1.1 \cdot \frac{C_L^2}{\Lambda \cdot \pi} + C_q |sin\alpha|^3 + C_{D0} \qquad (4.7)$$

Where

C_L = Rudder lift coefficient
$\Lambda = \frac{b^2}{A}$
C_q = resistance coefficient
α = angle of incoming fluid
C_{D0} = Surface friction coefficient

The drag coefficient of a rudder consist of three parts, contribution from the lift due to the rudder angle, extra drag due to the angle itself and one drag from the surface friction independent on the rudder angle, C_{D0}. Since C_{D0} is a contribution to the drag force on the rudder independent on the rudder angle, it will not be taken into the calculations in this thesis. This is because C_{D0} represents the resistance the ship gets from the rudder itself. Therefore the formula for the drag coefficient used in this thesis is reduced to the following:

$$C_D = 1.1 \cdot \frac{C_L^2}{\Lambda \cdot \pi} + C_q |sin\alpha|^3 \qquad (4.8)$$

The resistance coefficient, C_q, is assumed to be $C_q \approx 1$ if the rudder has sharp edges on the top and the bottom. (Grimstad, 2009). The rudder on the ships in this thesis has in fact sharp edges on the top and the bottom, therefore this assumption is applied.

The rudder lift coefficient, C_L, is given by the formula (Brix, 1993):

$$C_L = \frac{2\pi \cdot \Lambda \cdot (\Lambda + 1)}{(\Lambda + 2)^2} sin\alpha + C_q sin\alpha \cdot |sin\alpha| \cdot cos\alpha \qquad (4.9)$$

The rudder inflow speed is the propeller inflow speed plus the extra speed induced by the propeller thrust:

$$V_{ave} = V_{Prop.inflow} + U_A \qquad (4.10)$$

The inflow speed on the rudder varies over the height of the rudder; therefore an average velocity must be used. The velocity of the flow into the propeller is somewhat smaller than the ship velocity. This is because of the wake that occurs due to the friction between the hull and the water. Therefore the velocity of the flow into the propeller will always be less than the ship speed. The formula for the velocity of the flow into the propeller is given by(Minsaas & Steen, Ship Resistance, 2008):

$$V_{Prop.inflow} = V_{ship} \cdot (1 - w) \qquad (4.11)$$

Where

V_{ship} = velocity of the ship
w = Effective wake

One formula for estimating the effective wake by Holtrop and Mennen was presented in the project thesis (Aas-Hansen 2009). However, for the ships in this thesis a mean wake are given from a sea trial test.

The average flow velocity on the rudder, V_{ave}, can be estimated with momentum theory. In this method the propeller is assumed to be a disc with infinite amount of blades. The thrust is applied as a uniform pressure jump over the propeller disc. This method is described in the project thesis.

Since the thrust of the propeller can be estimated from the shaft power given in the form that is filled in by the crew, U_A can be found from the following equation which is found from the momentum theory method:

$$T = \rho \cdot U_A \cdot A_P \cdot \left(V_{Prop.inflow} + \frac{U_A}{2}\right) \tag{4.12}$$

This can be given as a second degree polynomial equation with U_A as the only unknown:

$$U_A^2\left(\frac{\rho \cdot A_P}{2}\right) + U_A\left(\rho \cdot A_P \cdot V_{Prop.inflow}\right) - T = 0 \tag{4.13}$$

Where

T = Propeller thrust
U_A = Axial velocity induced by the propeller
$V_{Prop.inflow}$ = Velocity of the flow into the propeller
A_P = Area of the propeller disc
ρ = Density of the water

Solved with respect to U_A the extra flow velocity induced by the propeller thrust can be found.

4.3.2 Resistance due to yaw

When the ship travels with a rudder angle, the lift force on the rudder makes the ship travel ahead with a yaw angle. This yaw angle causes an uneven flow round the ship. This uneven flow creates a pressure difference on both sides of the ship in the same way it does on a foil. The ship will therefore experience a drag force on the low pressure side. This phenomenon is illustrated in Figure 4-6.

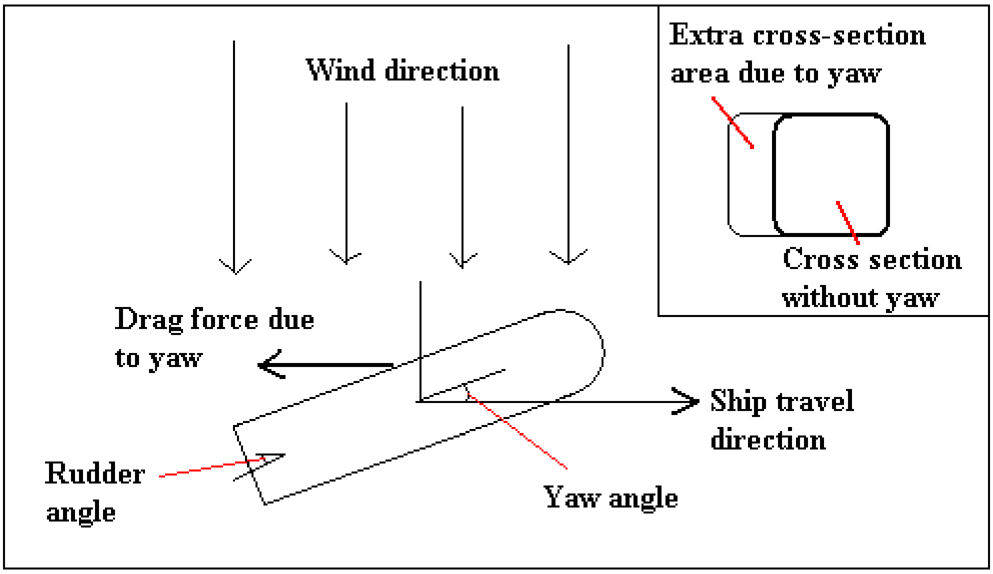


Figure 4-6: Illustration of the added resistance due to yaw angle on the ship

4.3.2.1 Method for calculating the added resistance due to yaw angle

There are different methods to calculate the added resistance contribution due to the yaw angle on the ship. One method presented by Norrbin (Norrbin, 1972) finds the added resistance due to yawing using centripetal force. However, the assumptions used in his model may not be accurate on ships today. For instance, the pivot point in his model is placed in the middle of the ship. Ships with a large C_B have a pivot point near the bow. (Grimstad, 2009).

The model for added resistance due to yawing that will be used in this thesis is presented in (Faltinsen, Hydrodynamics of high-speed marine vehicles, 2005). This is the method that is assumed the most accurate in (Grimstad, 2009) and will be presented in the following.

Faltinsen uses Newton's second law to show all the forces on the hull in the longitudinal direction:

$$M\left(\dot{u} - v\dot{\psi}\right) = X_{\dot{u}}\dot{u} - R_T(u) + (1-t)T(u,n) + X_{vv}V^2 + X_{v\dot{\psi}}v\dot{\psi} + X_{\dot{\psi}\dot{\psi}}\dot{\psi}^2 + X_{\delta\delta}\delta^2 \quad (4.14)$$

Where

$X_{\dot{u}}, X_{vv}, X_{v\dot{\psi}}, X_{\dot{\psi}\dot{\psi}}$ *and* $X_{\delta\delta}$ = Hydrodynamic forces on the hull and rudder.
R_T = Ship resistance
(1-t)T(u,n) = Thrust force with thrust reduction
$-Mv\dot{\psi}$ *and* $X_{v\dot{\psi}}v\dot{\psi}$ = Forces due to turning motion

(1-t)T(u,n) and $X_{\delta\delta}\delta^2$ are dependent on steering. In the calculation of the added resistance due to yawing, the parts of formula 4.14 that does not regard yawing forces may be excluded. This also applies for the forces that are dependent on steering, since steering forces is calculated in the rudder angle calculations. Formula 4.14 can be rewritten with only forces due to yawing. When using $U = R\dot{\psi}$ and $v = -u\beta$ the new relation can be expressed by:

$$\left(M + X_{v\dot{\psi}}\right)v\dot{\psi} = -(M + X_{v\dot{\psi}})\frac{u^2}{R}\beta \quad (4.15)$$

$\frac{u^2}{R}\beta$ is the x-component of the centrifugal acceleration. β will always be positive since the bow always will be pointing inward in a steady turn.

When all terms that gives a contribution to the added resistance due to yawing is included the total added resistance due to yawing is expressed by:

$$\Delta R_{yaw} = \left(M + X_{v\dot{\psi}}\right)\frac{u^2}{R}\beta - X_{vv}v^2 - X_{\dot{\psi}\dot{\psi}}\dot{\psi}^2 \quad (4.16)$$

In (Faltinsen 2005) the coefficient X_{vv} is defined as zero if the ship is symmetrical. $X_{\dot{\psi}\dot{\psi}}\dot{\psi}^2$ is very small compared to the other term in the equation because $\dot{\psi}^2$ will be very little. On the basis of this the equation may be simplified to the following:

$$\Delta R_{yaw} = \left(M + X_{v\dot{\psi}}\right)\frac{u^2}{R}\beta \quad (4.17)$$

Where

M = ship mass

u = velocity in the longitudinal direction
R = Turn radius of the ship
β = amplitude of motion

In this thesis this is the formula that is used for calculations of added resistance due to yawing. The turn radius of the ship is the turn radius the ship would have had if it had followed a circular path with the given rudder angle, as opposed to this case where the ship travels straight ahead.

The velocity in the longitudinal direction is expressed by

$$u = V \cdot \cos(\beta)$$

The coefficient $X_{v\dot{\psi}}$ is presented by Blanke in 1981 and is based on several model tests mainly on tankers. It is given by:

$$X'_{v\dot{\psi}} = 1.45m'\frac{T}{B} + 108 \cdot 10^{-5} \qquad (4.18)$$

This formula is non-dimensional. $X_{v\dot{\psi}}$ and m’ is given by:

$$X_{v\dot{\psi}} = X'_{v\dot{\psi}} \cdot \frac{1}{2}\rho L^3 \qquad (4.19)$$

$$m' = \frac{m}{\frac{1}{2}\rho L^3} \qquad (4.20)$$

4.3.2.2 Estimation of the extent in extreme cases

The method described above is carried through in this section; however, severe assumptions are used in order to get the input needed in the calculations. Therefore the values that are assumed will be overstated, in order to estimate the extent of added resistance due to yaw angle in extreme cases.

The first assumption is to consider the ship as a foil, and use foil theory (Minsaas & Steen, Foil Theory, 2008) to find the yaw angle of the ship. The velocity and draft of the ship in this calculation is the same reference velocity and draft as used in the rest of this thesis. V = 13 knots and T = 11.8 m. The rudder angle is set to five degrees.

Introducing Kutta Joukowsky’s theorem for lift force on a foil:

$$L = 2\rho V \Gamma b \qquad (4.21)$$

Where

L = lift force on the foil (in this case the ship)
V = Ship speed
Γ = Circulation round the foil
b = Half-span (in this case half the ship length)

With a simplification of the ships pivot point being in the bow of the ship, the lift of the ship as a foil is twice the lift force on the rudder due to moment. This is shown in the figure below.

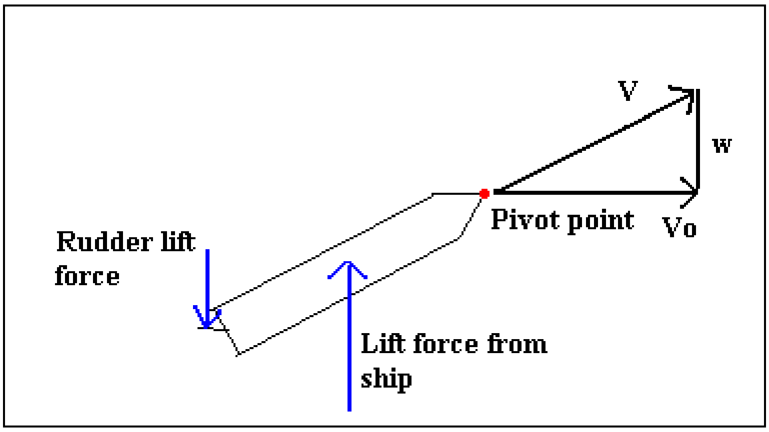


Figure 4-7: The ship as a foil

Now the formula for lift force (4.20) can be changed to be with respect to the circulation round the foil:

$$\Gamma = \frac{L}{2\rho V b}$$

The lift force from the rudder at 13 knots with a rudder angle of 5 degrees is calculated to 270200 N. This calculation method is described in chapter 4.3.1. This means that the counteracting lift force from the ship is **540200 N**.

The circulation Γ now in this case becomes **0.39 m^2/s**.

The length of w from Figure 4-7: The ship as a foil Figure 4-7 is given by:

$$w = \frac{\Gamma}{4\pi}\left(\frac{1}{b+y} + \frac{1}{b-y}\right) \tag{4.22}$$

y is here half the beam of the ship.

When w is calculated the value is w = $6.37*10^{-4}$. If w << V, V = V_0, and the angle between V and V_0 is

$$\beta = \frac{w}{V}$$

$$\beta = \frac{6.37 \cdot 10^{-4}}{6.6877} = 9.52 \cdot 10^{-5} \deg = \mathbf{1.66 \cdot 10^{-6}} \boldsymbol{radians}$$

The turn radius of the ship at the given rudder angle is unknown, and two approximations are carried through in order to get an estimation of the real value.

First approximation is based on the minimum turn radius of the ship, which is given at maximum rudder lift with a rudder angle equal to 50 degrees. Then the turn radius of the ship is 0.101 nautical miles or 185.2 meters. The figure below shows the lift coefficient versus the rudder angle for conventional rudders found in (Brix, 1993). The correlation between the rudder angle and the lift coefficient is linear from zero to maximum angle for these rudders. Therefore this linearity is assumed to be the case for the rudders on the ships in this thesis. Rudder characteristics can be found in the appendix.

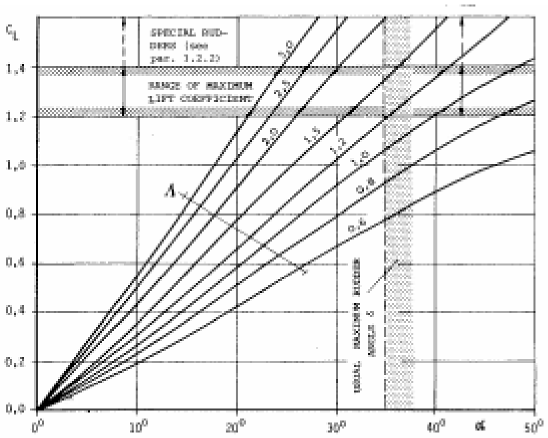


Figure 4-8: Lift coefficient versus rudder angle for conventional rudders (Brix, 1993)

From these assumptions the turn radius for 5 degrees is estimated.

$$\frac{50}{5} = 10 \ \rightarrow R = 185.2m \cdot 10 = \mathbf{1852m}$$

The second approximation for the turn radius of the ship is to use centripetal force. This is still under the assumption that the ship can be considered to behave like a foil. Then the lift force of the ship, which is calculated above, is the same as the centripetal force. Using this, the radius of the turn is given as the formula for centripetal force changed to be with respect to the radius:

$$R = \frac{mV^2}{F} \tag{4.23}$$

Where

m = mass of the ship
V = velocity of the ship
F = centripetal force/lift force

$$R = \frac{60595038kg \cdot (6.6877m/s)^2}{540200N} = \mathbf{5017.0m}$$

To get a highest possible value of the added resistance due to yaw angle, a small radius must be used. Therefore, on the basis of these two approximations it would be an overstatement to set the turn radius of the ship to be 1000m, which is well below the lowest approximation.

Now the added resistance due to yaw angle on the ship can be calculated:

$$X_{v\dot{\psi}} = X'_{v\dot{\psi}} \cdot \frac{1}{2}\rho L^3 = 36115782kg$$

$$\Delta R_{yaw} = \left(M + X_{v\dot{\psi}}\right)\frac{u^2}{R}\beta = (60595038kg + 36115782kg) \cdot \frac{(6.6877m/s)^2}{1000m} \cdot 1.66 \cdot 10^{-6} = \mathbf{7.2N}$$

This means that the added resistance due to a yaw angle induced by a rudder angle of 5 degrees is only 7.2 N or 0.73kg. On a ship that is almost 200 meters of length it is safe to say that this is completely neglectable.

<u>Therefore, the added resistance due to a yaw angle is neglected in all corrections in this thesis!</u>

4.4 Resistance due to trim

Estimating added resistance due to a trim angle on a ship is very difficult. There is no standard formula for estimating the resistance on a ship due to the trim angle accurately. This is because every ship has a different varying geometry with different trim angles; especially in the bow and the stern. In practice, every ship needs its own unique formula in order to estimate the added resistance due to trim.

Tests done by KGJS on the ship Emu Arrow shows that the speed increases at ballast draft while speed decreases at loaded draft. They have also done model tests that show that the effect of trim varies with the speed. The results show that the resistance is highly dependent of the draft of the ship.

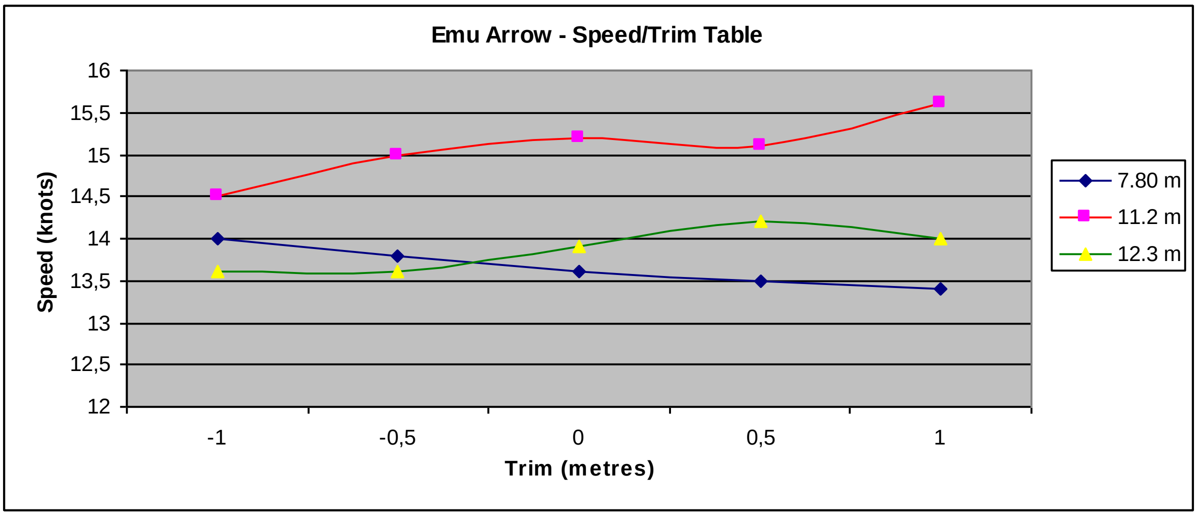


Figure 4-9: Speed versus trim on three different drafts based on model tests (Reinertsen, 2009)

The difference in speed versus trim is significant from T = 11.2 m to T = 12.3. And from the shapes of the curves it would probably have been very inaccurate to estimate linearity between the curves. This makes it very difficult predict the resistance for other drafts than the three in Figure 4-9.

Therefore there are no corrections for trim angle in this thesis. Besides, most measurements from the ship crew are without significant trim.

5 ShipX

ShipX is a hydrodynamic workbench made by Marintek which implements different other programs or plug-ins to make hydrodynamic calculations. The plug-in that predicts added wave resistance best is the Vessel Response program (VERES). For wind coefficients the Speed and powering plug-in is used. The Speed and Powering prediction program can also be used to find the speed loss in waves and wind using results from VERES.

5.1 Inputs

When the ship drawings only exists on paper, these drawings must be digitalized in order to be able to use computer power to calculate the behavior of the ship in waves, wind and different trim angles etc. This digitalizing involves dividing the ship drawings in lines which consists of several points in a three dimensional coordinate system.

The first step is to scan the drawings and open it in a digitalizing computer program. The computer program used in this case is called "WinDig". When the drawing is opened in WinDig, a coordinate system needs to be defined on the image. After this each point on the drawing which is clicked on becomes a coordinate in this coordinate system. To avoid unnecessary future scaling the coordinates should be defined so that the shape and measures is the same as the full scale ship. The job is then to manually click with sufficient steps on each line. When the points are connected the line that appears will resemble the original frame with satisfactory accuracy. The figure below shows the scanned ship drawing and frame number 20 digitalized and shown in a coordinate system.

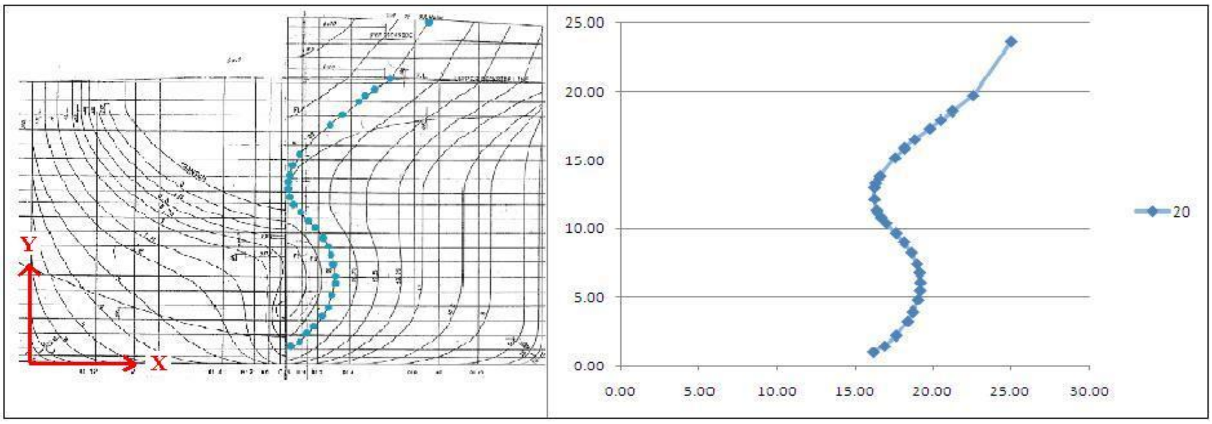
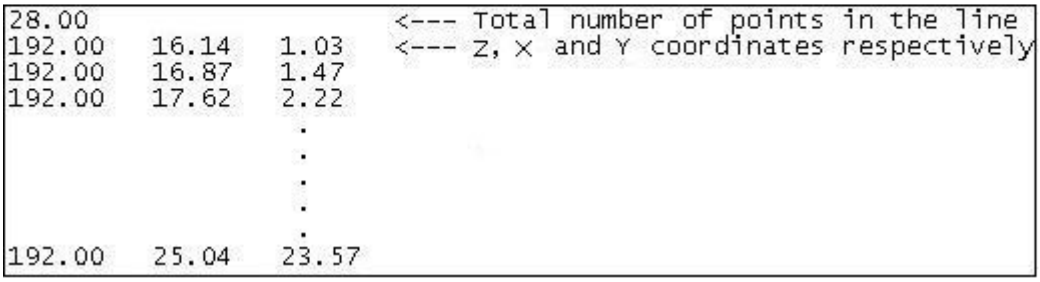


Figure 5-1: Digitalizing of ship drawings. Illustrating the points on a section

It is especially important to have small steps where the frame is curved. If the points are too far apart the line will be inaccurate and that can influence for instance the waterline area curve which is important for the added wave resistance calculations. When all the points are collected the points can be plotted, in this case in Excel, to see if the line looks exactly like the frame. If not, the point sampling process needs to be done again. The WinDig program stores the points in X- and Y- and Z-coordinates. But since the image is in 2D, the Z-coordinate is automatically set to be zero. This must be changed manually in order to get a 3D image of the drawing. A segment of the file that is created for frame number 20 is shown below.



```
28.00                                <--- Total number of points in the line
192.00    16.14    1.03              <--- Z, X and Y coordinates respectively
192.00    16.87    1.47
192.00    17.62    2.22
                     .
                     .
                     .
                     .
                     .
192.00    25.04    23.57
```

Figure 5-2: A segment of the *.dat file from section 20 created in WinDig.

When one file is created for each of the frames in the drawing, a plot with all the frames can be made. The result from visualization in Excel is shown in the figure below.

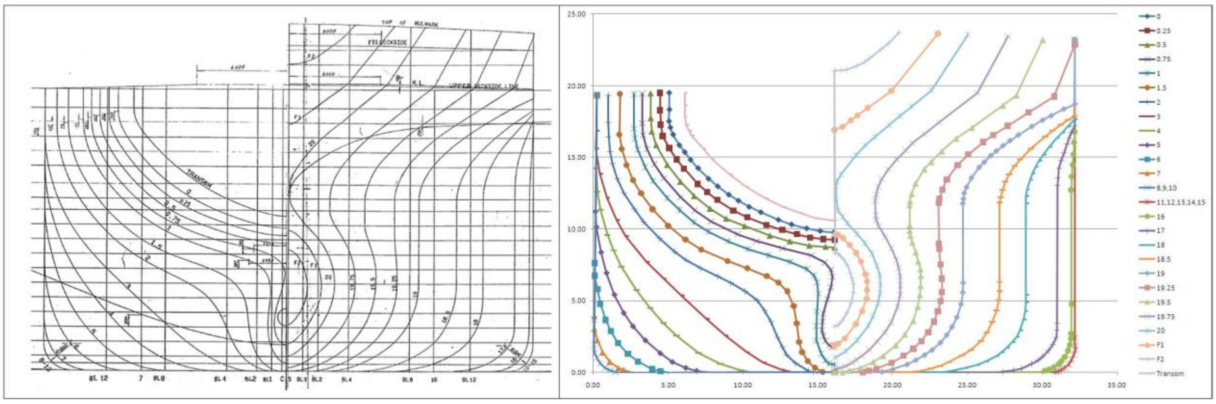


Figure 5-3: Digitalizing of ship drawings. All the sections are complete.

In order to be able to fully recreate the ship drawings in 3D, a contour line of the bottom along the ship length must be defined. This is done the same way as described above only with a drawing of the ship seen from the side, as shown by the blue line in the figure below.

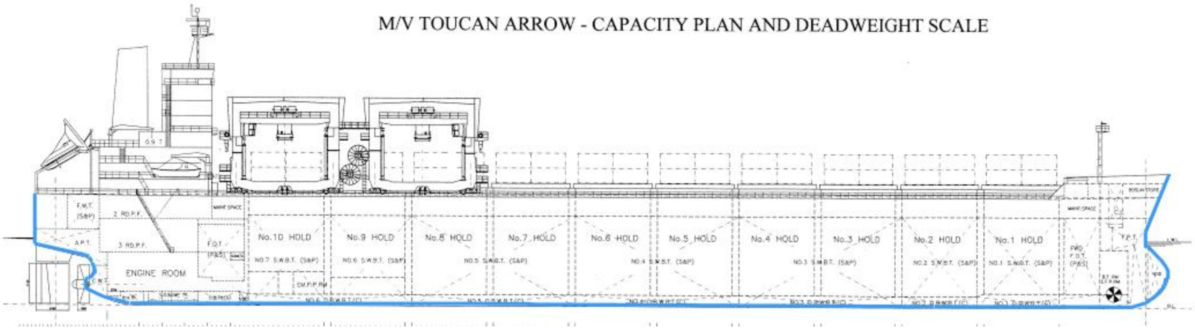


Figure 5-4: Bottom contour line of the ship

This line must be defined in the same coordinate relation as the rest of the lines. Without this line it would be impossible to create an accurate ship shape, especially in the bulb area and other edges where the ship drawing has an insufficient amount of lines.

When all the points that describes the ship in 3D is set up right in ShipX a 3D image of the hull can be shown. ShipX creates elements between the sections automatically. The result is shown in the figures below.

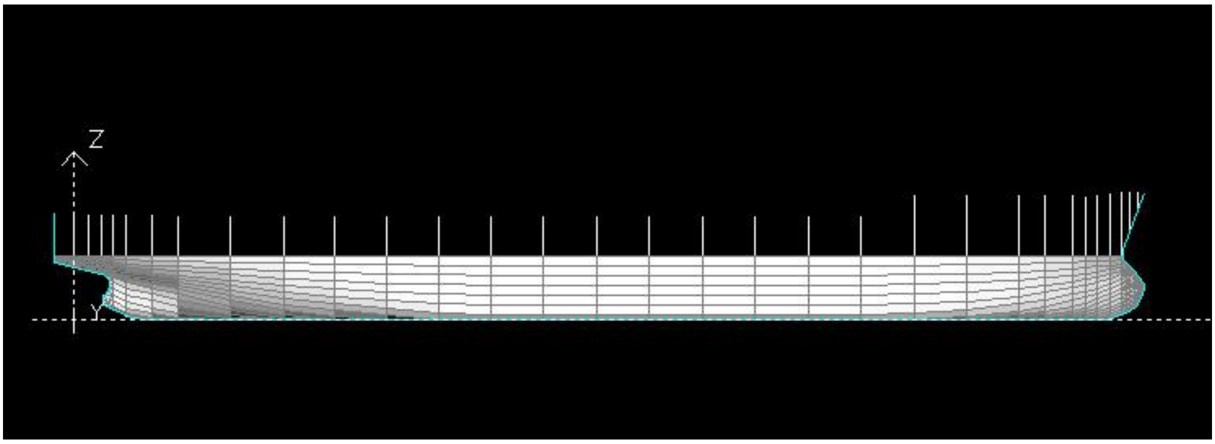


Figure 5-5: 3D image of the ship from the side

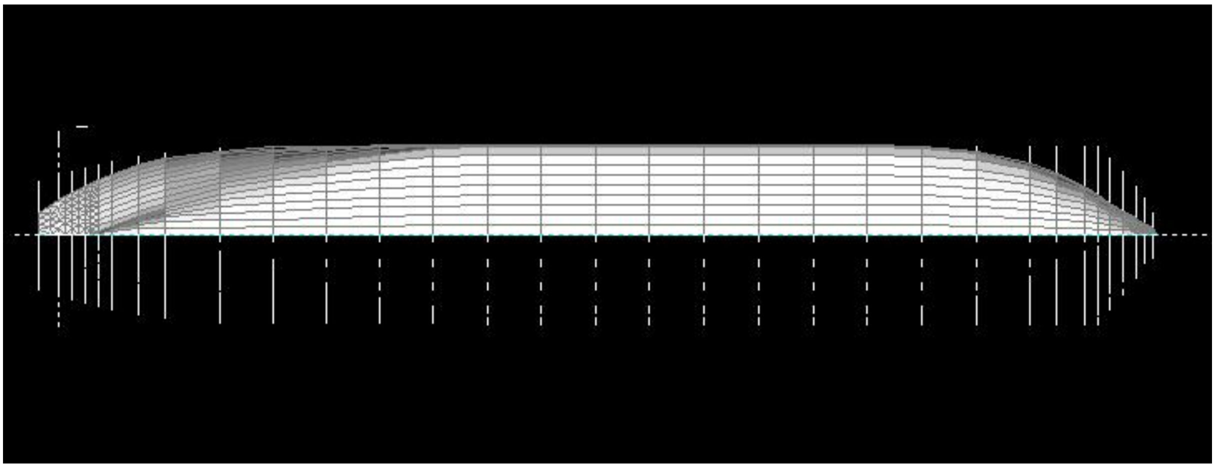


Figure 5-6: 3D image of the bottom of the ship

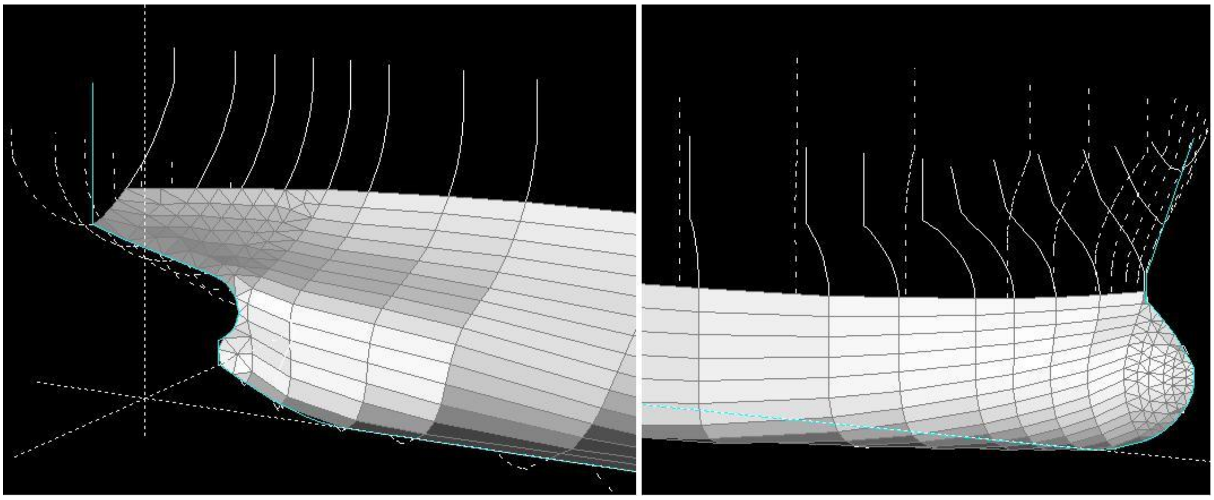


Figure 5-7: 3D image of the stern and bow respectively

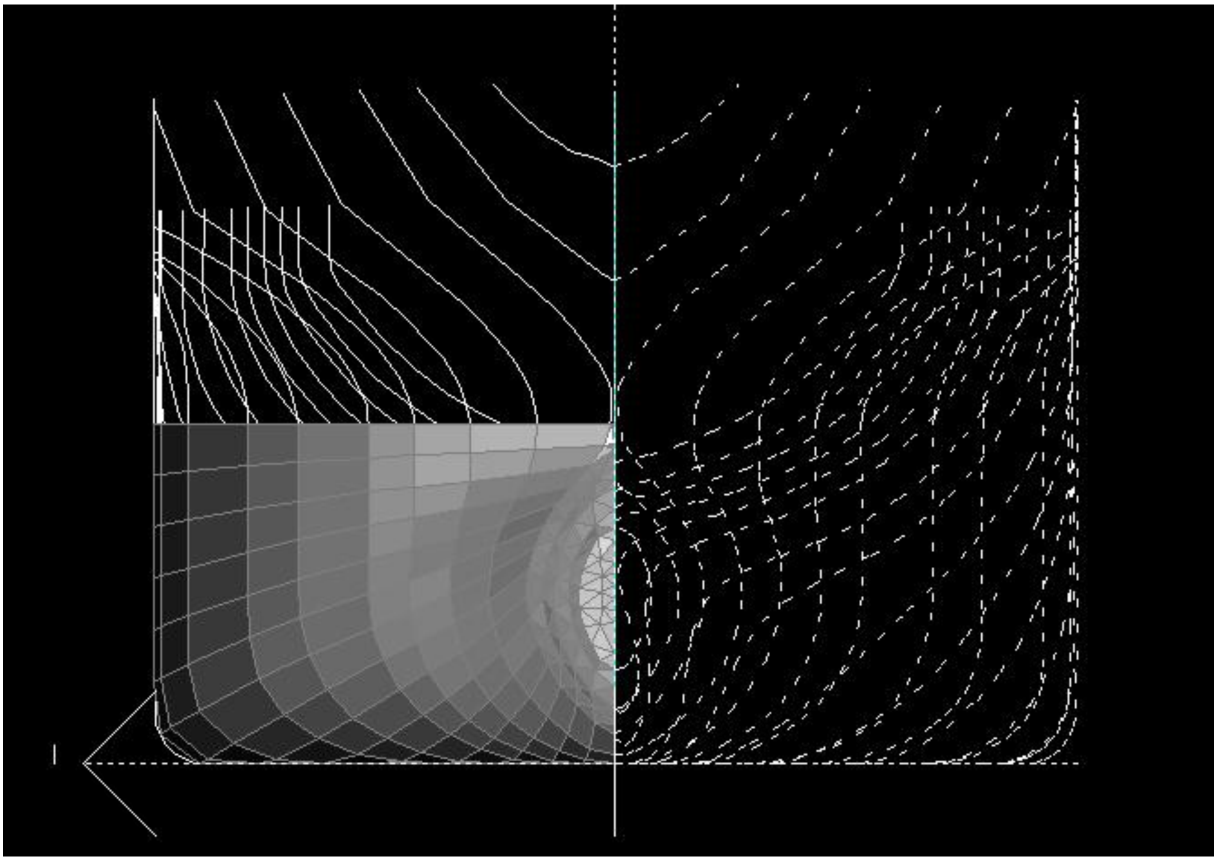


Figure 5-8: 3D image of the ship seen from the front

5.2 ShipX Vessel Responses (VERES)

The ShipX Vesses Resposes program consists of two parts. The main program calculates the transfer functions in six degrees of freedom. The other part of the program is a Postprocessor which is used to make reports and further calculation based on the transfer functions.

5.2.1 Inputs

After the ship has been implemented in ShipX, VERES needs some more specifications to be able to calculate the motion transfer functions. The roll radius of gyration for the ship in roll, pitch and yaw must be inserted. The formulas for these respectively are (Fathi, 2008):

$$r_{44} = \sqrt{\frac{\sum(y^2 + z^2) \cdot \Delta M}{M}} \tag{5.1}$$

$$r_{55} = \sqrt{\frac{\sum(x^2 + z^2) \cdot \Delta M}{M}} \tag{5.2}$$

$$r_{66} = \sqrt{\frac{\sum(x^2 + y^2) \cdot \Delta M}{M}} \tag{5.3}$$

The coordinates x, *y* and *z* are given relative to the center of gravity. Δ*M* is the weight of an item located at *(y, z*) and *M* is the total weight of the vessel. However, the center of gravity will change with different loading conditions, both depending on the placing of the load and the weight of it. This is impossible to know just from the draft measures, so simplified formulas are given.

Value	Description	Typical values
r_{44}	Radius of gyration in roll (m)	0.30 *B* - 0.45 *B*
r_{55}	Radius of gyration in pitch (m)	*0.20 LPP* - 0.30 *LPP*
r_{66}	Radius of gyration in yaw (m)	0.25 *LPP* - 0.30 *LPP*
r_{64}	Coupled radius of gyration in roll-yaw (m)	≈ 0.00

Table 5-1: Typical values of the radii of gyration (Fathi, 2008)

The range of the radii of gyration in roll is between 0.3*B and 0.45*B, where B is the breath of the ship (Fathi, 2008). For added resistance in waves this value has close to no influence on the added resistance calculation. This is shown in the graphs below.

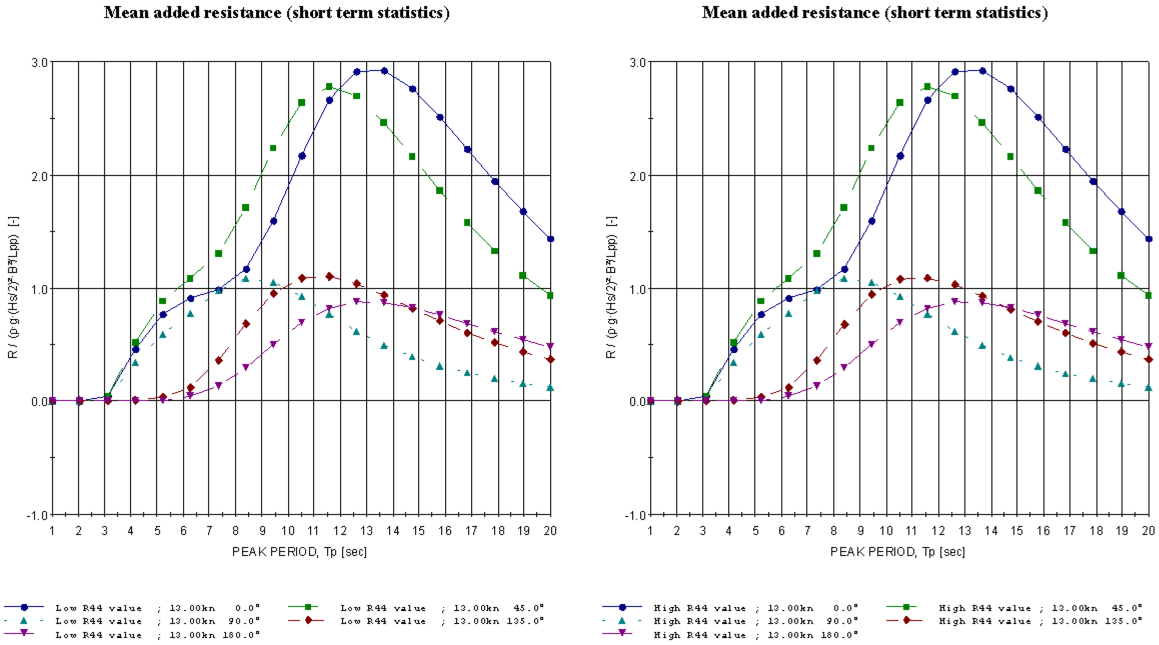
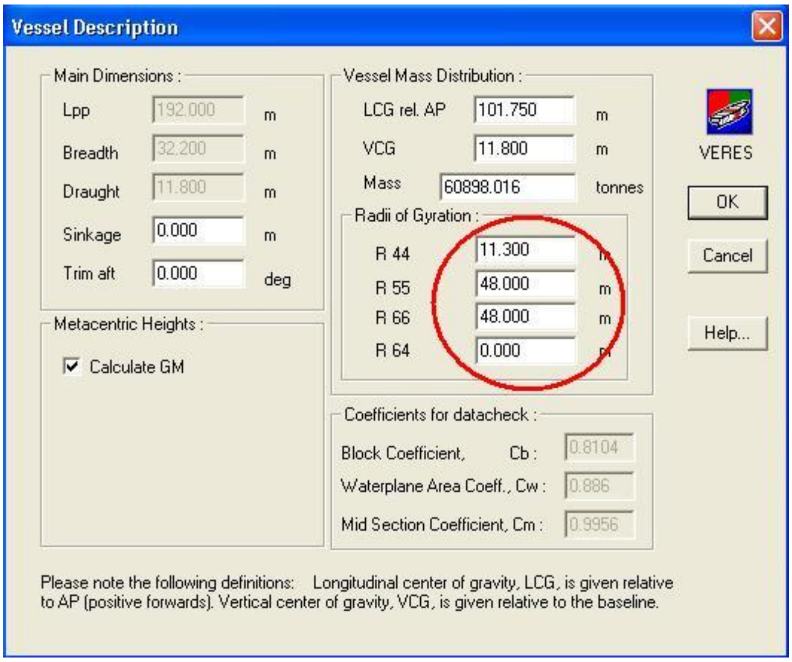


Figure 5-9: Added resistance for 13 knots at DWL. Low R44 to the left and high R44 to the right

The graph to the left in figure 4-7 is for lowest value of r_{44}, $r_{44} = (0.3 \cdot B)$ while the graph to the right is the highest value of r_{44}, $r_{44} = (0.45 \cdot B)$. As seen in the graphs for the added resistance coefficients in waves are virtually the same. On the basis of this the radii of gyration is set to be the mean value of the range on all VERES calculations on the ships in this thesis. The values are set to be as shown in the figure below.



Main Dimensions :
Lpp 192.000 m
Breadth 32.200 m
Draught 11.800 m
Sinkage 0.000 m
Trim aft 0.000 deg

Metacentric Heights :
☑ Calculate GM

Vessel Mass Distribution :
LCG rel. AP 101.750 m
VCG 11.800 m
Mass 60898.016 tonnes

Radii of Gyration :
R 44 11.300 m
R 55 48.000 m
R 66 48.000 m
R 64 0.000 m

Coefficients for datacheck :
Block Coefficient, Cb : 0.8104
Waterplane Area Coeff., Cw : 0.886
Mid Section Coefficient, Cm : 0.9956

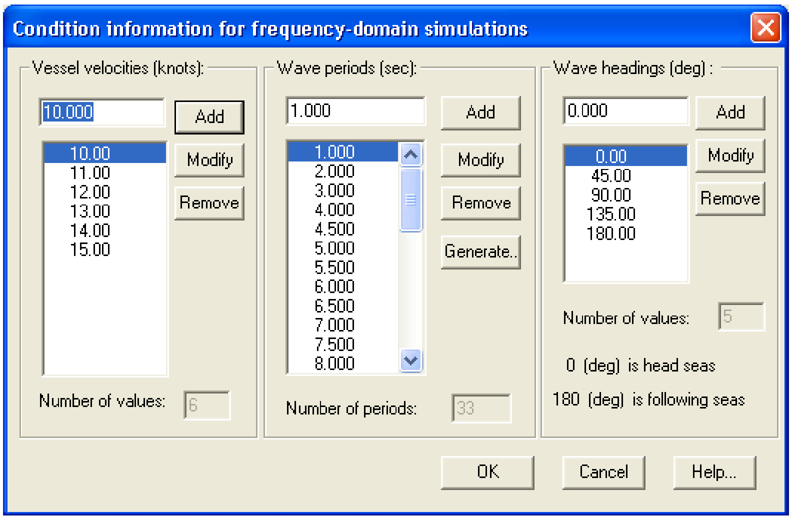
Please note the following definitions: Longitudinal center of gravity, LCG, is given relative to AP (positive forwards). Vertical center of gravity, VCG, is given relative to the baseline.

Figure 5-10: Screenshot from VERES, vessel description input

The wanted ship velocities must be selected. The service speeds on these ships usually varies between 10 and 15 knots. However, the variation in the results with respect to velocity is not particularly high. Therefore, the velocities that are calculated are only integer numbers between 10 and 15 knots as seen in figure 4-9.

Relevant wave periods must also be selected. In most of the sea states that the ships will experience the wave period, T_P, will not exceed 10-12 seconds. However, in order to get a smooth and complete added wave resistance graph the wave periods that are calculated reaches 25 seconds.

Wave headings must also be selected. Since the ship form asks for a number between 1 and 8 relative to the ship, the wave headings in the calculations will of course be the same. This includes 0 degrees (head seas), 45 degrees, 90 degrees, 135 degrees and 180 degrees (following seas). 225 degrees, 270 degrees and 315 degrees will not be calculated since they are the same as 135 degrees, 90 degrees and 45 degrees respectively.



Vessel velocities (knots):
10.000
10.00
11.00
12.00
13.00
14.00
15.00
Number of values: 6

Wave periods (sec):
1.000
1.000
2.000
3.000
4.000
4.500
5.000
5.500
6.000
6.500
7.000
7.500
8.000
Number of periods: 33

Wave headings (deg) :
0.000
0.00
45.00
90.00
135.00
180.00
Number of values: 5
0 (deg) is head seas
180 (deg) is following seas

Figure 5-11: Screenshot from VERES, condition information input

5.2.2 Calculation method for wave resistance

The calculation method for added resistance in waves that is used in Veres in this thesis is the direct pressure integration method. This method is described in chapter 3.1.2.

5.2.3 Wave spectrum

The wave spectrum that has been used to recreate a wave environment as close to the reality as possible is the Pierson-Moskowitz spectrum. This is because the PM spectrum is suitable for a fully developed sea. This is when the ship crew has been told to fill out the form. A fully developed sea is a sea state where the wind has been blowing long enough over a sufficiently open stretch of water. What happens then is that the high frequency waves have reached equilibrium. At this point the waves are breaking slightly. (Fathi, 2008)

5.3 Speed and powering plug-in

This ShipX platform plug-in can be used to predict the speed loss of ships due to waves and wind. In this thesis the program has been used to find the wind coefficients.

Required input for speed loss calculation:

- Calm water performance.
- Added resistance and RAO (hull motion transfer functions) from Vessel Response calculation which is done in Veres.

Since ship dimensions are used for generating correct input data for calculation, ShipX needs correct hull data. It is possible to either import hull geometry into ShipX or select to give the required hull data manually.

Speed-loss calculations require a large set of input data. The engine and propeller characteristics must be known, as well as the total still-water resistance and added resistance in waves. If speed loss calculations are to be performed for an irregular sea-state, the wave spectrum defining the sea-state is required input. The ship motions are input for the calculation of thrust reduction in waves.(Berget, Fathi, & Ringen, 2009)

5.4 Results from ShipX

5.4.1 Wave resistance

The added wave resistance varies with both speed of the vessel and draft. Therefore calculations have been made for several velocities and drafts. The usual service speeds of the ships are between ten and fifteen knots. The difference in added wave resistance with respect to the velocity is not particularly large. Therefore, I consider it sufficient with calculations between ten and fifteen knots with one knot steps. This means that there have been made calculations for six different velocities.

The waterline area of the ship changes with the draft of the ship as shown in the figure below:

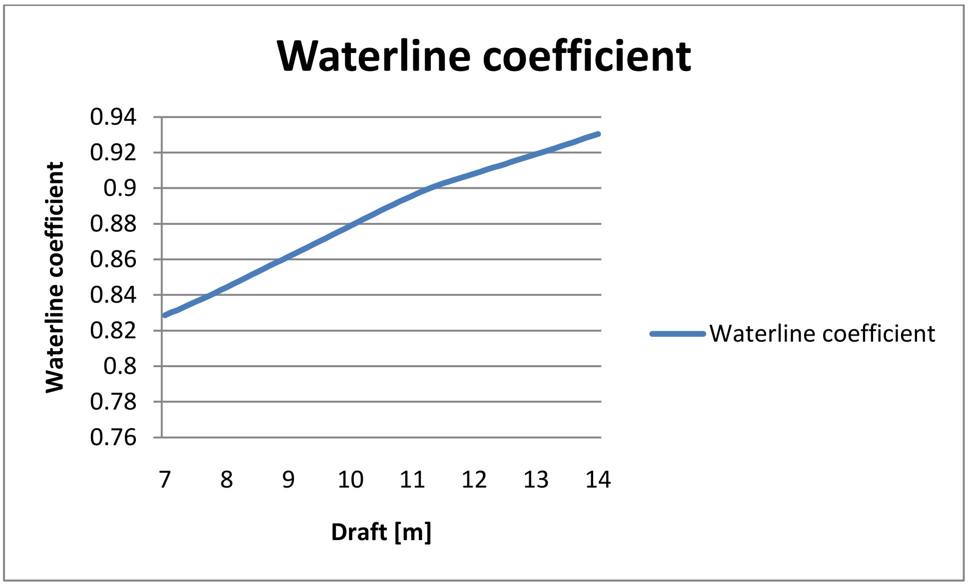


Figure 5-12: Waterline coefficient

The waterline coefficients are found from hydrostatics calculation for the ships provided by KGJS.

The change of the waterline coefficient with respect to the draft is one reason for that the added wave resistance will change with the draft. The change in added wave resistance due to change in draft is considered. For every velocity the added resistance in waves has been calculated with seven different drafts, 7m, 8m, 9m, 10m, 11m, 11.8m (DWL) and 13.5m. From the graph it can be seen that the slope decreases after T = 11.8m. And results shows that the difference in added wave resistance between T = 11.8m and T = 13.5m is minor.

In total 42 added wave resistance calculations have been made. One example of the result is shown in Figure 5-13. All other results from the calculations are given in the appendices 6-11. All calculation consists of the same wave heading angles as the ship form asks for. This involves every 45th degree from zero to 360 degrees.

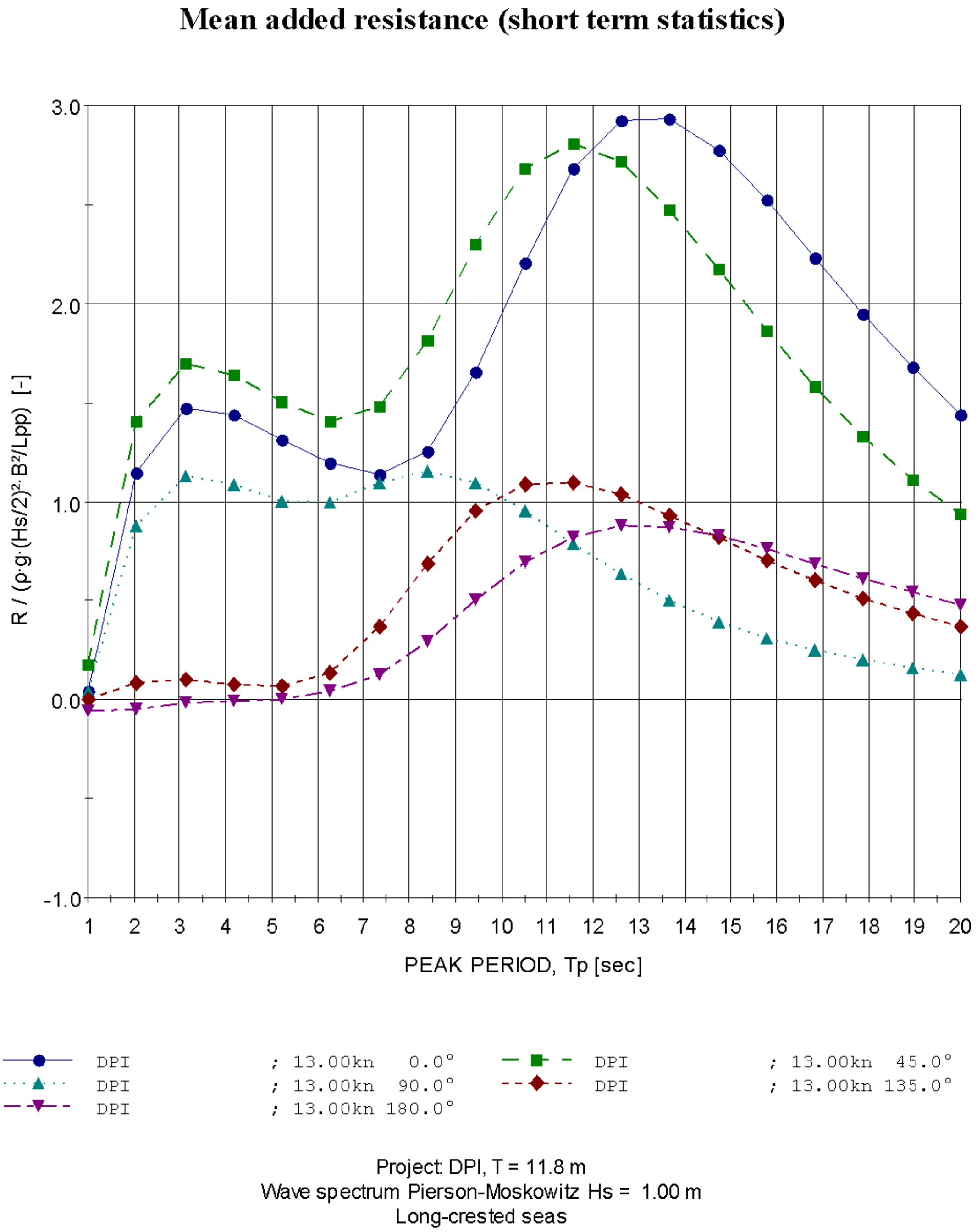
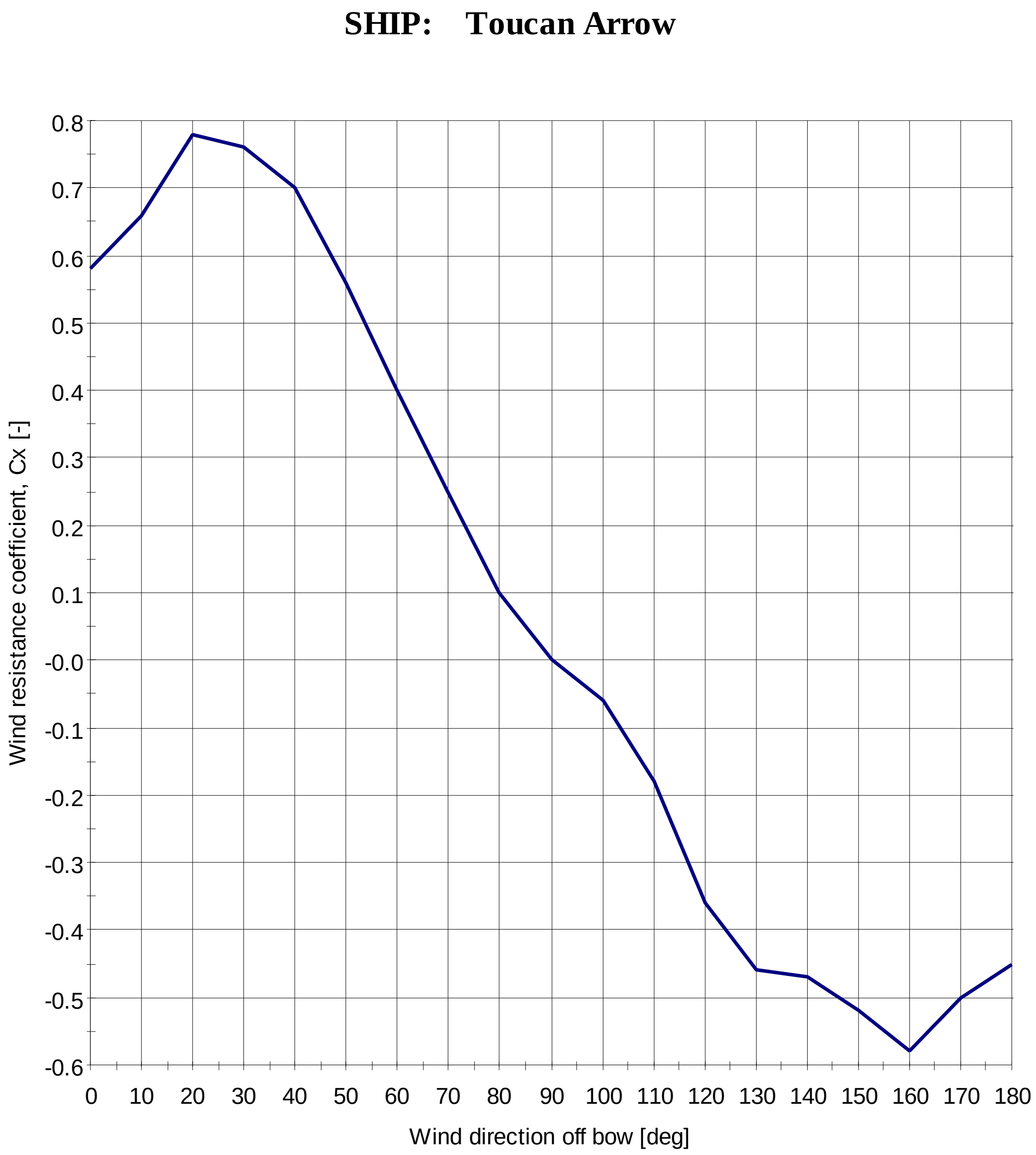


Figure 5-13: Added resistance in wave coefficients for design waterline at service speed of 13 kn.

5.4.2 Wind resistance

The wind coefficients given from ShipX Speed and Powering is shown in the Figure 5-14.



Run description: From 10-15 knots
Front projected wind area for prognosis = 992.0 m²
Wind coefficients based on: Cargo vessel, Lpp=145m, B=23m, Al=1970m², At=490m²

Figure 5-14: Wind coefficients for the ships from ShipX Speed and Powering Prediction plug-in

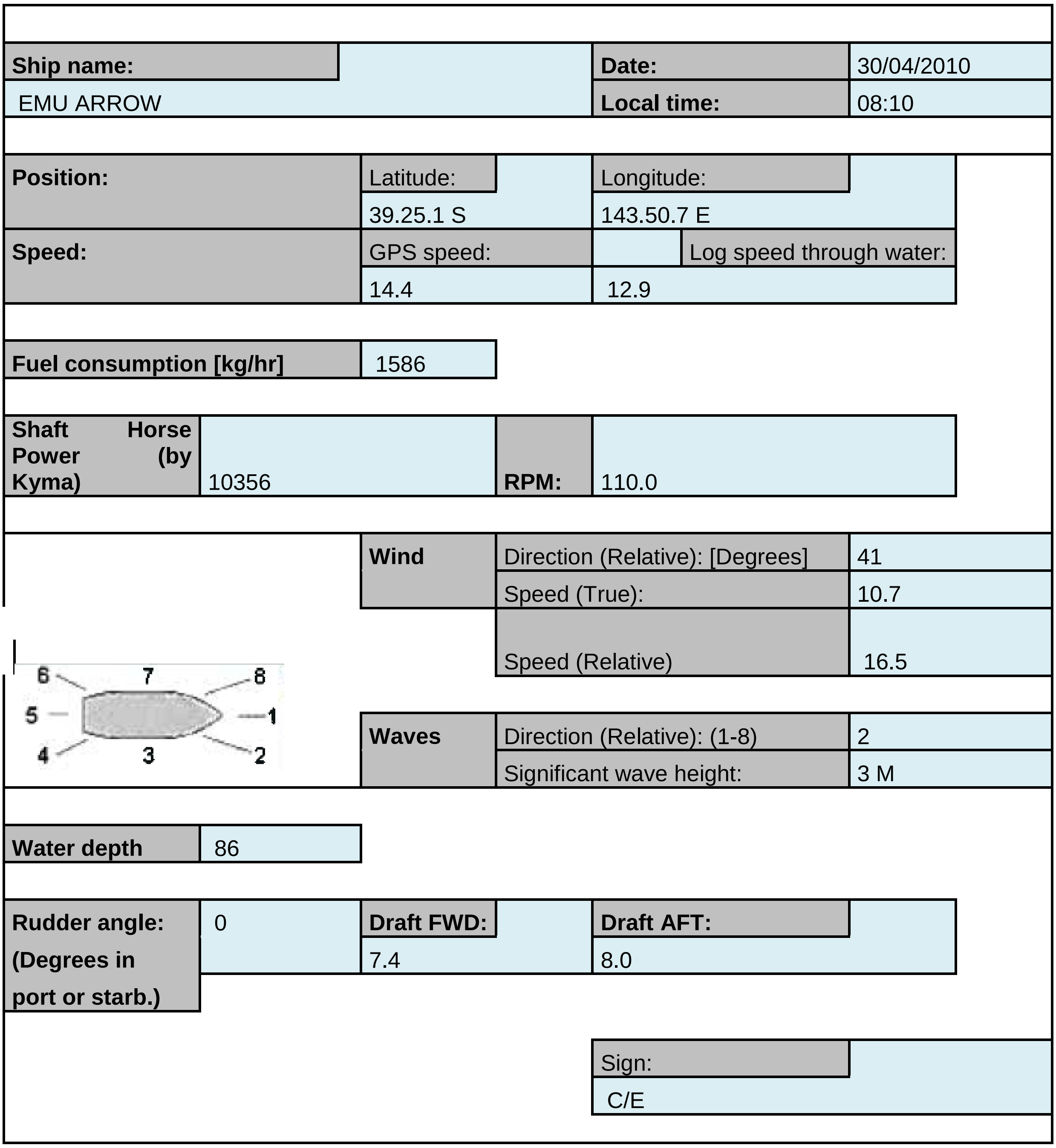
The wind coefficient is based on wind tunnel results for a model of a cargo vessel with dimensions Lpp = 145m, B = 23m, Al = 1970m and At = 490m^2. Since the shape of this ship is similar the wind resistance coefficient can be used on the ships in this thesis. The difference in results comes with the front projected area of the ship which is 992m^2 on the ships in this thesis.

6 Calculations in Excel

The calculations in this thesis are made in Microsoft Excel. Matlab would also have been a suitable tool to accomplish these calculations and show the results in well arranged figures. However, a calculation sheet in Excel is easier to learn to use for others than a program made in Matlab. Besides, Excel is a program installed on most computers, while Matlab is expensive. How the Excel sheets works and how to use it will be explained in this chapter.

6.1 Inputs

6.1.1 The ship form



Ship name:		**Date:**	30/04/2010
EMU ARROW		**Local time:**	08:10
Position:	Latitude:	Longitude:	
	39.25.1 S	143.50.7 E	
Speed:	GPS speed:	Log speed through water:	
	14.4	12.9	
Fuel consumption [kg/hr]	1586		
Shaft Horse Power (by Kyma)	10356	**RPM:**	110.0
Wind	Direction (Relative): [Degrees]	41	
	Speed (True):	10.7	
	Speed (Relative)	16.5	
Waves	Direction (Relative): (1-8)	2	
	Significant wave height:	3 M	
Water depth	86		
Rudder angle: (Degrees in port or starb.)	0	**Draft FWD:**	**Draft AFT:**
		7.4	8.0
Sign:	C/E		

Figure 6-1: The ship form for data collection given to the ship crew on each of the five ships

Comments:

1. Wind speed in knots shall be from anemometer readings.
2. Rudder angle shall be reported with degrees in addition to the direction. Ex: “3 port”
3. Speed must be by Doppler log and through water, kindly confirm with bridge that speed actually is through water and not over ground, i.e. that Doppler log is in water track mode.
4. Speed and power should be recorded at constant navigation. I.e. your current speed, course, power and RPM should be kept constant during measurements and it should have been kept constant for at least 30 minutes prior to measurements in order to secure constant navigation. Kindly confirm with bridge that constant navigation can be achieved during measurements, i.e. no change of course, rpm or speed.
5. Water depth should be at least 100 m. If not achievable, kindly advise actual water depth.
6. The observed wave height should be less than 3.0 m and the true wind speed should be less than 25 knots. The sea state should preferably not be confused with wind generated waves and swell from different directions.

The comments number one to six on the form is attached in order to ensure that the crew understands the form and completes it properly. The comments are written in cooperation with Willy Arne Reinertsen in KGJS.

6.1.1.1 Ship speed

The ship speed must be given both as ground speed, the speed relative to the ground (GPS speed in the form) and speed through water. The speed through water is used when added wave resistance calculations are made. This is because when calculating added resistance due to waves, it is vital to know the speed relative to the water, and not ground. Also when calculating resistance due to steering, the speed through water is used. In wind resistance calculations on the other hand, the speed relative to the ground is used. This is because the wind is given relative to the ground.

6.1.1.2 Shaft horse power

The power which is monitored on the ship is the shaft horse power. The shaft horse power is being corrected in the calculations, and shown over time to present the resistance increase over time.

6.1.1.3 Waves

In the added wave resistance calculations the wave direction relative to the ship is used. Data about the waves, both height and direction are the most uncertain part of the form. There are no devices that measure the wave height and direction. Mostly the wave height is found visually by the crew and or found as a corresponding value to the wind data from the Beaufort scale (Table 8-1). The direction of the waves is given as a number from one to eight relative to the ship.

6.1.1.4 Wind

The wind data including wind speed and wind direction are collected by anemometers mounted on vessels. This gives an accurate measurement of both true wind speed and direction and speed and direction relative to the ship. The wind direction which is used in the calculations is the direction relative to the ship. The same applies for the wind speed. The relative wind speed is the one used in the air resistance calculations.

6.1.1.5 *Rudder angle and forward and aft draft*

The rudder angle must be given in order to calculate the added resistance due to the rudder. The draft is vital in the resistance correction. The reason for why forward and aft draft is reported is to know if the ship travels with a trim. Added resistance due to trim is very difficult, but normally the ship travels relative evenly. As long as the draft difference forward and aft is not to big the change due to trim is assumed to be zero.

6.1.1.6 *Remaining sections*

Some of the remaining sections of the form like position, time and true wind speed are asked for so that it can be possible to double check the weather and sea conditions. Especially the wave height and direction is uncertain. The water depth is also requested because I need to know if the calculations can be made under the assumption of infinite water depth.

6.1.2 Routines and accuracy of the form filling

In the end of February I personally stayed at one of the ships in my calculations for six days. The ship was “Penguin Arrow” and travelled from Bristol in England to Flushing in the Netherlands while I was on board. The purpose of my trip was to get firsthand experience regarding the methods the crew uses to fill out my form.

This ship type has many electronic devices to help the crew fill out the form I have given them. However, it is unclear how accurate some of the devices are; for instance fouling on the speed log transducer will affect the logged speed on the ship. It can occur that the devices are not properly calibrated. There might also be other inaccuracies like for instance fouling on the transducer to the speed-through-water measurement system. The accuracy of the data filled in the form has very little probability for influence of human errors. The only factor that has a high probability of uncertainty from the ship crew is the wave height and direction. There are no devices that measure this.

6.1.2.1 *Ship speed*

Figure 6-2: Penguin Arrow: Speed through water and speed over ground monitoring

The ship speed is given both in GPS speed (speed relative to the ground) and the speed through water. The GPS speed shown will of course be correct. The speed through water on the other hand has more uncertainties bound to it. Suppliers of speed logs claims that the accuracy is around 1 pct, or 0.1 knot, provided calibrated properly during sea trial/retrofit. (Reinertsen, 2009). This vessel has installed an electromagnetic speed log, and it is assumed that it is properly calibrated. However, if the transducer gets growth on it, it may become inaccurate. The transducer is mounted in the bow of this ship. This indicates that the accuracy will not be significantly affected by the changing wake as the fouling on the hull increases. This is more important when the transducer is mounted in the aft or low on the body. The pitch motion of the ship may also change the flow over an aft mounted transducer, so this source of error may also be neglected. However, a drawback of a bow mounted transducer is aeration of the water. This means air bubbles that appear when the bow encounters the meeting water and waves. This can especially be a problem in high seas and in high speeds.

A speed correction factor is given by KGJS for each of the ship, which is multiplied by the speed given by the crew. The correction factor is probably not completely right. However, it is assumed more accurate to apply it rather than only trust the speed given by the crew.

Ship	Speed log correction factor
Emu Arrow	1.026
Merlin Arrow	1.048
Penguin Arrow	1.015
Plover Arrow	1.031
Weaver Arrow	1.034

Table 6-1: Speed log correction factors

6.1.2.2 Wave height and direction

The collection of wave data is as mentioned the most inaccurate in the form. It is very difficult to estimate the wave height from an elevated position. Therefore the crew mostly use own judgement or, if uncertain, the Beaufort scale from wind speeds to estimate the significant wave height.

Wind force	Wind speed [m/s]	Wind description	Hs [m]
0	<0.3	Calm	0
1	0.3-1.5	Light air	0-0.2
2	1.6-3.4	Light breeze	0.2-0.5
3	3.4-5.4	Gentle breeze	0.5-1
4	5.5-7.9	Moderate breeze	1-2
5	8.0-10.7	Fresh breeze	2-3
6	10.8-13.8	Strong breeze	3-4
7	13.9-17.1	Near gale	4-5.5
8	17.2-20.4	Gale	5.5-7.5
9	20.8-24.4	Strong gale	7-10
10	24.5-28.4	Storm	10-12.5
11	28.5-32.6	Violent storm	11.5-14
12	>32.6	Hurricane	>14

Table 6-2: The Beaufort scale

Reinertsen in KGJS has compared the wave heights given by the crew with satellite data for four different trips on one ship. He found that for small wave heights (Hs < 1.5m) the crew mainly reported correct wave heights. For large wave heights (Hs > 3.5 m) the crew tended to underestimate the value.

The wave direction is often the same direction as the wind. But this is not always the case. The wind direction can change much faster than the wave direction. And in some cases, especially in my experience on a ship in small waves, it can be difficult to see exactly where the waves are coming from. When this is the case the crew often makes a qualified guess, which is highly uncertain. This is why I ask for a number between 1 and 8 and not degrees in the wave direction section in the form.

6.1.2.3 Wind speed and direction

The wind speed and direction are given by an anemometer both for the relative wind speed and direction and a calculated true wind speed and direction. They are given accurately in degrees, but the values changes rapidly and become a source of uncertainty. It appears that after a while of monitoring the changes in degrees that is shown is within an interval of not more than 10 – 15 degrees. This means that it is more adequate to ask for a specific degree rather than a number from 1 – 8 relative to the ship, which gives a possible deviation of 45 degrees. The placing of these numbers is shown in the original crew form (Figure 6-1).

WIND 292° 4kn
S/D 054° 1.0kn

WIND 016° 11kn
S/D 000° 0.0kn

Figure 6-3: Penguin Arrow: True and relative wind monitoring

6.1.2.4 Rudder angle

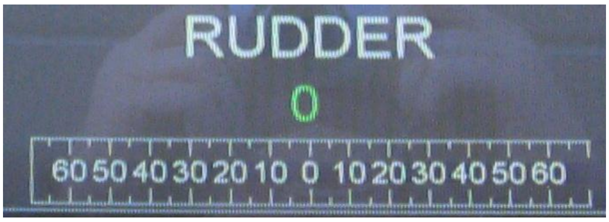


Figure 6-4: Penguin Arrow: Rudder angle monitoring

The rudder angle is given accurately in degrees as shown in the image above.

6.1.2.5 Draft

The draft in the bow and the stern is registered visually at the draft marks on the ship in port after the ship is done with loading. This is very accurate since it is easy to see the waterline on the draft markings on the ship side in still water.

6.1.2.6 Position

LAT 50°12.063'N
LON 005°48.225'W

Figure 6-5: Penguin Arrow: position monitoring

The position of the ship in latitude and longitude is given by GPS in an easy-to-follow way; therefore it is reason to expect this data to be correct. This data is given on several screens on the bridge. A segment of one of these screens is shown in the figure to the left.

6.1.2.7 Shaft power, RPM and fuel consumption

The ship has a shaft power meter mounted, so the shaft power is assumed to be as accurate as possible. The shaft power, the shaft RPM and the fuel consumption in kg/hr is given by the shaft power monitor.

Figure 6-6: Penguin Arrow: Shaft power meter monitoring by KYMA

6.1.2.8 Water depth

The water depth is given by a standard echo sounder, and is assumed to be accurate. Besides the reason that I ask for the water depth is only to ensure that the water depth is enough to use deep water calculations with confidence.

6.2 Assumptions

In the process of correcting the added resistance and then correct the values to a reference speed and draft there are several uncertainties. These uncertainties are not found by a given method or answer. Therefore, some qualified and reasoned assumptions must be made. These are accounted for in this chapter.

6.2.1 Extrapolation in the BHP vs. speed diagram

The sea trial is performed in velocities from 11 to 16.5 knots for the design water line at 11.8 m and from 12 to 16.5 knots in the ballast water line at 7.3 m. The results from the sea trial are shown below.

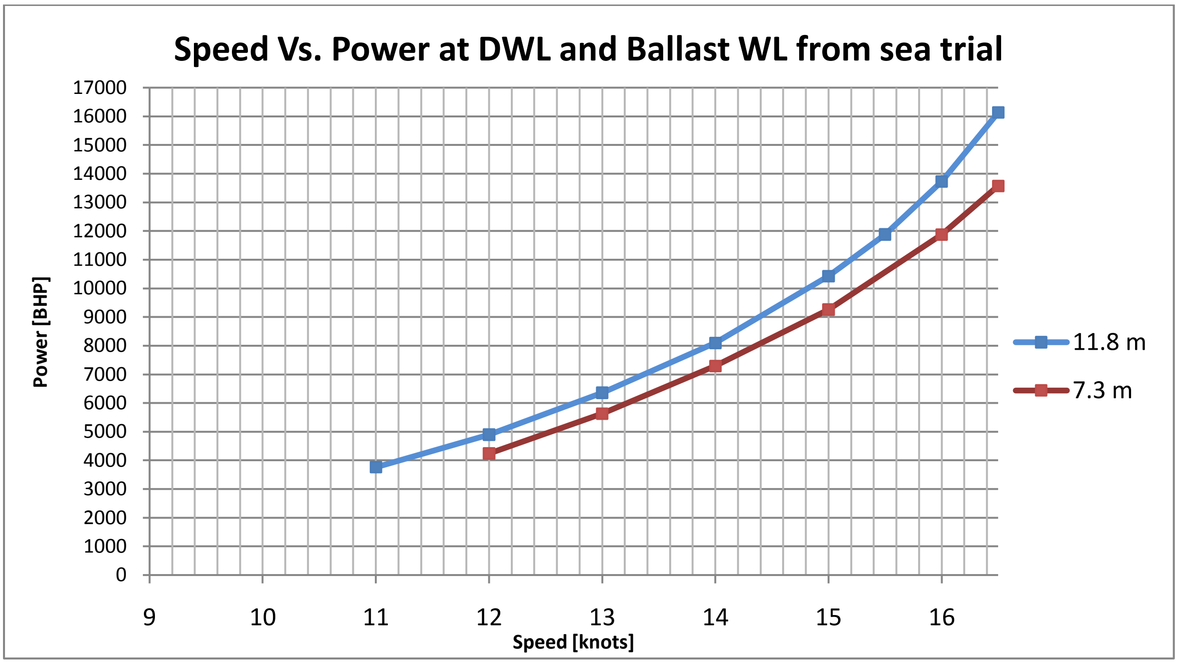


Figure 6-7: Speed versus power diagram for the ships from sea trial results

The problem with the velocities in the sea trial is that they are too high compared to the regular service speed. The ships often travel at velocities as low as 9 knots. Velocities like this are not shown in the sea trial results. Therefore I have extrapolated the graphs above so that they cover velocities from 9 knots. This is done by using linearity from plots of the admiralty coefficient. The admiralty coefficient assumed to be constant and is given by:

$$Ac = \frac{\Delta^{2/3} \cdot V^3}{P} \qquad (6.1)$$

Where

Δ = Displacement
V = Ship velocity
P = Engine power

The admiralty coefficients are shown below for both drafts. It can be seen that for high velocities, velocities over 13-14 knots, Ac is exponential. For lower velocities, below 12-13 knots, Ac is nearly linear. In the extrapolated values, Ac is assumed to be linear.

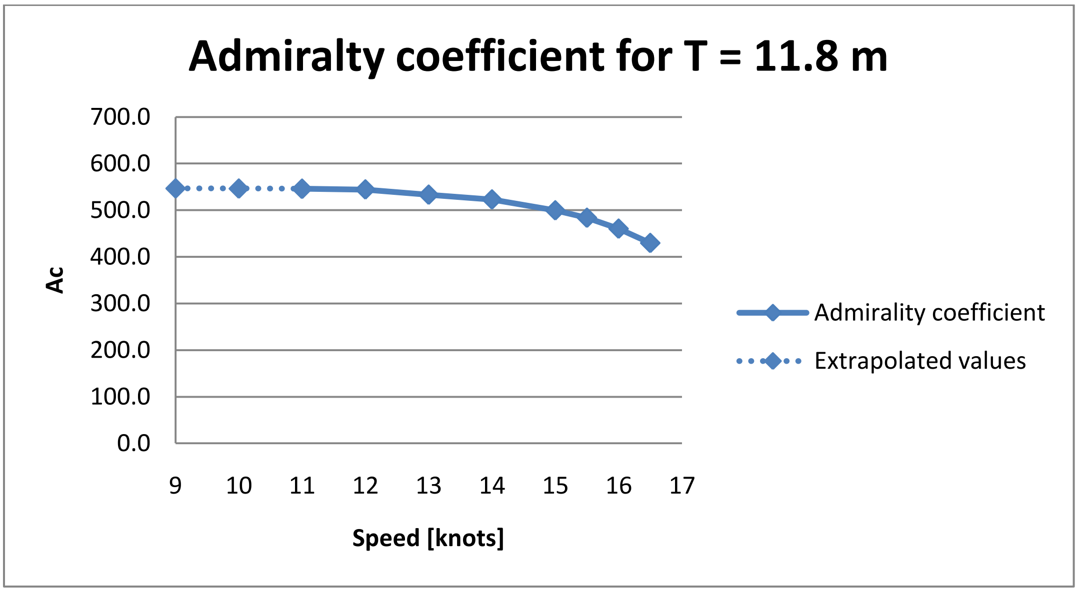


Figure 6-8: Admiralty coefficient for T = 11.8 m

In Figure 6-8 it can be seen that the admiralty coefficient is linear and almost constant in velocities below 12 knots.

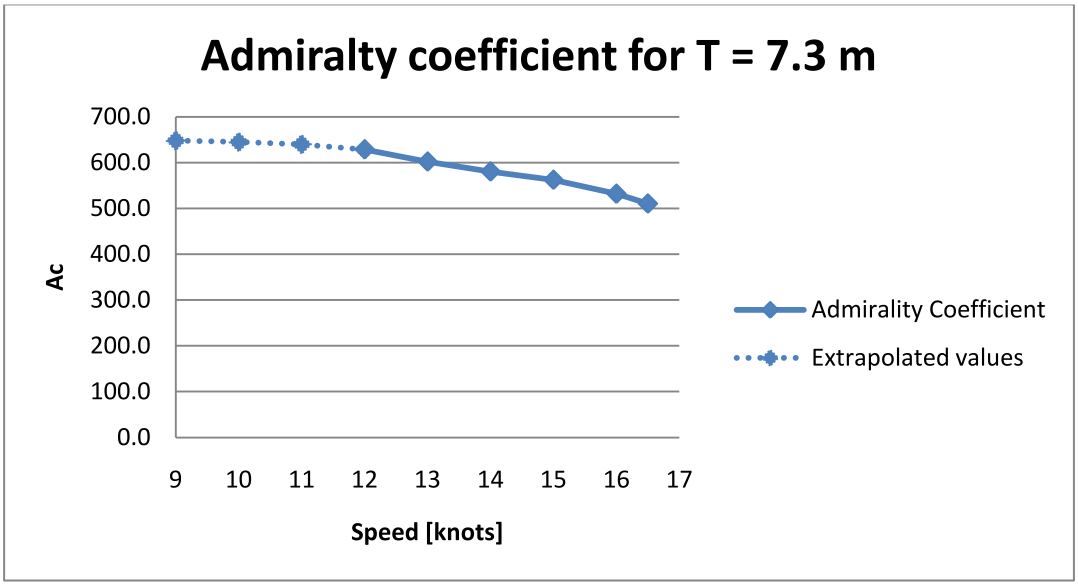


Figure 6-9: Admiralty coefficient for T = 7.3 m

In Figure 6-9 it can be seen that the extrapolated values of the admiralty coefficient is close to linear below 12 knots and almost constant below 11 knots.

The values of the admiralty coefficient are then used to calculate engine power at the velocities that are lower than the sea trial values. The admiralty coefficient formula (6.1) is changed to be with respect to engine power.

$$P = \frac{\Delta^{2/3} \cdot V^3}{Ac}$$

The extrapolated values from this approach are shown in the graph over speed versus power below.

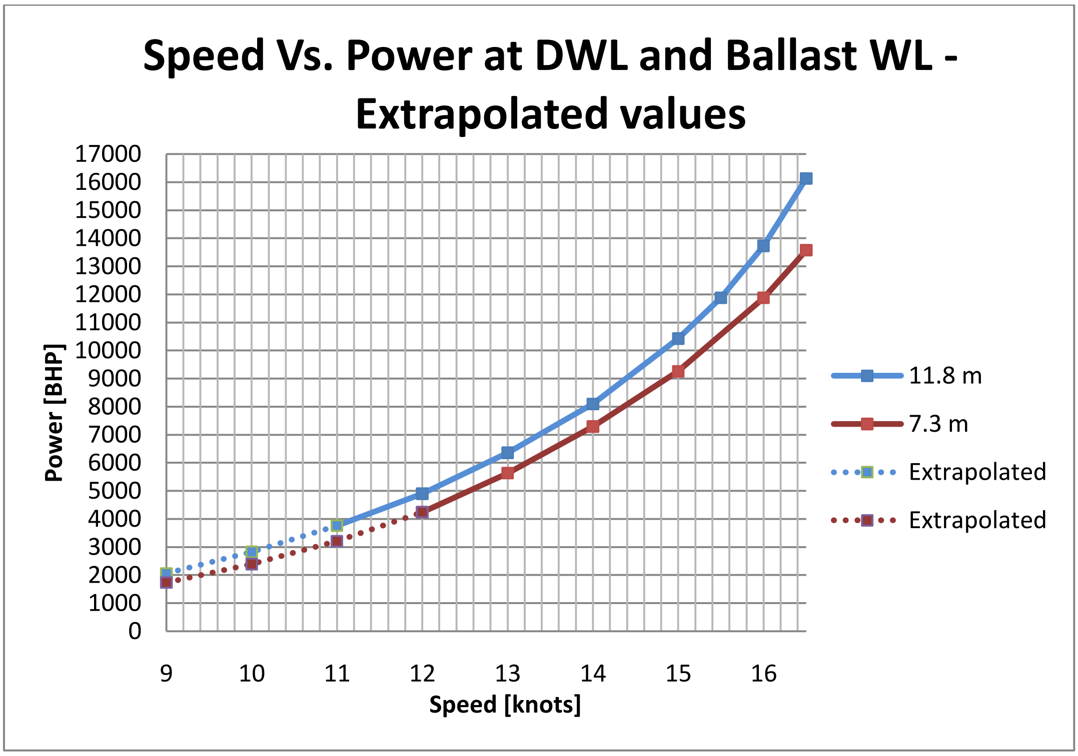


Figure 6-10: Speed versus power with extrapolated values for velocities below 11 and 12 knots

The relationship between the two lines is relatively constant in the towing tank results.

$$\frac{BHP\ at\ DWL}{BHP\ at\ BWL} \approx Constant\ at\ any\ given\ velocity$$

This relationship is held constant in the extrapolated lines. The level of uncertainty in the extrapolated part of the graphs is difficult to estimate. However, it is assumed that the level of uncertainties are of no larger extent than the general uncertainty of for instance the data collecting form, or the added resistance predictions.

6.2.2 Correction to reference speed and draft

It is virtually impossible to discover a trend in increased power usage over time only by looking at data corrected for added resistance. This is because the data is collected with different velocities and drafts. The power usage of the ship is strongly dependent on the velocity of the ship and also very dependent of the draft of the ship. Therefore, all the added resistance corrected values must be corrected to the same speed and draft. The reference speed is set to 13 knots and the reference draft is set to 11.8 m (DWL). To be able to correct to the reference speed and draft, some assumptions has been made.

First assumption is that there are linearity between T = 11.8 m and T = 7.3 m in the speed versus power diagram (Figure 6-10). This makes it easier to correct the values to the reference draft. BHP is added if the measured draft is less than 11.8 m or subtracted if the measured draft is more than 11.8

m on each point. The amount added or subtracted is the relative value between the lines at the measured velocity.

A hypothetically example to clarify the assumption:

> *If the distance between the lines at T = 11.8 m and T = 7.3 m at 16 knots is 2000 BHP and the ship traveled with T = 9.55 m (which is the middle between 11.8 m and 7.3 m), the value corrected to reference draft would have been the measured value plus half the distance between the graphs which is 1000 BHP.*

Second assumption is that when the ship is corrected to reference draft at 11.8 m the ship follows the speed versus power graph for 11.8 m regardless of how the fouling condition is on the hull. This is used in the process of correcting the ship to the reference speed.

First the point which is corrected for added resistance is corrected to the reference draft. When this is done each draft-corrected point is simply moved along the graph for T = 11.8 m to 13 knots, maintaining the same distance from the graph. This is shown in the figure below.

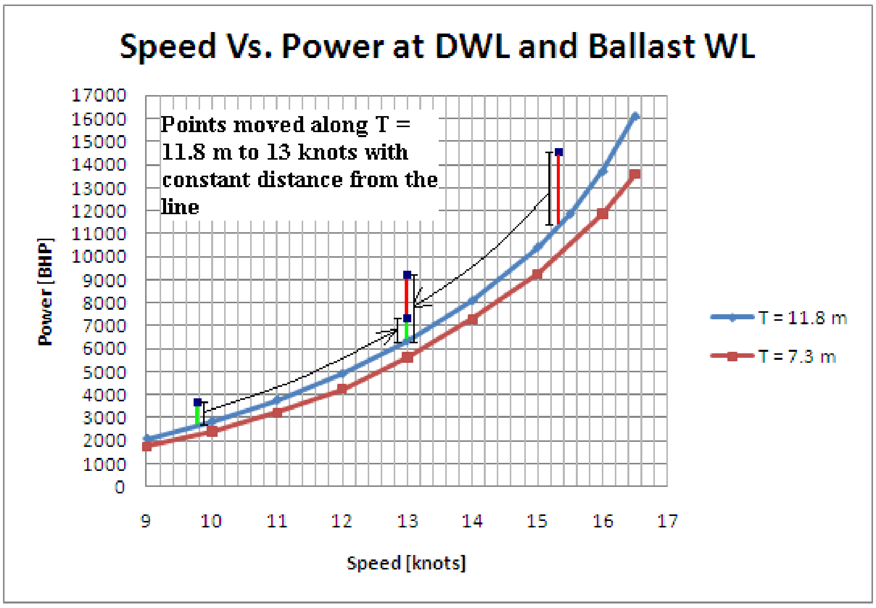


Figure 6-11: Correcting the ship to reference speed

A formula for the speed versus power for T = 11.8 m is found in Excel by fitting a polynomial of fourth degree to the points.

$$y = 6.1093x^4 - 280.47x^3 + 4904.2x^2 - 37494x + 106666 \qquad (6.2)$$

This is the formula that is used to correct the points to the reference speed. Each measured point is inserted in the formula and the distance between the numbers from this to the corresponding point on the blue line gets added to the blue line at 13 knots.

6.2.3 Significant wave height versus peak period

In the added wave resistance calculations the graphs that are used is the resistance relative to the peak period Tp. The relation between Hs and Tp varies. Factors that influence the relation can be a recent change in wind direction or velocity, water depth or land mass near the ship. However, if the ship travels in stable weather far from land and in deep waters, these factors may be neglected. In this case the relation between Hs and Tp is assumed constant and the typical values are given in ShipX. These values are used in this thesis and are shown in the table below.

Hs [m]	Tp [s]
0.2	1.15
1	4.74
2	7.59
3	9.34
4	10.55

Table 6-3: Hs vs. Tp

For values between the given wave heights third degree polynomial fitting between the points are used. This is shown in the figure below.

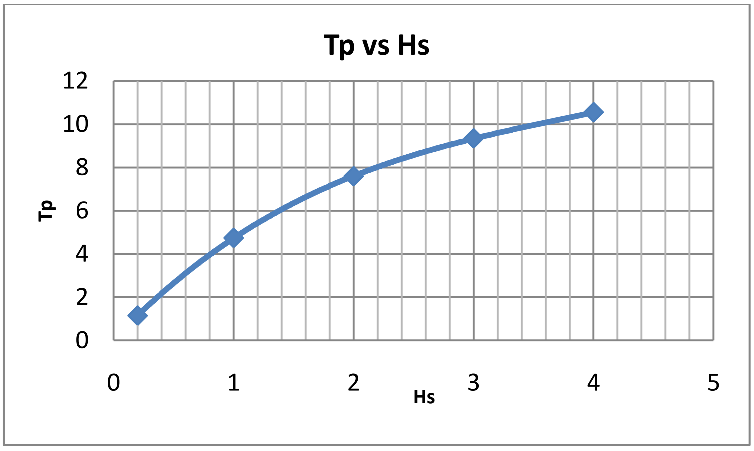


Figure 6-12: Tp vs. Hs

6.2.4 Calculating resistance in Newton to corresponding Horse Power

All added resistance calculations are in Newton. In order to include them in the speed versus power diagram, the resistance must be calculated to BHP. The coefficients needed for this calculation can be found from the ship propeller diagram. However, in this thesis these coefficients are given in the performance prediction documents of the ship.

The added BHP due to added resistance in Newton is given by:

$$BHP = \frac{R \cdot V \cdot 0.7}{\eta_0} \tag{6.3}$$

Where

R = Added resistance
V = Ship speed through water
η_0 = Propeller efficiency coefficient

The propeller efficiency coefficient changes with the velocity of the ship. Values for the propeller efficiency for velocities between 11 and 15 knots are given in the performance prediction report of the ships. These values for η_0 is given in the table below:

Speed [knots]	Propeller efficiency, η_0
11	0.571
12	0.567
13	0.568
14	0.564
15	0.561

Table 6-4: Propeller efficiency

The relationship between the highest and the lowest value is close to one ($\frac{0.561}{0.571} = 0.98$). The majority of the measured velocities are between 11 and 13 knots. Therefore, in order to simplify the calculation model in Excel, the propeller efficiency is set constant: $\boldsymbol{\eta_0 = 0.57}$.

6.2.5 Calculating the relative wind speed

The first version of the ship form given to the crew did not request the relative wind speed. This was a mistake from the undersigned. After the first 3-4 measurements the mistake was discovered, and the ship form was corrected. However, to be able to use the first measurements without the relative wind speed, it had to be calculated from the relative wind direction and the true wind speed. To do this simple trigonometry was utilized. If the velocity of the ship, the relative wind direction and the true wind speed is known, the relative wind speed can be calculated as shown in the figure below.

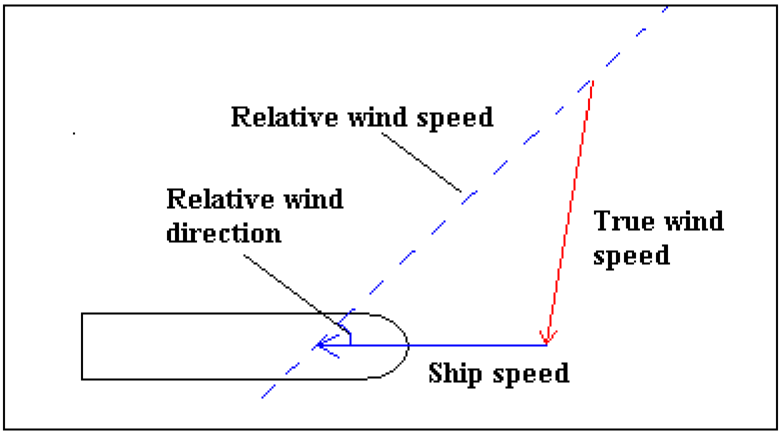


Figure 6-13: Relative wind speed calculation

6.2.6 Shallow water

The resistance of a ship increases in shallow waters. And there are simple formulas for this speed loss estimation.

The first form given to the crew did not take the shallow water effect into consideration. Therefore, in the first three or four measurements there is a possibility for shallow water. In the revised ship form given to the ships (Figure 6-1) the crew is kindly asked to fill in the form when the ship travels in waters deeper than at least 100 m. And if nothing else is possible they must report the actual depth. Then an eventual decrease in speed may be corrected for.

ITTC has presented a formula for speed loss due to shallow water given by Lackenby (Lackenby, 1962):

$$\frac{\Delta V_s}{V_s} = 0.1242 \cdot \left(\frac{A_M}{H^2} - 0.05\right) + 1.0 - \tanh\left(\frac{gH}{V_s^2}\right) \qquad (6.4)$$

Where

H = Water depth in m

A_M = Middle ship section area under water in m^2

ΔV_S = Speed loss due to shallow water in $^m/_s$

V_S = Ship speed

Used with specifications for the ships in this thesis the speed loss can be seen in Figure 6-14. The calculations are performed with DWL = 11.8 m and a service speed of 13 knots. The middle ship section area under water is calculated with C_M = 0.9963 found in hydrostatics calculations from the ships.

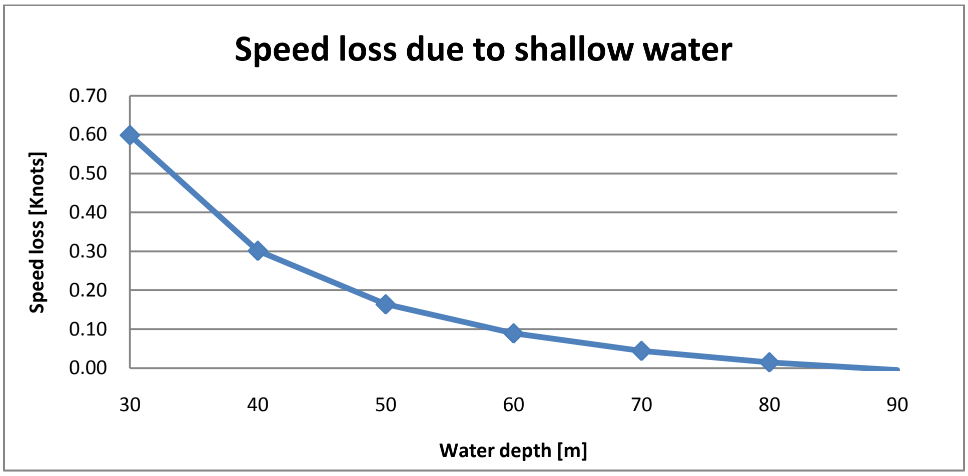


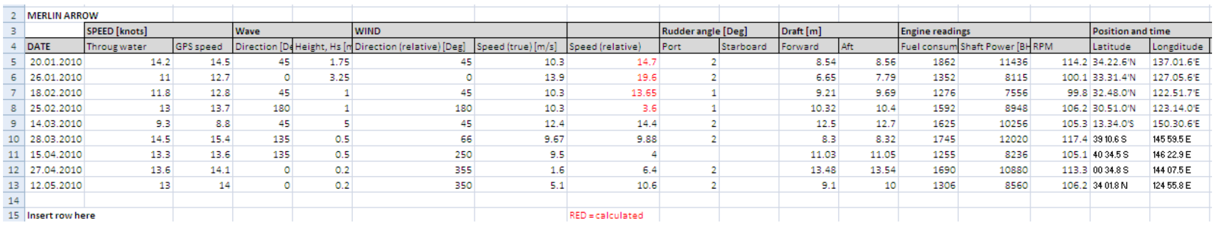
Figure 6-14: Speed loss due to shallow water

6.3 How to use the Excel spreadsheet

It can be difficult to learn an Excel spreadsheet that others have made. In this part the usage of the Excel spreadsheet will be explained step by step. The formulas behind the calculations are explained in chapter 4. Other assumptions are explained in chapter 6.2.

Every ship in the calculation process has an own banner. Each banner has the same calculations and looks the same. This is to make it easier to use and to have a better overview over the progress of each ship.

First step is to insert the numbers collected in the form (Figure 6-1) from the ship crew as seen in Figure 6-15.

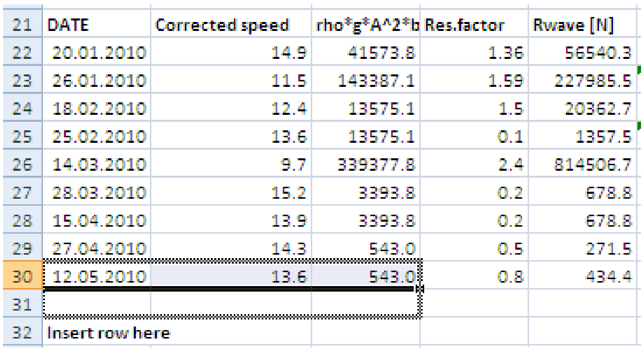


2	MERLIN ARROW																
3		SPEED [knots]		Wave		WIND				Rudder angle [Deg]		Draft [m]		Engine readings			Position and time	
4	DATE	Throug water	GPS speed	Direction [De	Height, Hs [m	Direction (relative) [Deg]	Speed (true) [m/s]	Speed (relative)	Port	Starboard	Forward	Aft	Fuel consum	Shaft Power [BH	RPM	Latitude	Longditude
5	20.01.2010	14.2	14.5	45	1.75	45	10.3	14.7	2		8.54	8.56	1862	11436	114.2	34.22.6'N	137.01.6'E
6	26.01.2010	11	12.7	0	3.25	0	13.9	19.6	2		6.65	7.79	1352	8115	100.1	33.31.4'N	127.05.6'E
7	18.02.2010	11.8	12.8	45	1	45	10.3	13.65	1		9.21	9.69	1276	7556	99.8	32.48.0'N	122.51.7'E
8	25.02.2010	13	13.7	180	1	180	10.3	3.6	1		10.32	10.4	1592	8948	106.2	30.51.0'N	123.14.0'E
9	14.03.2010	9.3	8.8	45	5	45	12.4	14.4	2		12.5	12.7	1625	10256	105.3	13.34.0'S	150.30.6'E
10	28.03.2010	14.5	15.4	135	0.5	66	9.67	9.88	2		8.3	8.32	1745	12020	117.4	39 10.6 S	145 59.5 E
11	15.04.2010	13.3	13.6	135	0.5	250	9.5	4			11.03	11.05	1255	8236	105.1	40 34.5 S	146 22.9 E
12	27.04.2010	13.6	14.1	0	0.2	355	1.6	6.4	2		13.48	13.54	1690	10880	113.3	00 34.8 S	144 07.5 E
13	12.05.2010	13	14	0	0.2	350	5.1	10.6	2		9.1	10	1306	8560	106.2	34 01.8 N	124 55.8 E
14																	
15	Insert row here							RED = calculated									

Figure 6-15: Excel spreadsheet: Ship form input

It is of course important to fill in numbers with the right denomination.

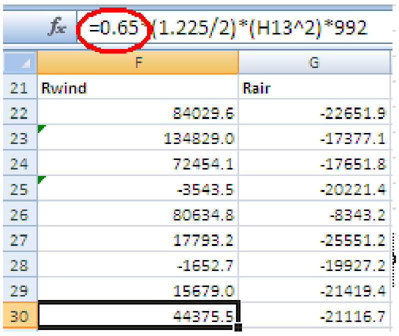
Second step is to drag the columns “Date”, “Corrected speed” and “rho*g*A^2*b^2*Lpp/2” down one line. The formulas behind will automatically adapt to the next line and fit with the new numbers that are filled in which are described above. The corrected speed column is the original speed from the ship form plus a correction factor for the speed measurement system on the ship. The next column is the number which is to be multiplied with the dimensionless wave resistance factor in the next column to get the added wave resistance in newton. This wave resistance factor is found from the added resistance in waves plots from the results in Veres. Example is shown in Figure 5-13. The rest of the plots are found in the appendixes. There is one plot for each ship speed, integers from 10 to 15 knots. For each speed there is one plot for each draft. (The drafts calculated are integers from 1 m to 11 m plus DWL at 11.8 m and 13.5 m). In total there are 42 plots and one that fits the speed and draft best is to be used. On each plot there are calculations for the same eight angles of wave direction as shown in the crew form (Figure 6-1).



21	DATE	Corrected speed	rho*g*A^2*b	Res.factor	Rwave [N]
22	20.01.2010	14.9	41573.8	1.36	56540.3
23	26.01.2010	11.5	143387.1	1.59	227985.5
24	18.02.2010	12.4	13575.1	1.5	20362.7
25	25.02.2010	13.6	13575.1	0.1	1357.5
26	14.03.2010	9.7	339377.8	2.4	814506.7
27	28.03.2010	15.2	3393.8	0.2	678.8
28	15.04.2010	13.9	3393.8	0.2	678.8
29	27.04.2010	14.3	543.0	0.5	271.5
30	12.05.2010	13.6	543.0	0.8	434.4
31					
32	Insert row here				

Figure 6-16: Excel spreadsheet: Corrected speed and wave resistance

Third step is to drag the columns wind resistance “Rwind” and air resistance “Rair” down one line. However, it is important to change the wind resistance coefficient C_{airp} to the correct value with respect to the relative wind direction with the right positive or negative sign. This factor is found in Figure 5-14. The wind resistance coefficient and where to change it is shown in Figure 6-17.

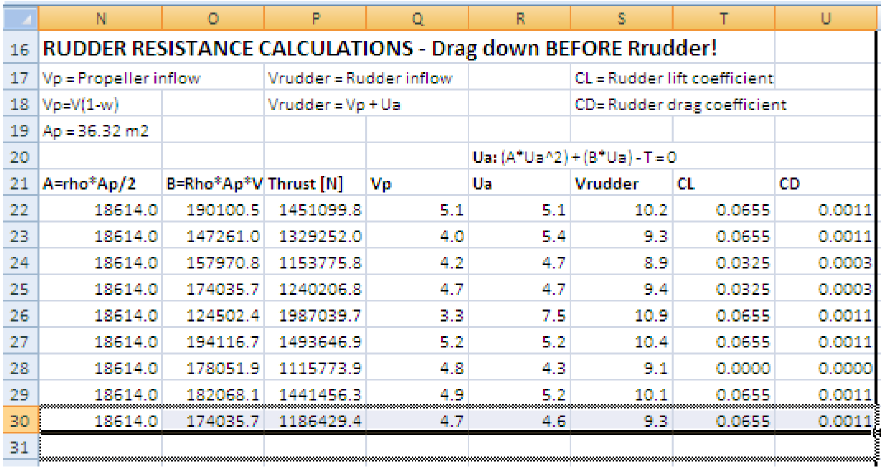


```
=0.65*(1.225/2)*(H13^2)*992
```

	F	G
21	Rwind	Rair
22	84029.6	-22651.9
23	134829.0	-17377.1
24	72454.1	-17651.8
25	-3543.5	-20221.4
26	80634.8	-8343.2
27	17793.2	-25551.2
28	-1652.7	-19927.2
29	15679.0	-21419.4
30	44375.5	-21116.7

Figure 6-17: Excel spreadsheet: Wind and air resistance

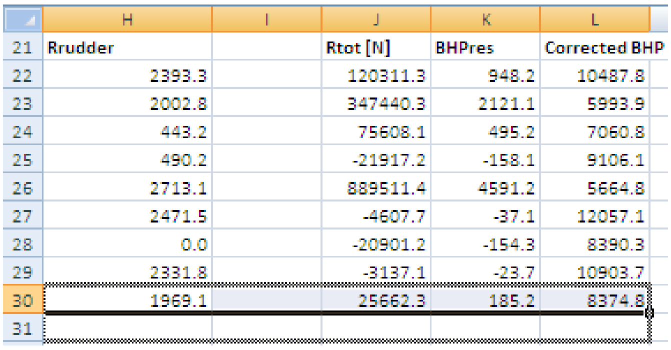
The next step is to find the resistance due to rudder angle. In this step all the calculations will change correctly when the columns are dragged down on line. First the basic calculations which are inputs in the main rudder resistance formula must be made. This is shown in the figure below.



	N	O	P	Q	R	S	T	U
16	RUDDER RESISTANCE CALCULATIONS - Drag down BEFORE Rrudder!							
17	Vp = Propeller inflow		Vrudder = Rudder inflow			CL = Rudder lift coefficient		
18	Vp=V(1-w)		Vrudder = Vp + Ua			CD= Rudder drag coefficient		
19	Ap = 36.32 m2							
20					Ua: (A*Ua^2) + (B*Ua) - T = 0			
21	A=rho*Ap/2	B=Rho*Ap*V	Thrust [N]	Vp	Ua	Vrudder	CL	CD
22	18614.0	190100.5	1451099.8	5.1	5.1	10.2	0.0655	0.0011
23	18614.0	147261.0	1329252.0	4.0	5.4	9.3	0.0655	0.0011
24	18614.0	157970.8	1153775.8	4.2	4.7	8.9	0.0325	0.0003
25	18614.0	174035.7	1240206.8	4.7	4.7	9.4	0.0325	0.0003
26	18614.0	124502.4	1987039.7	3.3	7.5	10.9	0.0655	0.0011
27	18614.0	194116.7	1493646.9	5.2	5.2	10.4	0.0655	0.0011
28	18614.0	178051.9	1115773.9	4.8	4.3	9.1	0.0000	0.0000
29	18614.0	182068.1	1441456.3	4.9	5.2	10.1	0.0655	0.0011
30	18614.0	174035.7	1186429.4	4.7	4.6	9.3	0.0655	0.0011
31								

Figure 6-18: Excel spreadsheet: Rudder resistance calculations part 1

When this is done the main rudder resistance column may be dragged down along with the columns “Rtot”, “BHPres” and “corrected BHP”. Rtot is the total added resistance from waves, wind, air and rudder. “BHPres” is the extra power need in brake horse power to cope with the calculated added resistance. “Corrected BHP” is the measured shaft horse power minus the extra power need.



	H	I	J	K	L
21	Rrudder		Rtot [N]	BHPres	Corrected BHP
22	2393.3		120311.3	948.2	10487.8
23	2002.8		347440.3	2121.1	5993.9
24	443.2		75608.1	495.2	7060.8
25	490.2		-21917.2	-158.1	9106.1
26	2713.1		889511.4	4591.2	5664.8
27	2471.5		-4607.7	-37.1	12057.1
28	0.0		-20901.2	-154.3	8390.3
29	2331.8		-3137.1	-23.7	10903.7
30	1969.1		25662.3	185.2	8374.8
31					

Figure 6-19: Excel spreadsheet: Rudder resistance, total resistance, BHP and corrected BHP

Now the added resistance calculations are made, and the results with the corrected BHP along with original measured BHP can be shown in the same graph as the power usage from sea trial tests.

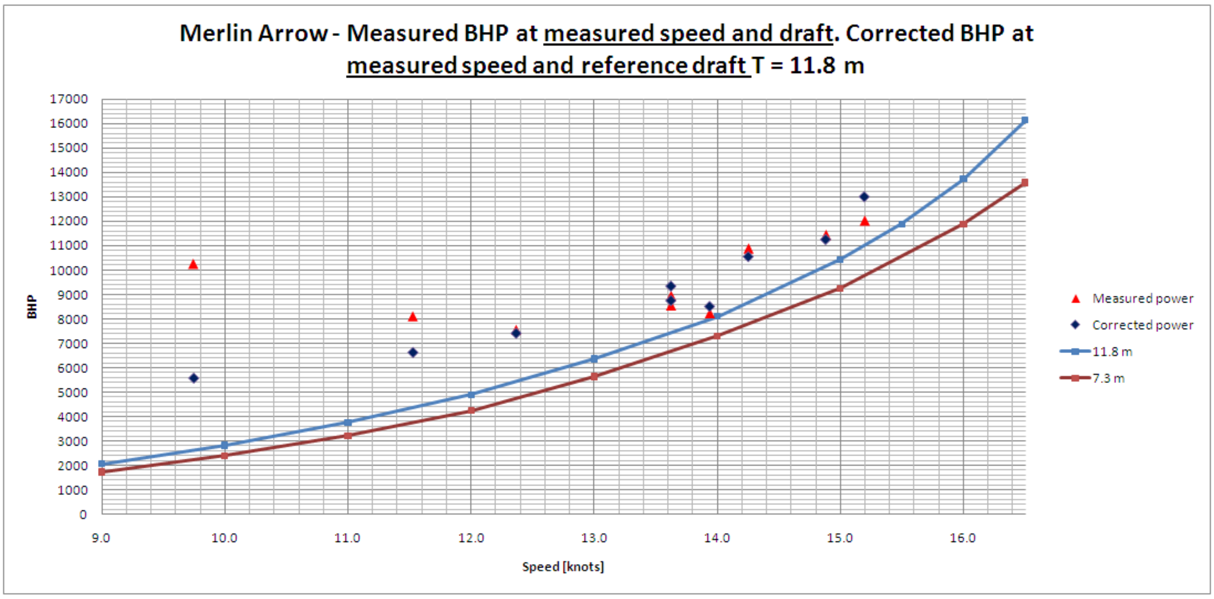
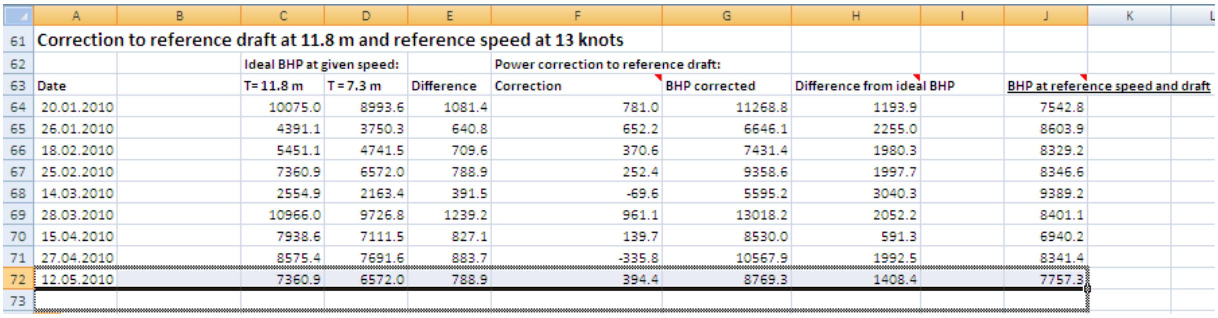


Figure 6-20: Excel spreadsheet: Result of the added resistance calculations at measured speed

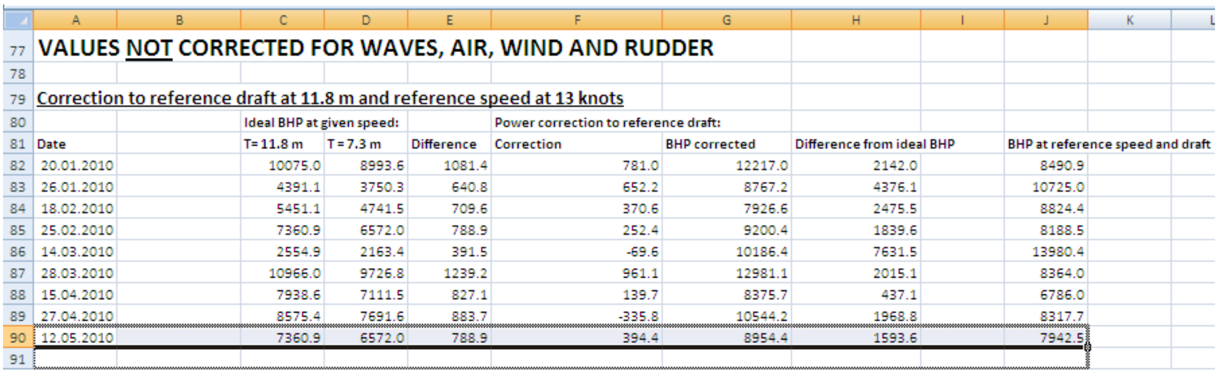
The results and trend over time is easier to see if the results are corrected to the same reference speed and draft and plotted over time. This correction is done in the next step. To carry out these corrections the columns “T=11.8m”, “T=7.3m” , “Difference”, “Correction”, “BHP Corrected”, “Difference from ideal BHP” and “BHP at reference speed and draft” are to be dragged down on line. The calculations will automatically fit the new input. This step is shown in the figure below.



	A	B	C	D	E	F	G	H	I	J	K
61	Correction to reference draft at 11.8 m and reference speed at 13 knots										
62			Ideal BHP at given speed:			Power correction to reference draft:					
63	Date		T= 11.8 m	T = 7.3 m	Difference	Correction	BHP corrected	Difference from ideal BHP		BHP at reference speed and draft	
64	20.01.2010		10075.0	8993.6	1081.4	781.0	11268.8	1193.9		7542.8	
65	26.01.2010		4391.1	3750.3	640.8	652.2	6646.1	2255.0		8603.9	
66	18.02.2010		5451.1	4741.5	709.6	370.6	7431.4	1980.3		8329.2	
67	25.02.2010		7360.9	6572.0	788.9	252.4	9358.6	1997.7		8346.6	
68	14.03.2010		2554.9	2163.4	391.5	-69.6	5595.2	3040.3		9389.2	
69	28.03.2010		10966.0	9726.8	1239.2	961.1	13018.2	2052.2		8401.1	
70	15.04.2010		7938.6	7111.5	827.1	139.7	8530.0	591.3		6940.2	
71	27.04.2010		8575.4	7691.6	883.7	-335.8	10567.9	1992.5		8341.4	
72	12.05.2010		7360.9	6572.0	788.9	394.4	8769.3	1408.4		7757.3	
73											

Figure 6-21: Excel spreadsheet: Correction to reference speed and draft

In order to see the impact of the added resistance calculations, the results are shown in the same graph as the measured result. Both corrected to the same reference speed and draft. To correct the measured data to the reference speed and draft drag the columns down one line as shown in the figure below.



VALUES NOT CORRECTED FOR WAVES, AIR, WIND AND RUDDER

Correction to reference draft at 11.8 m and reference speed at 13 knots

	Ideal BHP at given speed:			Power correction to reference draft:			
Date	T = 11.8 m	T = 7.3 m	Difference	Correction	BHP corrected	Difference from ideal BHP	BHP at reference speed and draft
20.01.2010	10075.0	8993.6	1081.4	781.0	12217.0	2142.0	8490.9
26.01.2010	4391.1	3750.3	640.8	652.2	8767.2	4376.1	10725.0
18.02.2010	5451.1	4741.5	709.6	370.6	7926.6	2475.5	8824.4
25.02.2010	7360.9	6572.0	788.9	252.4	9200.4	1839.6	8188.5
14.03.2010	2554.9	2163.4	391.5	-69.6	10186.4	7631.5	13980.4
28.03.2010	10966.0	9726.8	1239.2	961.1	12981.1	2015.1	8364.0
15.04.2010	7938.6	7111.5	827.1	139.7	8375.7	437.1	6786.0
27.04.2010	8575.4	7691.6	883.7	-335.8	10544.2	1968.8	8317.7
12.05.2010	7360.9	6572.0	788.9	394.4	8954.4	1593.6	7942.5

Figure 6-22: Excel spreadsheet: Correction of measured data to reference speed and draft

Now the results of the added resistance calculations can be shown along with the measured values. Both corrected to the reference speed and draft and plotted over time.

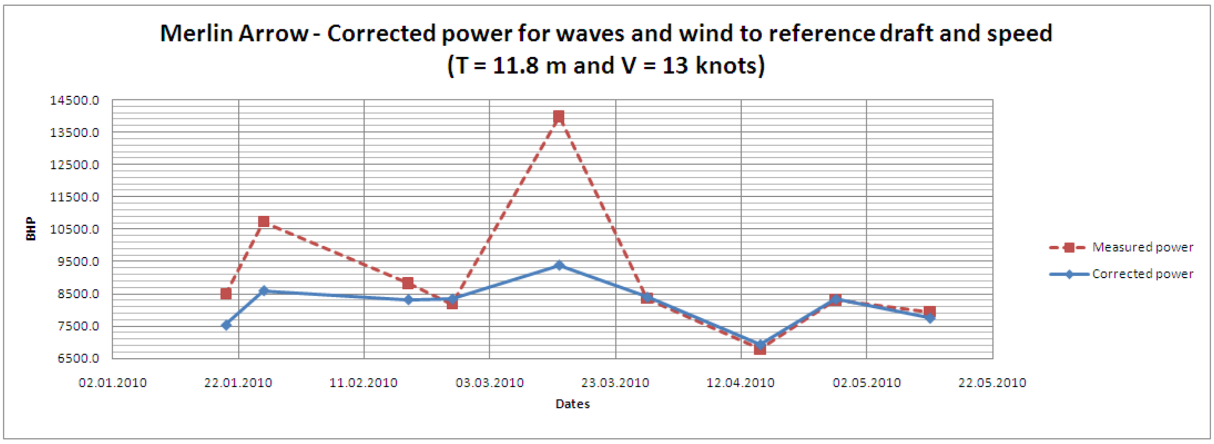


Figure 6-23: The measured and the corrected BHP over time

This plot makes it easier to see the importance of the added resistance calculations. The plot also makes the trend easier to discover since the values are given as a function of time.

7 Presentation of the results

In this chapter the results of the added resistance correction for each ship will be presented. This includes the results corrected to the reference speed and draft. There will be no evaluation of the results in this chapter, simply a display of the output from the Excel spreadsheet calculations. Evaluations and hypothesis of the results from the undersigned will be presented in chapter 8. In the graphs where the dates are not used, measure numbers are given to the measurements in chronological order. These measure numbers are indicated on the corrected values (blue points) in the power versus speed diagram for each ship.

7.1 Emu Arrow

From Figure 7-1 it can be seen that the difference in the measured and the calculated values of Power deviates. This means that the corrections have had an impact on the results.

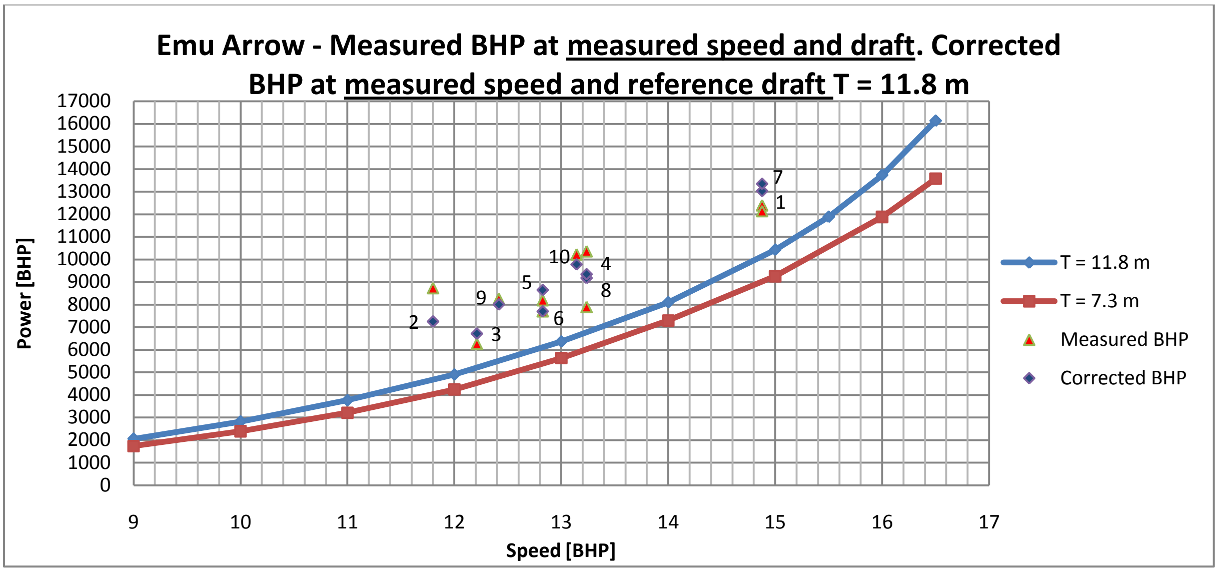


Figure 7-1: Emu Arrow: Measured and corrected BHP at measured speed

In Figure 7-2 it can be seen that this correction is insufficient to make a completely smooth line. The corrections have got ridden of the highest peak values; however the line for corrected values (blue line) is still quite rough. The values for middle of February and the end of March are very low.

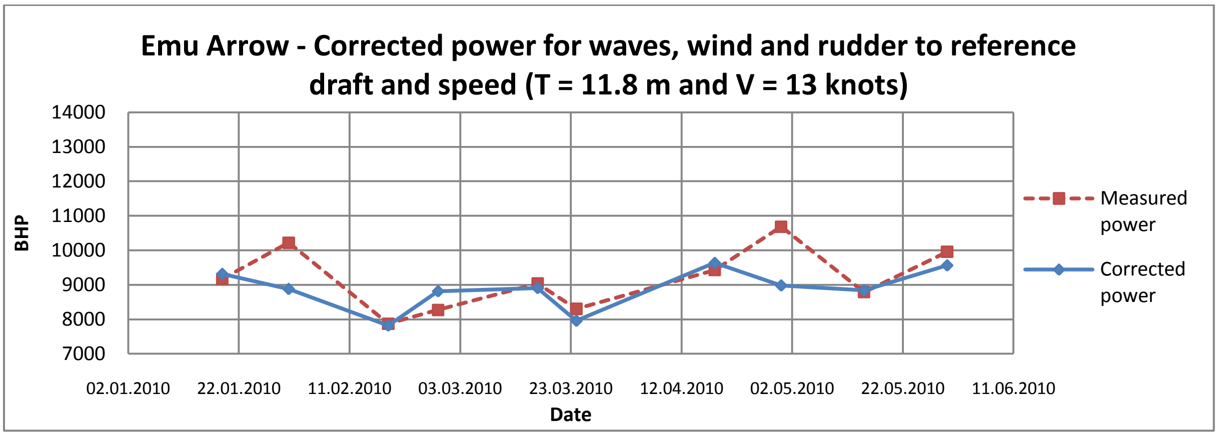


Figure 7-2: Emu Arrow: Measured and corrected power to reference speed and draft

The dates where the corrected values are above the measured values are where there has been little added resistance, following wind or the ship has been traveled with T above DWL.

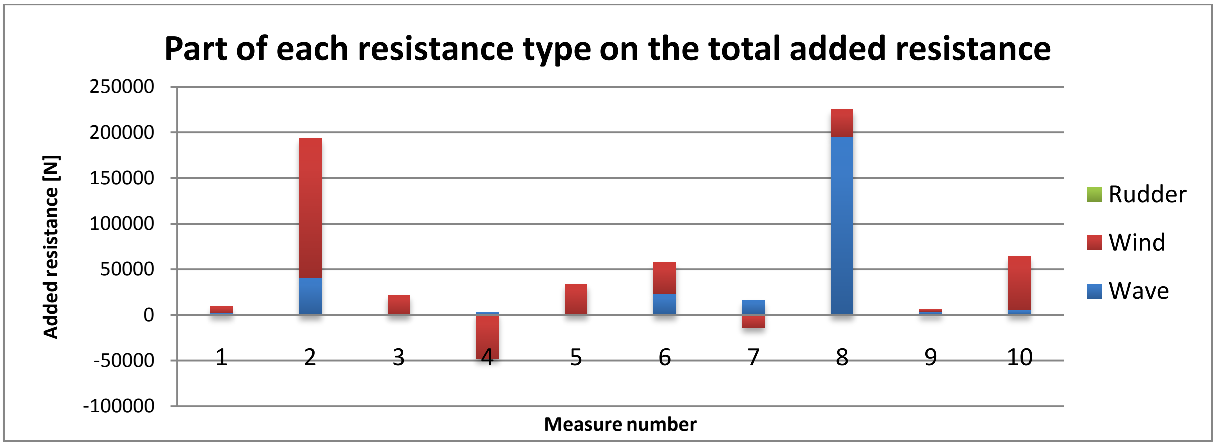


Figure 7-3: Emu Arrow: Part of each resistance type on the total added resistance

From Figure 7-3 we can see that the main part of the added resistance on Emu Arrow is the wind resistance, except for measure number eight where there has been high seas. Emu has not had a rudder angle on any of the measurements.

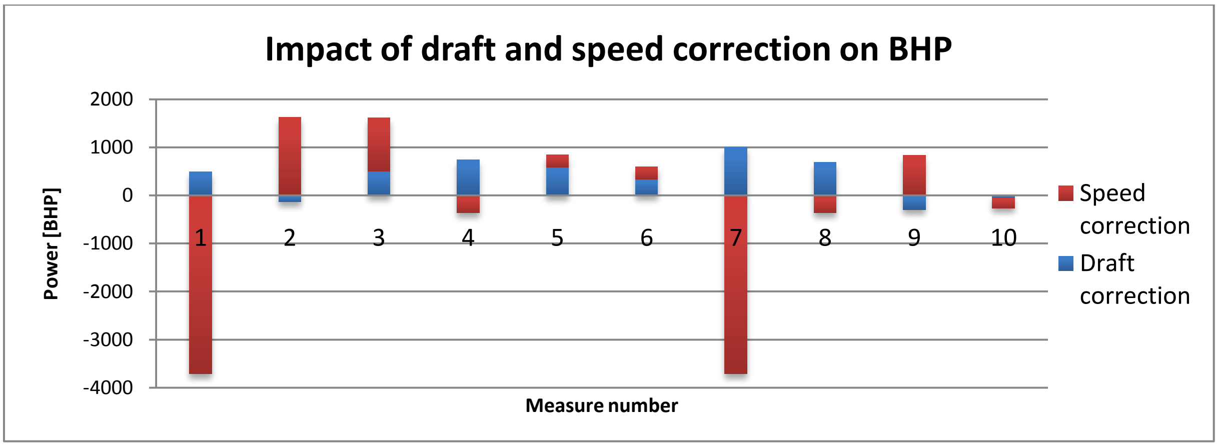


Figure 7-4: Emu Arrow: Impact of draft and speed correction on BHP

Draft and speed correction for Emu Arrow is shown in Figure 7-4. In the measurements where the ship has had a draft larger than T = 11.8 m the correction is negative, and where the ship has had a draft less than T = 11.8 m the correction is positive. Where the ship velocity is above 13 knots the speed correction are negative, and where the ship velocity is below 13 knots the correction is positive.

7.2 Merlin Arrow

Figure 7-5 shows that the corrections mainly have been small. Except from a couple of dates where the corrections are extremely large. These days the weather has been bad and the waves have been high. The variation of velocities is high, which means that the correction to reference speed is large.

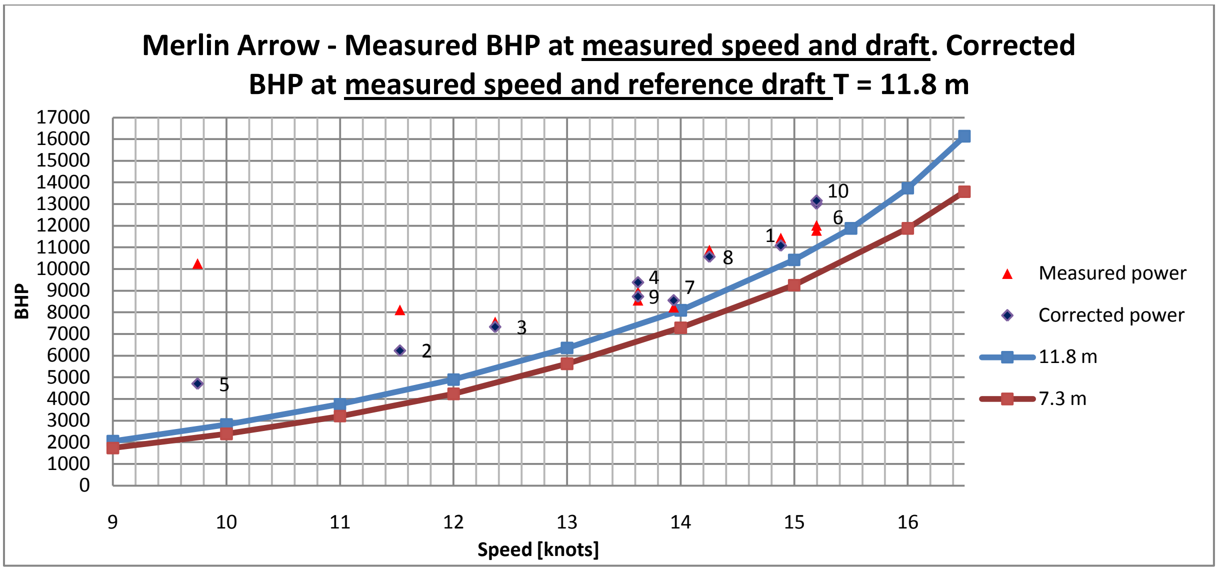


Figure 7-5: Merlin Arrow: Measured and corrected BHP at measured speed

In Figure 7-6 the corrections can be seen clearer relative to the general trend. It seems that where the weather has been bad the added resistance corrections seem to correct the measurements quite well, and a smooth line has occurred. Especially for the measurement of the middle of March, where the waves was up to five meters, the added resistance calculations have made sufficient corrections. The last five measurements have been in relative calm weather, but still the results vary. This cannot be explained by under- or overestimated added resistance calculations due to the calm weather.

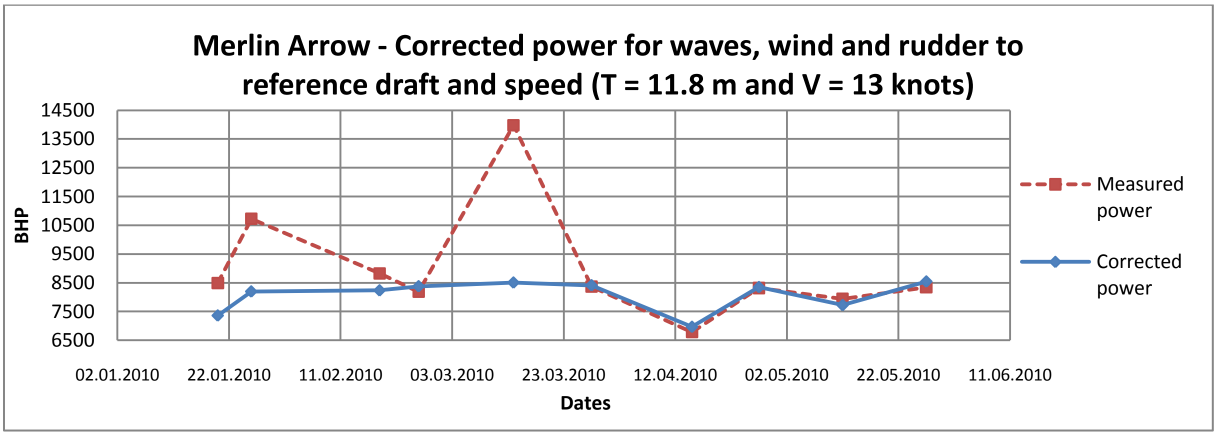


Figure 7-6: Merlin Arrow: Measured and corrected power to reference speed and draft

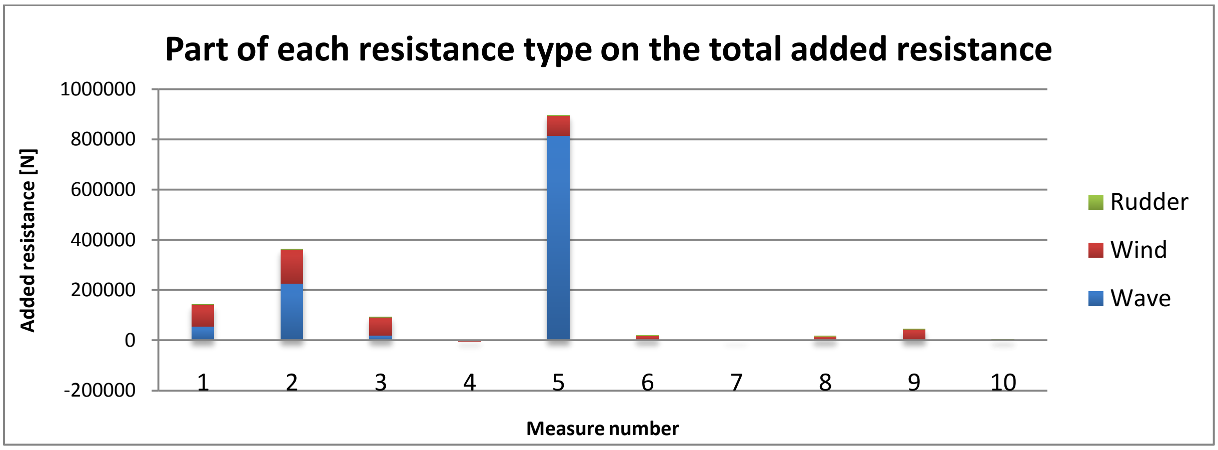


Figure 7-7: Merlin Arrow: Part of each resistance type on the total added resistance

Figure 7-7 shows that the added resistance due to waves is the most important one. On measure number six to nine wind is the most important one; however, the total added resistance on those measurements are very low.

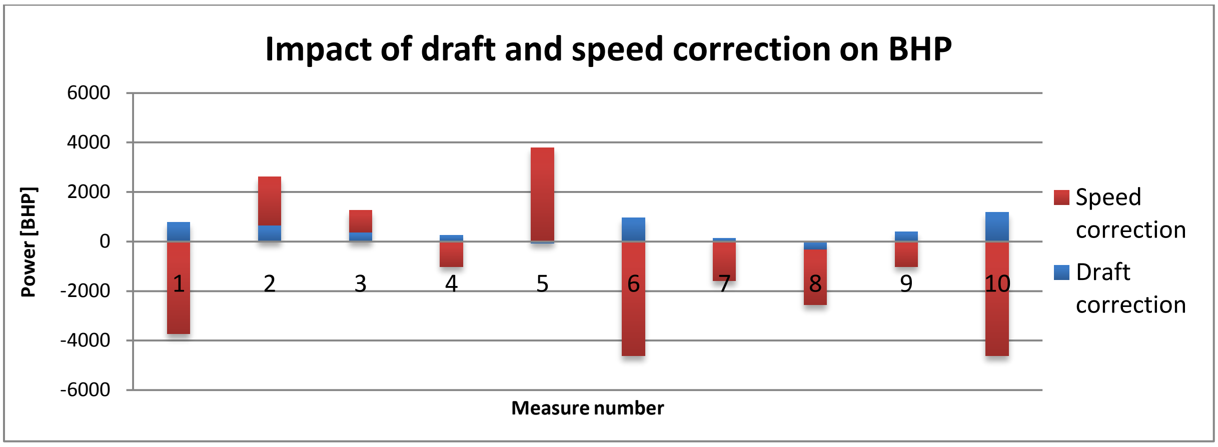


Figure 7-8: Merlin Arrow: Impact of draft and speed correction on BHP

7.3 Penguin Arrow

Penguin arrow has mainly had good weather in all measurement dates. This can be seen in the small corrections in Figure 7-9. All velocities have also been between 12 and 14 knots, and this makes the velocity corrections to 13 knots relatively small.

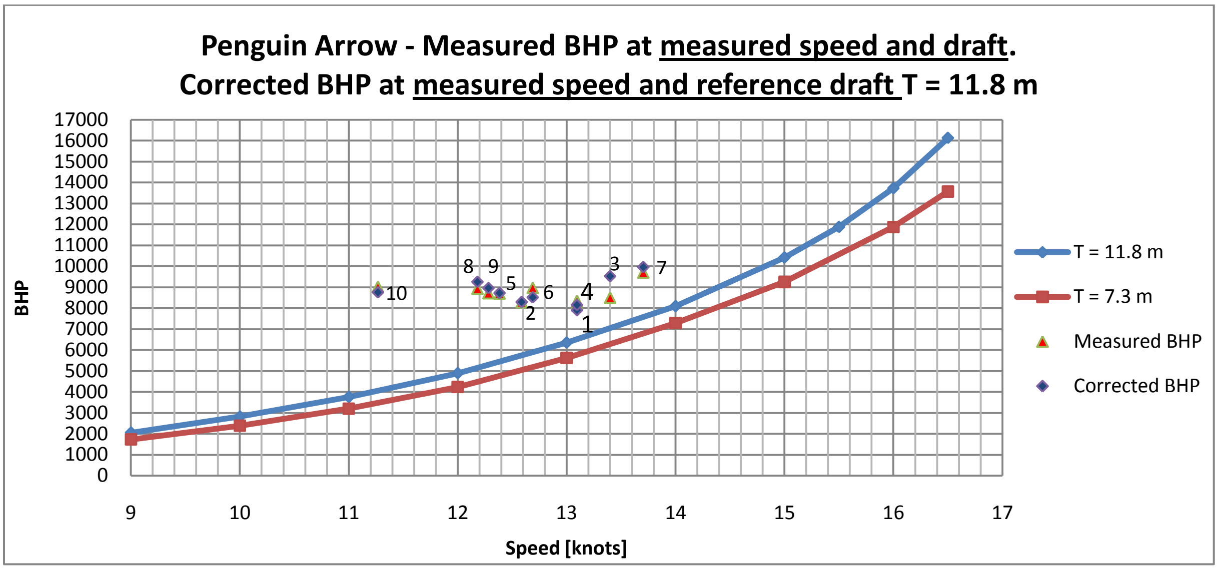


Figure 7-9: Penguin Arrow: Measured and corrected BHP at measured speed

Penguin has had an increasing trend during the period of measurement, and except a couple of measurements the curve is relatively smooth.

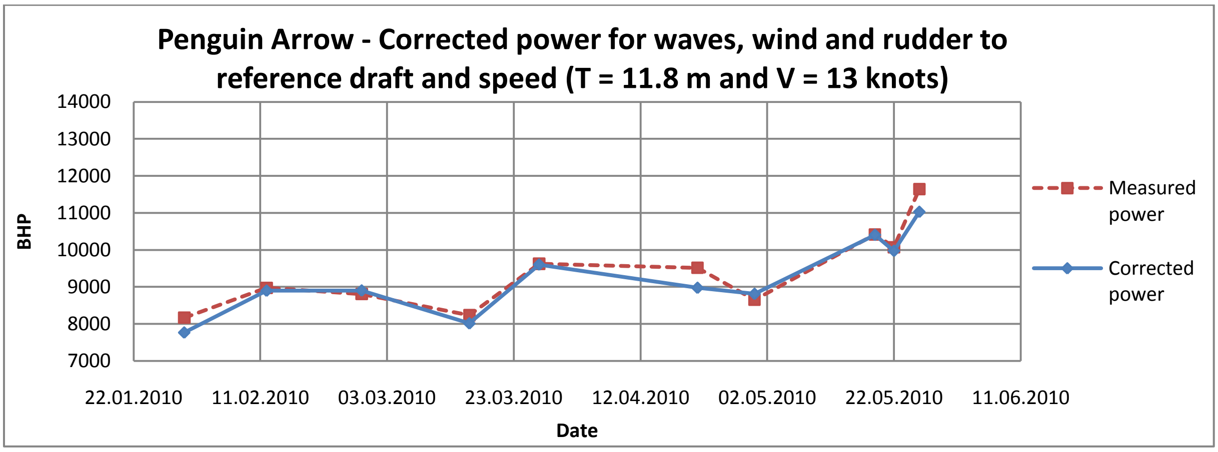


Figure 7-10: Penguin Arrow: Measured and corrected power to reference speed and draft

When the measurement from middle of May was as high as it was, the ship was asked to measure one more time in order to check if the numbers were consistent. The two last measurements are in the same range, which means that the increase in resistance probably is correct. The last measurement was done while the ship traveled with a trim difference of 1.5 m between AP and FP. This can have had an effect on the result; however, it is not further investigated.

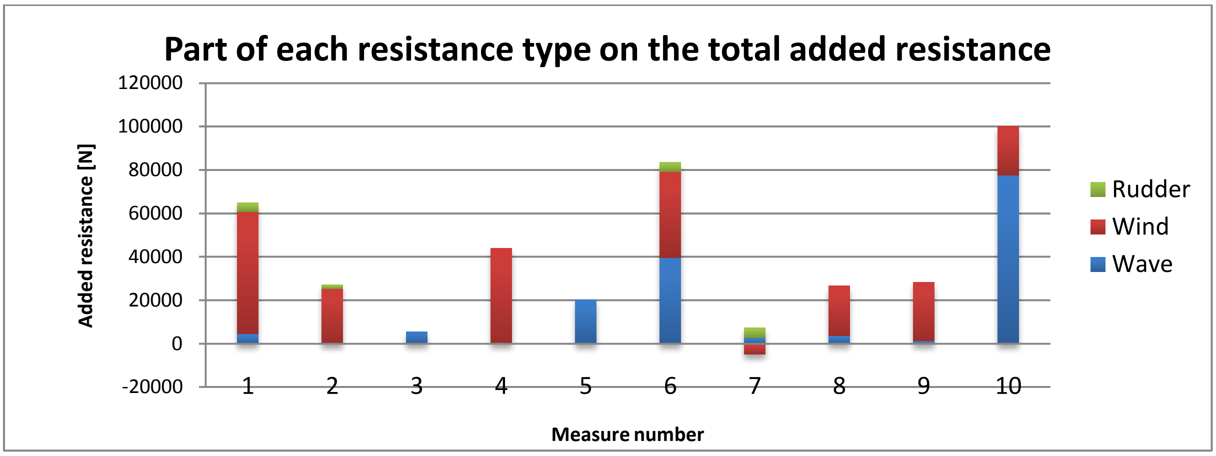


Figure 7-11: Penguin Arrow: Part of each resistance type on the total added resistance

Figure 7-11 shows that the wind resistance has a large impact on the total added resistance on Penguin Arrow in these measurements. The added resistance part from the rudder is generally very small.

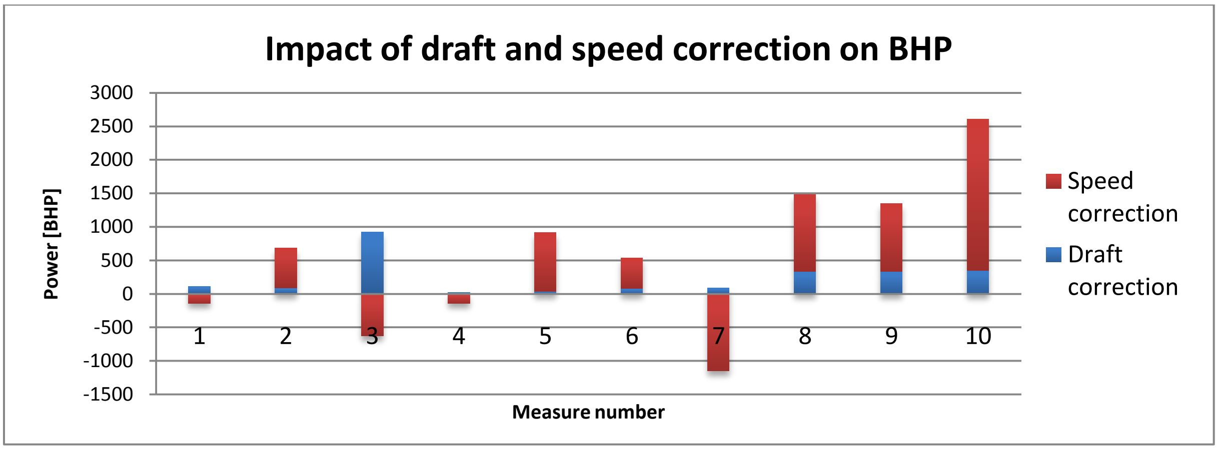


Figure 7-12: Penguin Arrow: Impact of draft and speed correction on BHP

7.4 Plover Arrow

Plover Arrow has mainly had small corrections on the added resistance due to relatively calm weather during the measurements.

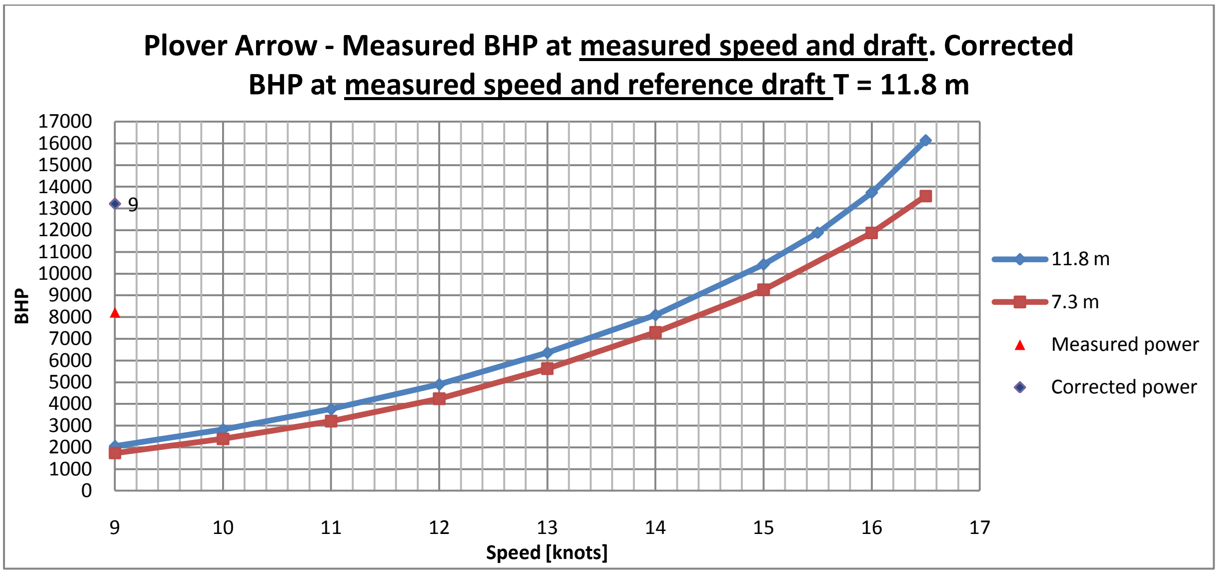


Figure 7-13: Plover Arrow: Measured and corrected BHP at measured speed

Plover has experienced a relatively stable increasing trend until the beginning of May. In the middle of May the ship had a hull scrubbing due to large amount of fouling on the hull. This explains the low value of the last measurement, which was after this hull scrubbing. The second last measurement was right before the hull scrubbing, so the low value can only be explained by incorrect form filling, or unstable conditions during the form filling.

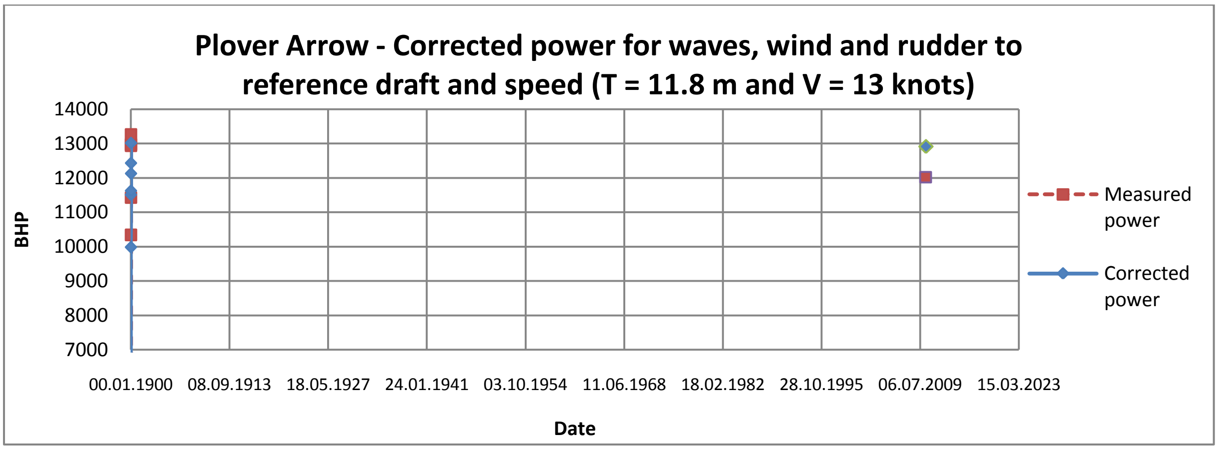


Figure 7-14: Plover Arrow: Measured and corrected power to reference speed and draft

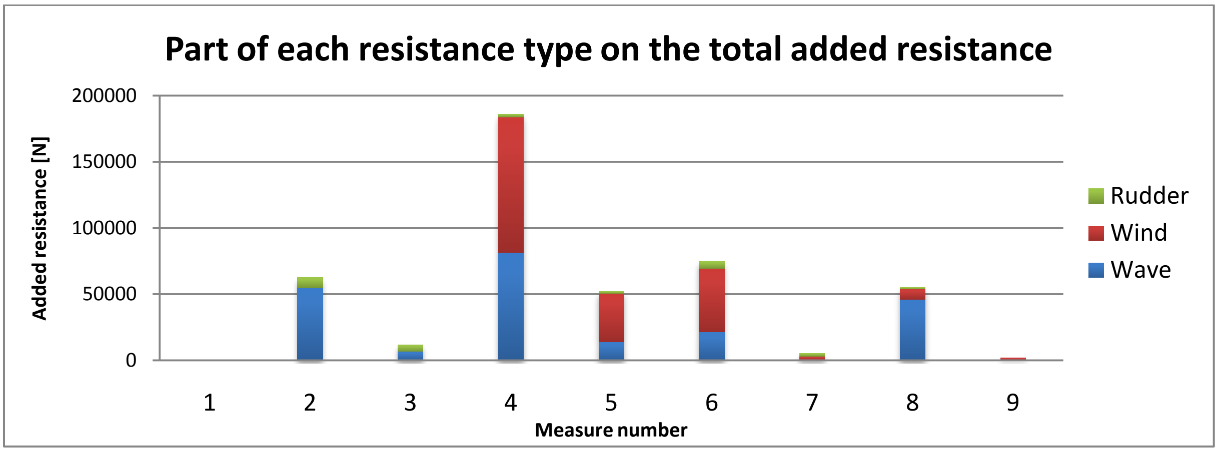


Figure 7-15: Plover Arrow: Part of each resistance type on the total added resistance

From Figure 7-15 it can be seen that the added resistance in waves and wind both are important for the total added resistance. Added resistance due to rudder angle is very small.

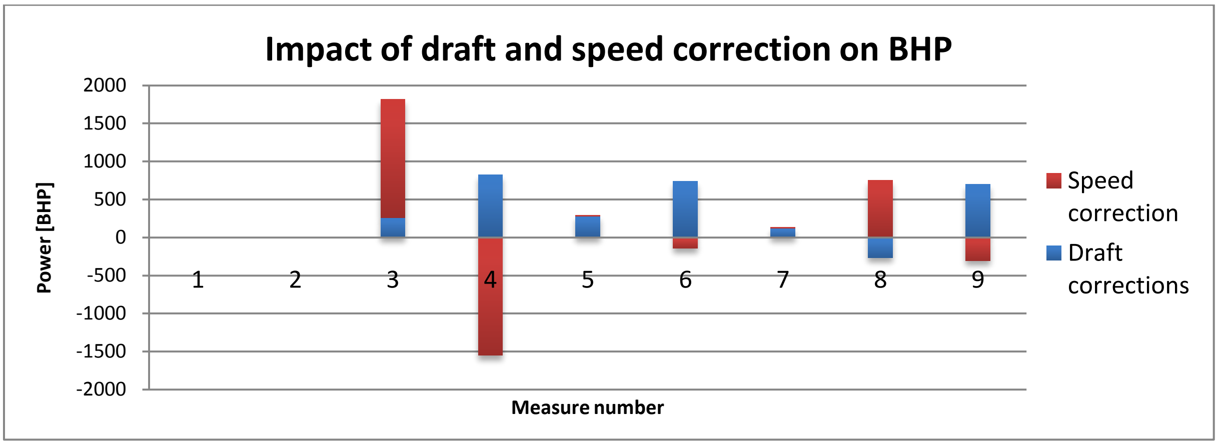


Figure 7-16: Plover Arrow: Impact of draft and speed correction on BHP

7.5 Weaver Arrow

The corrections of Weaver Arrow have been relatively stable in all measurements. This ship is the one with values of power closest to the ideal conditions from speed trial.

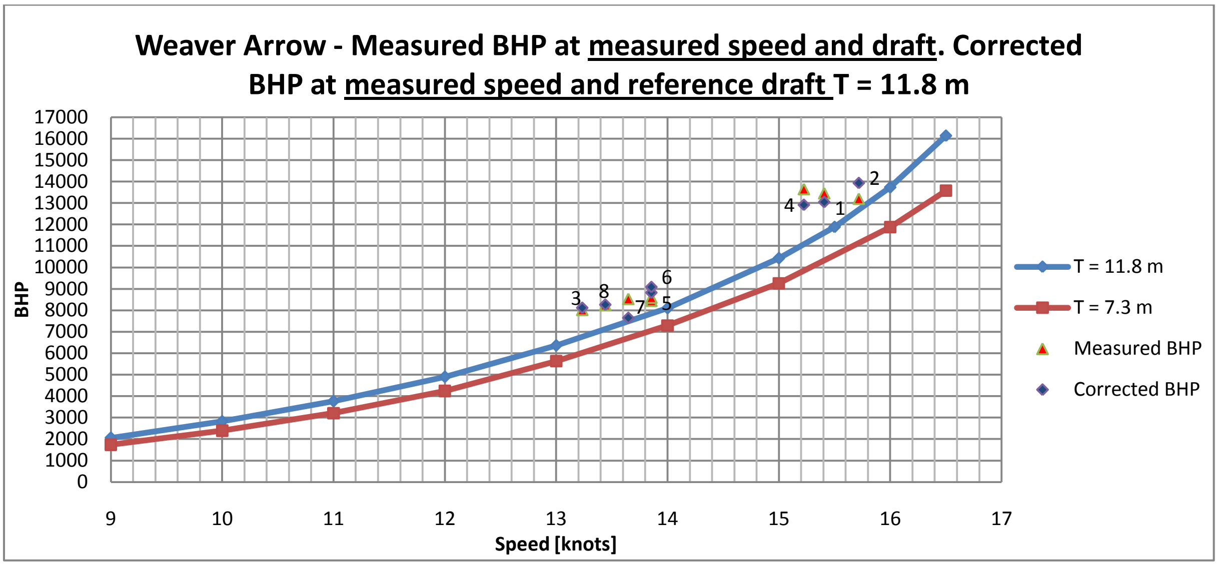


Figure 7-17: Weaver Arrow: Measured and corrected BHP at measured speed

Figure 7-18 shows that Weaver Arrow has had the smoothest and most stable progress of the ships in this correction. Except from two measurements, the end of March and the middle of May, the power usage is almost constant.

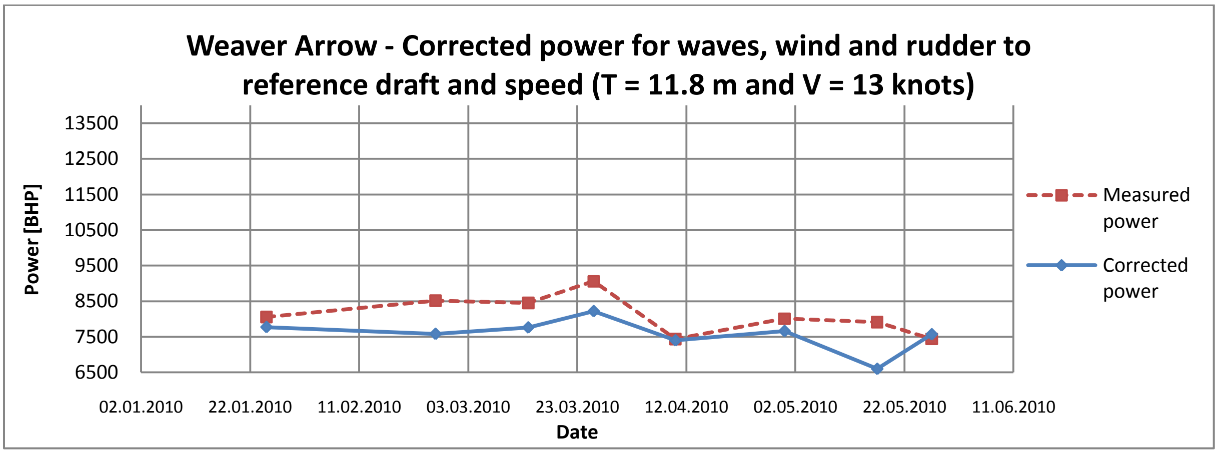


Figure 7-18: Weaver Arrow: Measured and corrected power to reference speed and draft

The smoothness of the corrected line can show that the crew on this ship has been dedicated to follow the guidelines when they have filled in the form.

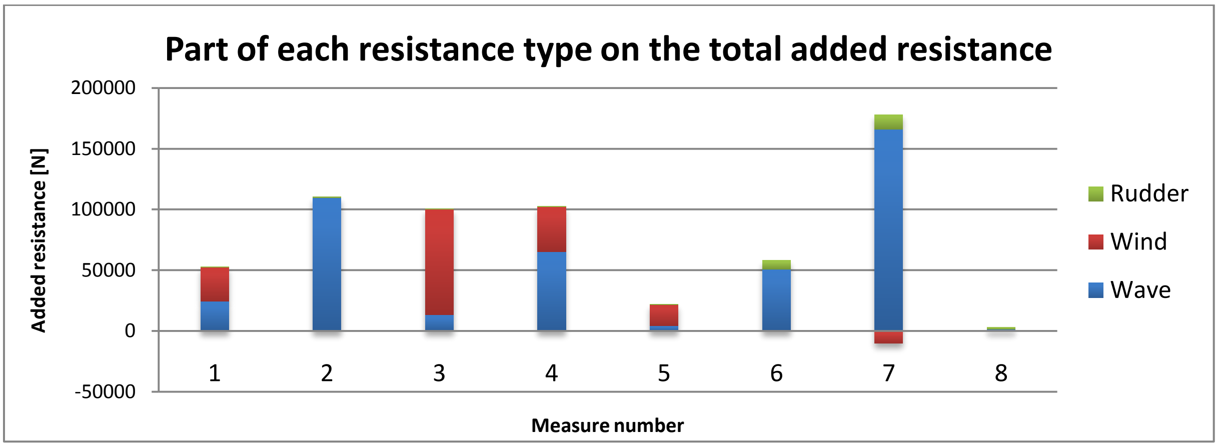


Figure 7-19: Weaver Arrow: Part of each resistance type on the total added resistance

Weaver Arrow has been experienced relatively much waves, and therefore it can be seen in Figure 7-19 that the added resistance in waves are the most important of the added resistance types. Except from measure number one and three where the wind has played an important role. The added resistance due to rudder angle is also here generally very low; however, on the three last measurements the rudder has been of relevance for the total added resistance.

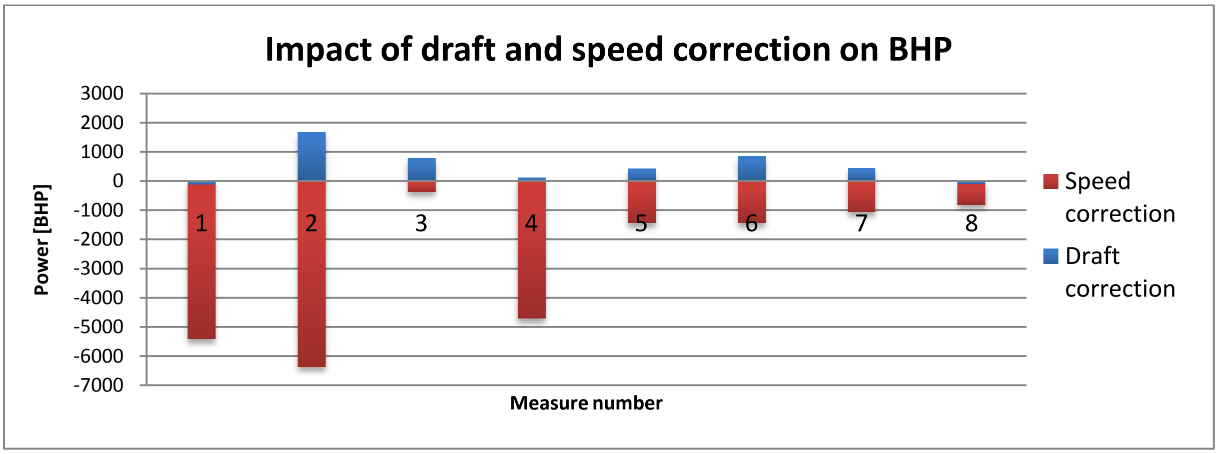


Figure 7-20: Weaver Arrow: Impact of draft and speed correction on BHP

As shown in Figure 7-20 all the speed corrections are negative for Weaver Arrow, and this corresponds to Figure 7-17 where all measured velocities are above 13 knots. At the same time all draft corrections are positive which is because the ship has never been loaded above design waterline in the measurements in this thesis.

8 Evaluation of the results

In this chapter the results found from the calculations will be evaluated. All assumptions, where nothing else is stated, are personal considerations from the undersigned. Statistical calculations are based on input that are considered appropriate and well-founded and the evaluation is performed as objective as possible.

8.1 Linear trends in the measured time period

Below the results for each ship at all measured dates are given in the same figure. The linear trend is also shown for each ship.

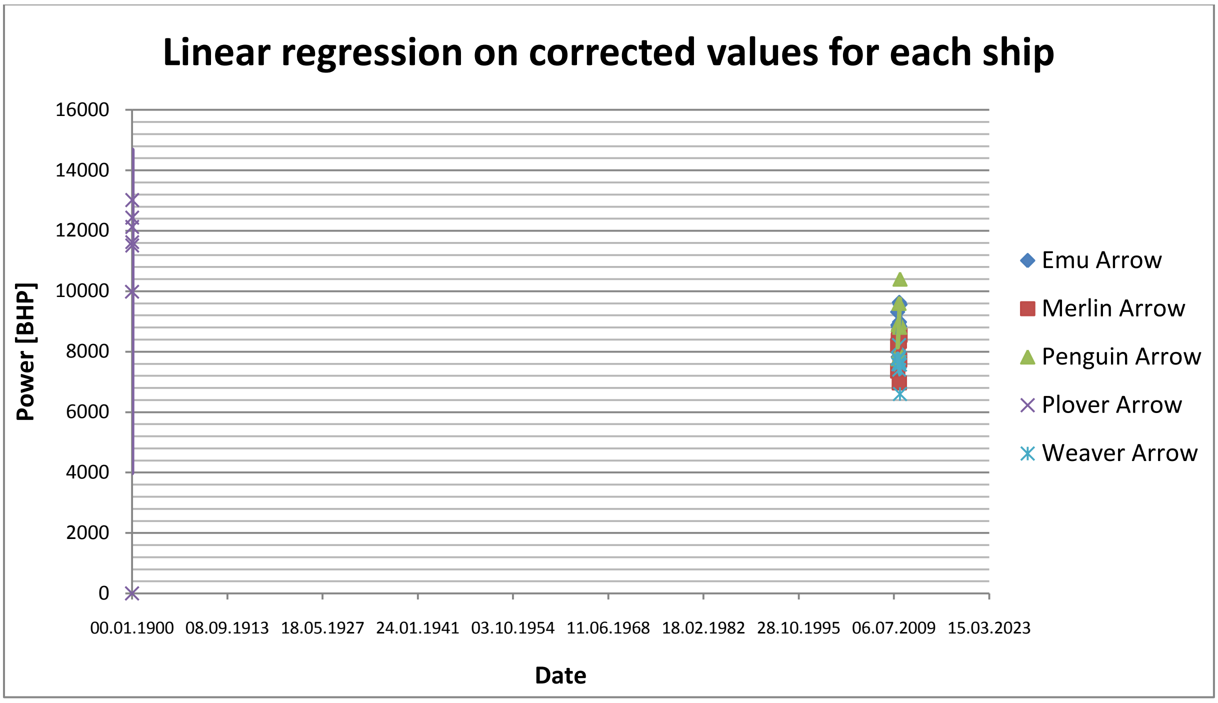


Figure 8-1: Linear regression on corrected values for each ship

The immediate impression of the figure is that one of the ships, Plover Arrow, has much higher values of power than the others. The other ships are in the same power range. From this we can assume that Plover Arrow has the largest extent of fouling and therefore probably has gone the longest time without hull treatment.

It seems that the trend lines vary with each ship, some is positive and some is negative. Ideally each trend would be positive, since none of the ships has received hull treatment in the actual period of measurements. However, since each ship only has 8-10 measurements, the selection is too small to have sufficient statistical weight. One single new measurement can easily change the slope of the trend radically. The length of the period the measurements have taken place is also too small, therefore the uncertainty increases additionally.

To deal with the problem of few measurements for each ship, it can be an option to merge all results together. Then, instead of 8-10 measurements in the selection, we get 44. The problem now is that the growth rate of the fouling is unknown. Once some fouling has set on the hull it is assumed that the growth rate increases since the flow past the hull will decrease as a result of higher friction. This assumption has been confirmed by Reinertsen. Therefore it would be wrong to use the results from Plover Arrow, since this ship clearly lies in a higher level of resistance. Without the measurements from Plover Arrow the selection is reduced to 36. Although 36 also is a relatively small selection, the result from this calculation will be much more statistically justified. However, it cannot be trusted to be more correct. After all, the measurements are from different ships.

Before calculation of the merged trend line can be accomplished correctly, another complication must be dealt with. The four ships does not have an equally amount of measurements. Therefore, the solution can be a weighted average calculation. The heaviness of each line will depend on how many measurements it is based on. The slope of the trend and the amount of measurements for each ship is as follows:

Ship	Slope number [BHP/day]	Amount of measurements
Emu Arrow	4.3097	10
Merlin Arrow	1.0943	10
Penguin Arrow	14.649	8
Weaver Arrow	-5.3907	8

Table 8-1: Slope number for BHP increase per day for each ship

Since the three last measurements on Penguin Arrow was with only a couple of days apart, only one of them is used in order to get the result as correct as possible.

The formula for the merged slope is then given by:

$$Merged\ slope = \frac{SN_{Emu} \cdot A_{Emu} + SN_{Merlin} \cdot A_{Merlin} + SN_{Penguin} \cdot A_{Penguin} + SN_{Weaver} \cdot A_{Weaver}}{Total\ amount\ of\ measurements}$$

Where

SN = Slope number in BHP/day
A = Amount of measurements

The merged slope number becomes **3.559 [BHP/Day]**. This means that from 36 measurements, it can be estimated that the average increase in power need due to fouling on the hull is 3.559 BHP per day.

This result means that over a period of two years the increased power need is approximately 2600 BHP. Note: this is only the result from this estimation, and not the final predicted value of the linear trend.

8.2 Trend as a function of days since docking

Since the growth rate, as indicated above, in reality is not linear, it can be a good idea to use another approach. Figure 8-1 shows the power usage of the ships at the given date of measurement. Instead of the actual date of measurement, the total amount of days since last docking can be shown for each measurement. The date of the last dry dock on each ship is given in the table below:

Ship	Last dry dock
Emu Arrow	August 2007
Merlin Arrow	June 2008

Penguin Arrow	November 2005
Plover Arrow	August 2005
Weaver Arrow	March 2007

Table 8-2: Dry dock history for each ship

Now the power usage over days since last docking can be shown. Since the actual day is not specified in the docking history the day count starts at the 1st of the actual month of docking on each ship.

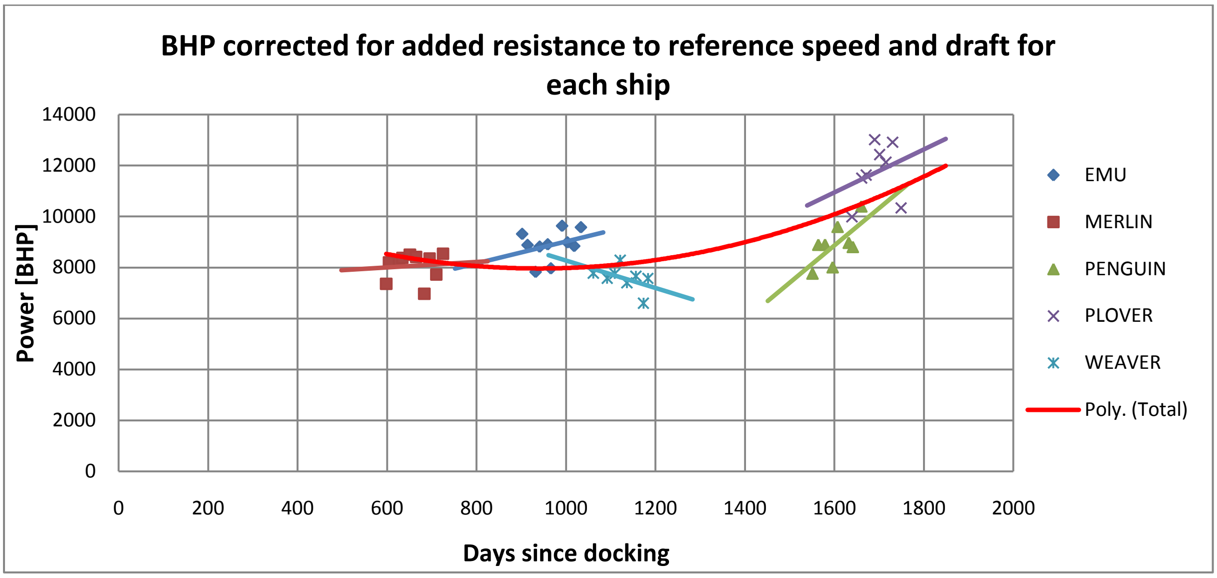


Figure 8-2: Corrected BHP, each measured point in days since last dry dock

From this figure the linear trend for each ship is shown more clearly. The slope of each trend varies a lot between the ships. It is also easier to see that the assumption of too few measurements probably is correct. The entire time base is almost five years, while the measured values are collected only within the last four months. This is why it wouldn't be statistical correct to trust the trend lines separately, even though they are a pointer of the realistic trend.

From Figure 8-2 it can be seen that the trend might start to get exponential after approximately 1000 days. Penguin and Plover is the ships that have sailed the longest without dry docking. The slopes of the trend lines for these ships seem conspicuously steep. At the same time, these are the ships with the highest value of BHP.

The red line is the second degree polynomial fit line to all measurements. However, this line would not fit at an early stage (less than approximately 1000 days since docking) under the assumption that the resistance trend line is linear until it gets exponential. If this line is considered trustworthy, the exponential increase in resistance due to fouling starts at around 1000 days.

The formula for the trend line is:

$$y = 0.0049x^2 - 9.1712x + 12273$$

$$\frac{dy}{dx} = 0.0098x - 9.1712$$

The derivative of y gives the slope number at a given day. After 1500 days the increase of resistance is **5.529 BHP/day** and after 1800 days the increase of resistance is **8.469 BHP/day**. From the assumptions in this thesis the fouling on the hull makes the ship require 8.469 BHP extra each day to maintain the same speed if 1800 days has passed since the last docking.

Penguin Arrow seems to be in a different phase in the fouling process than Emu, Merlin and Weaver. As seen in Figure 8-2, Penguin Arrow has reached the exponential phase. Therefore, it is considered to be more correct to exclude Penguin from the merged slope of fouling calculated in chapter 8.1. If this is done the new merged slope, slope of the linear phase, becomes:

$$Merged\ slope = \frac{SN_{Emu} \cdot A_{Emu} + SN_{Merlin} \cdot A_{Merlin} + SN_{Weaver} \cdot A_{Weaver}}{Total\ amount\ of\ measurements} \approx \mathbf{0.390}[\frac{\boldsymbol{BHP}}{\boldsymbol{day}}]$$

This means a daily increase of needed power of 0.390 BHP. Annually, this will correspond to around 140 BHP. After three years, roughly when the exponential phase seems to begin, the increase of power need has become around **430 BHP**. This is more in the range of power increase over time due to fouling presented in ITTC document 7.5-02-03-01.5.

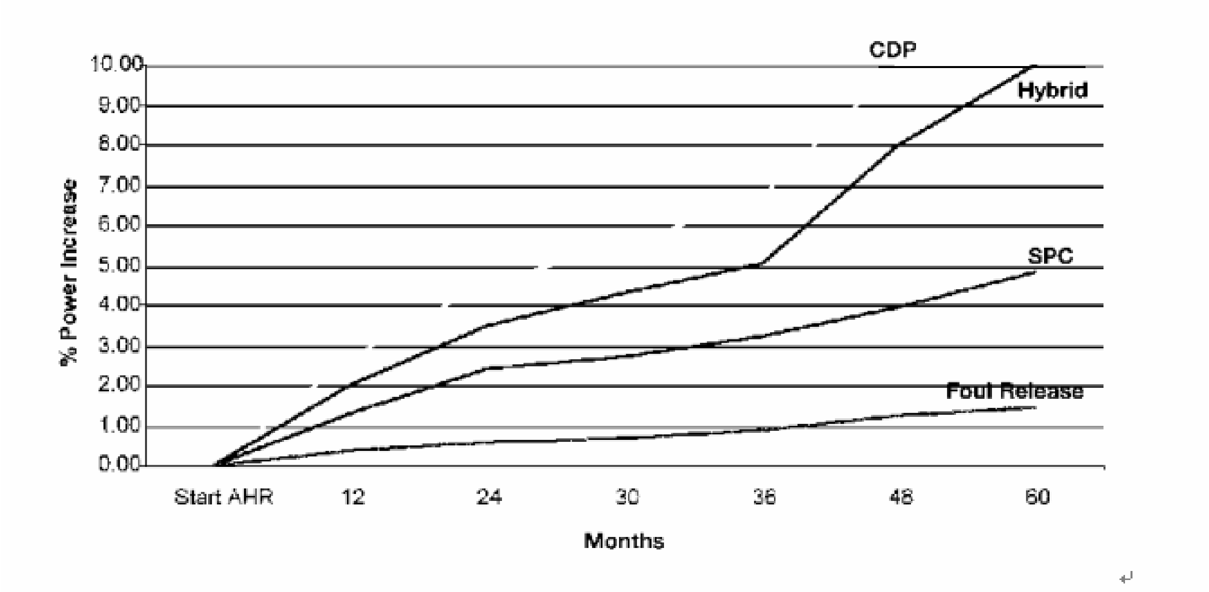


Figure 8-3: Power increase due to fouling over time for three different types of antifouling coating (ITTC, 7.5-02-03-01.5)

Figure 8-3 shows the increase in power need to maintain the same speed over time for four different antifouling coatings. The coating used on the ships in this thesis is none of the exact ones in the figure above. The coating used on these ships is tin free self polishing antifouling coating from KCC. However, the order of magnitude of the power increase is approximately the same. This figure shows a power increase of approximately 2.8 % over a period of three years on the SBC coating and 4.5 % on the hybrid.

The percentage of power increase after three years for the estimated linear trend found in this thesis is:

$$\frac{430BHP \cdot 100}{9000BHP} = 4.7\ \%$$

9000 BHP is an estimated mean value of needed power for reference speed for a newly painted hull. Therefore this percentage estimation is highly uncertain.

Figure 8-3 does not seem to fit the trend for the antifouling coating used on the ships in this thesis. According to KGJS, the ships have a self polishing TBT-SBC coating, which means that the trend the first two-three months is a decrease in power use before it gets linear with a . Figure 8-3 shows a steep increase in power use from day one. Therefore, this figure is not used to other comparisons than to validate the slope of the linear trend found in this chapter.

8.3 Added resistance in waves: Direct Pressure Integration vs. ITTC's Basic formula

The direct pressure integration method is the method used to calculate the added resistance in waves in this thesis. However, this method is difficult to carry through if a suitable calculation program like ShipX is not available. For a ship owning company it would be cheaper and much easier to use a simpler method if the results are close to accurate.

The basic formula for added resistance in waves presented in ITTC report 7.5-04-01-01.2 and is given by Kreitner, presented in chapter 4.1, is also used to calculate the added resistance in all measurements in this thesis. This is to compare the results with the direct pressure integration method and consider the accuracy of the basic formula.

In the comparison the direct pressure integration method is considered the correct method, and the accuracy of the basic formula by Kreitner is considered relative to the values from the direct pressure integration method.

Values from added resistance calculations from both direct pressure integration method and the basic formula given by Kreitner for each ship are presented in the following figures. Instead of dates, each measurement is given a number in chronological order. This number is found in the power versus speed diagram in the results for each ship.

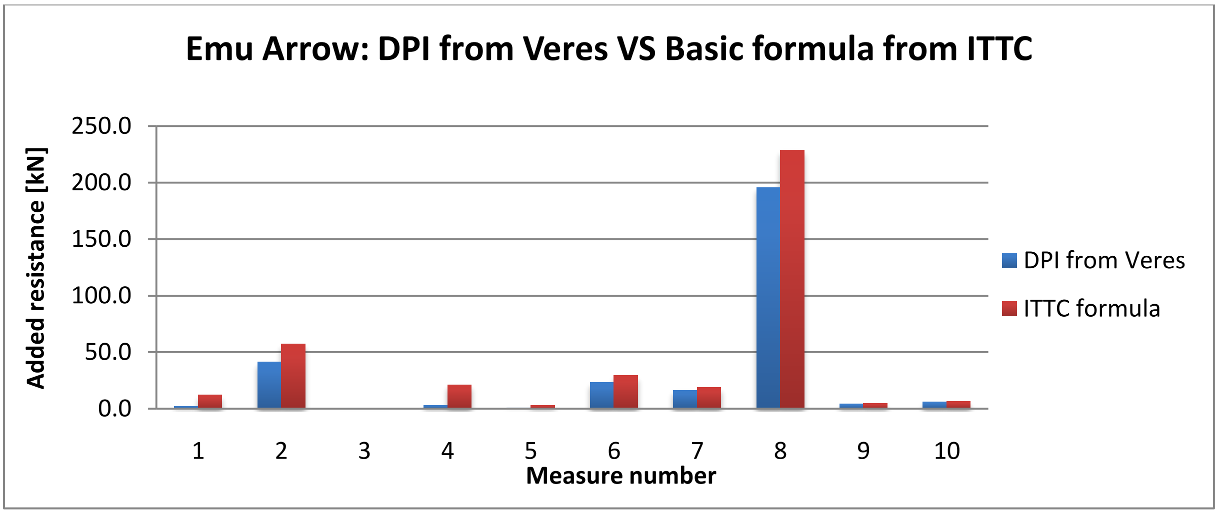


Figure 8-4: Emu Arrow: DPI from Veres vs. Basic formula from ITTC

In Figure 8-4 the ITTC formula for added resistance in waves correlates relatively well with the direct pressure integration method. The difference is that the ITTC formula over predicts the added resistance compared to DPI. However, this is not necessarily wrong, since the DPI sometimes seems to underestimate the added resistance. The values from measure number one and four is more than three times larger for the ITTC formula as for the calculation with DPI. In both of these measurements there are waves with an angle of 135 degrees.

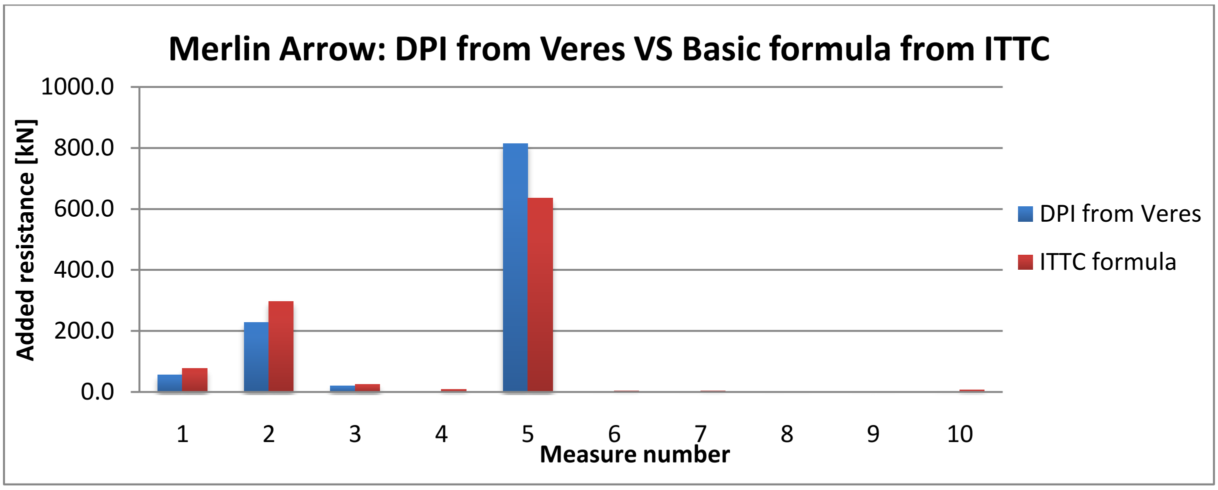


Figure 8-5: Merlin Arrow: DPI from Veres vs. Basic formula from ITTC

Merlin Arrow has not experienced very much added resistance in waves in the last four measurements. Also here the ITTC formula seems to overestimate compared to DPI except from measure number five where DPI has the highest value. This measurement reported very high seas with waves with Hs = 5 meters from an angle of 45 degrees.

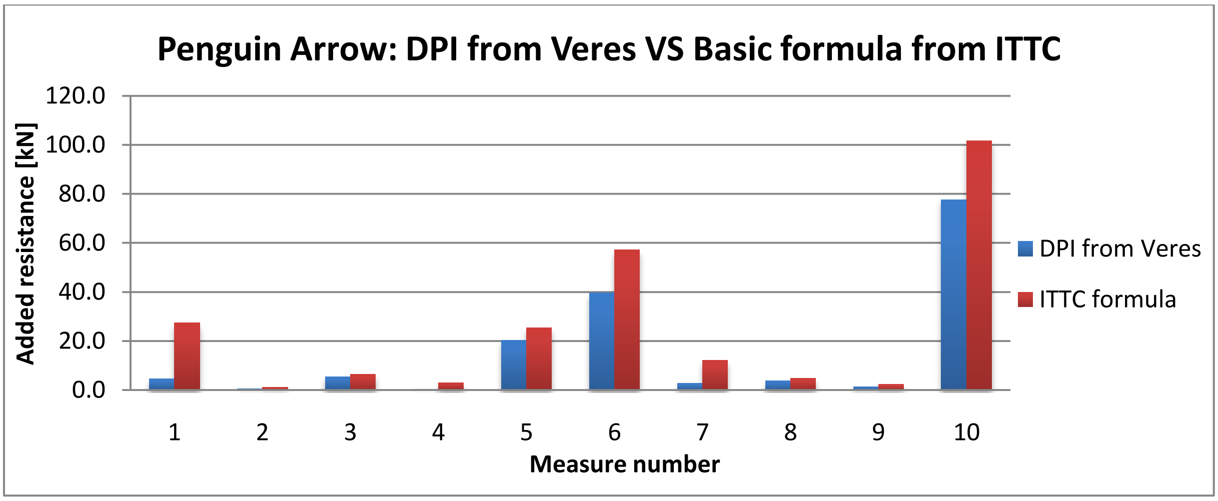


Figure 8-6: Penguin Arrow: DPI from Veres vs. Basic formula from ITTC

Figure 8-6 shows also that the ITTC formula over predicts the calculations from DPI. Especially in measure number one, four and seven the ITTC formula has a much higher value relative to DPI. All of these measure numbers reports waves from a 135 degree angle. The results from this and the results from Emu Arrow can show that the ITTC formula especially over predicts the added resistance in waves in following seas.

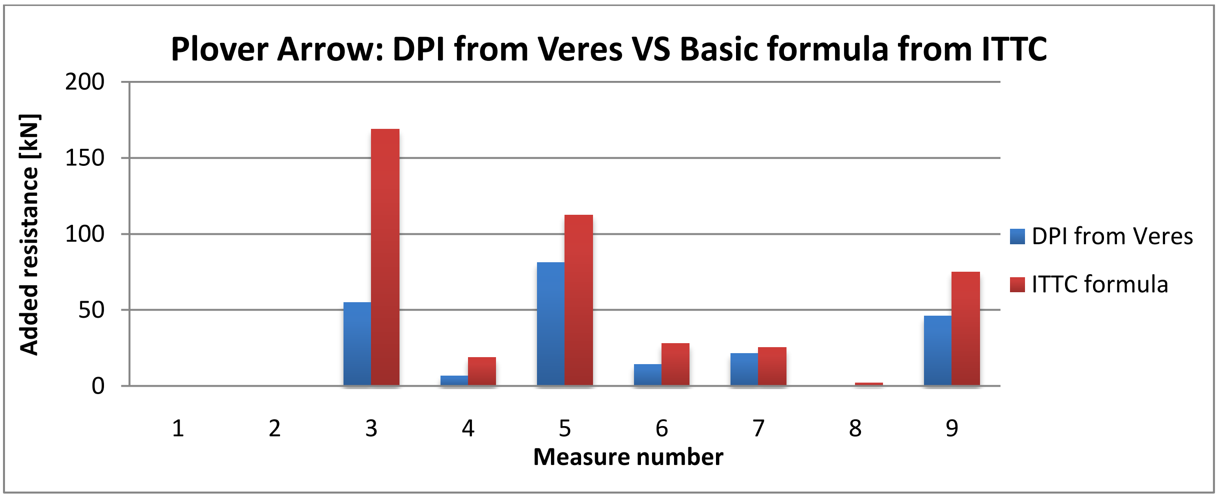


Figure 8-7: Plover Arrow: DPI from Veres vs. Basic formula from ITTC

From Figure 8-7 it is also clear that the ITTC formula generally has a higher value than the calculations with DPI. The results from measure one and two show that ITTC has a much higher value compared to the results from DPI, approximately three times as large. Both of these measurements reports waves from a 90 degree angle, directly from the side.

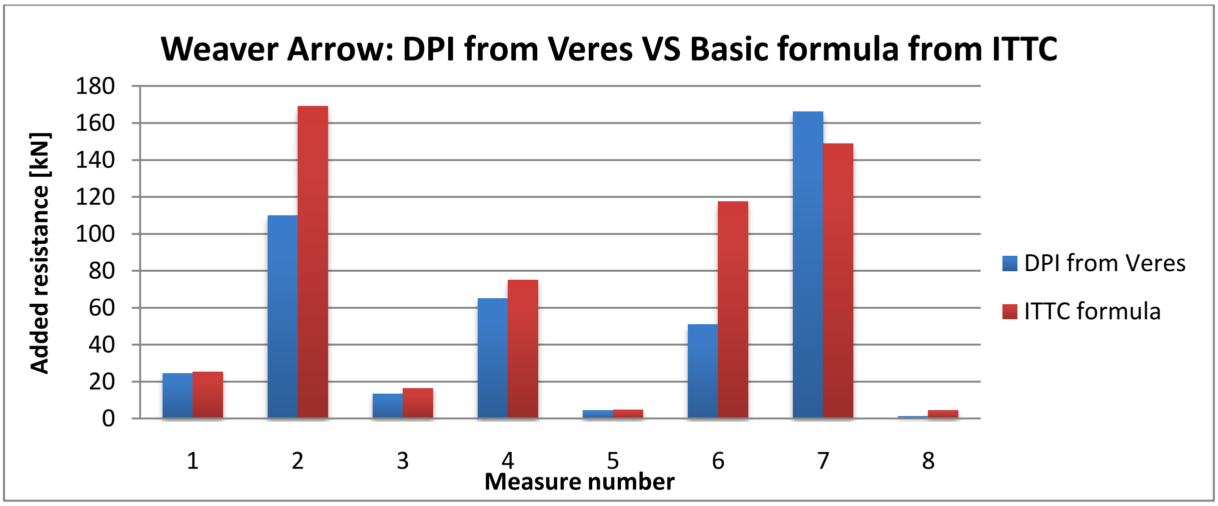


Figure 8-8: Weaver Arrow: DPI from Veres vs. Basic formula from ITTC

Figure 8-8 also shows that the ITTC formula generally overestimates the calculations from DPI. The exception is measure number seven. In this case the reports showed following seas from 135 degrees. Usually the ITTC formula has overestimated following seas; however the significant wave height Hs here was very high, Hs = 3.5 meters.

The direct pressure integration method is assumed the correct method in the comparison of these two methods for calculating added resistance in waves. It seems from these results that the ITTC formula by Kreitner generally overestimates the wave resistance. The ITTC formula especially overestimates the added resistance in following waves. The only condition where the direct pressure integration method gives the highest value is for high seas. However, the formula by Kreitner is meant to be used for waves smaller than 2 meters.

9 Error sources

Many of the calculations that are carried out in this thesis are based on assumptions in some extent. These calculations are based on inputs that also often are bound with some uncertainties. The levels of these uncertainties diverse and the impact of the final results vary. Therefore, it is essential to be aware of these uncertainties in order to be able to draw a conclusion that is as correct as possible.

9.1 Error in calculations

Errors in the calculations will be biased errors. Once they are made, they will follow the calculations regardless of the persons involved. For instance it can be an error inside one of the formulas in the Excel spreadsheet, or it can be an incorrect choice of calculation method.

9.1.1 Lack of calculations

Due to limitations in time, work amount and input data, not all added resistance types is corrected for in this thesis. The added resistance types which are corrected for in this thesis are the ones that are assumed to have the most impact on the total resistance and at the same time are feasible to calculate relatively accurate with the available input data. This means that some factors that contribute to additional added resistance are neglected. The most important ones of these are described in this part of this chapter.

9.1.1.1 Shallow water

The first draft of the ship form (Figure 6-1) did not contain the water depth. Therefore, the first three measurements may have been done in shallow water without the ship crew reporting it. However, the corrections made where the crew has reported shallow water the speed corrections never exceeded 0.02 knots. Therefore it is assumed that an eventual shallow water report would not have affected the final result.

9.1.1.2 Water temperature and salt content

Water temperature and salt content can change the viscous resistance of the ship. However, this has not been taken into consideration in this thesis. Therefore, the ship crew has not been asked to report water temperature and salt content in the water. The ship has a water temperature measurement on board, but they have no devices to measure the salinity in the sea.

If both of water temperature and salinity in the sea at measurement point is given, the change in correction can be calculated by a formula found in the (ISO 15016, 2002):

$$R_{AS} = R_{T0}\left(1 - \frac{\rho}{\rho_0}\right) - R_F\left(1 - \frac{C_{F0}}{C_F}\right) \qquad (9.1)$$

Where

R_{T0} = Total resistance at contractually specified water temperature and salt content.
R_F = Frictional resistance at actual water temperature and salt content.
C_F = Frictional resistance coefficient for actual water temperature and salt content.
C_{F0} = Frictional resistance coefficient for the contractually specified water and salt content.
ρ = Water density for actual water temperature and salt content.
ρ_0 = Water density for the contractually specified water and salt content.

9.2 Errors due to human factors

The corrections in this thesis are in some cases based on human assumptions like for instance the wave height and the wave direction. Errors due to human factors will vary with the persons involved. For instance, the wave height is mainly found from visual estimation from the bridge. Whether the sea state is developed or not or if the weather has been stable long enough to fill in correct values to the form is up to the crew to decide.

9.2.1 Unstable conditions during form filling

A large ship has much inertia; sudden changes in forces will not affect the ship motions. Therefore the accuracy of the numbers collected in the ship form strongly depends on stable conditions. For instance, if the wind suddenly changes from head wind to wind directly from the side during the form filling, the calculations will show no wind resistance although the ship speed has been affected by head wind.

The crew on the ships has been informed of the importance of this, but experience on one of the ships says that the probability is high for occasional carelessness. This may be one of the reasons for the large variation in results with only two weeks interval. An example of this variation can be seen in the results for Penguin Arrow.

10 Conclusion

In this thesis five bulk ships from Kristian Gerhard Jebsen Skipsrederi AS has been observed in order to develop a method for monitoring the hull condition with respect to the fouling. The basic scope of this thesis was to correct each ship for added resistance over time in order to find the increasing rate of fouling on the hull. Each ship has filled in a form (Figure 6-1), which contains weather information, engine information, and loading condition, twice a month. From the information collected by the ship form each measurement has been corrected for added resistance to a state which corresponds to the ship in calm weather. This has been done over a period of 4-5 months parallel with the work of this thesis.

The added resistances on the ship which are considered in this thesis are:

- Added resistance in waves
- Added resistance in wind
- Added resistance due to steering
    - Added resistance due to rudder angle
    - Added resistance due to yaw angle on the ship
- Changing resistance with different drafts
- Increased resistance due to shallow water

Added resistance in waves is found by the direct pressure integration method used in the program Veres in the ShipX workbench. This calculation has been the most comprehensive one because the calculations are done with the exact geometry for these ships. The ship drawings has been digitalized and fitted into ShipX.

Added resistance in wind is found by a general formula with wind coefficients found in ShipX.

Together with wind resistance, the added resistance in waves is definitively the one with most impact on the total added resistance on the ships in this thesis.

Added resistance in steering has a rather small impact on the total added resistance. However, added resistance due to rudder angle is large enough to have been included in the corrections. Resistance due to yaw angle on the ship is found to have close to no impact on the added resistance, and is therefore neglected in the corrections.

The ship crew has been asked to fill in the form in deep waters to avoid the shallow water complications. However, where this is not possible the speed losses due to shallow water are estimated with a speed loss formula given by Lackenby.

Each corrected measurement is corrected to a reference draft and speed of T = 11.8 m and 13 knots respectively, to be able to compare the results.

The results from these corrections are shown in the figure below.

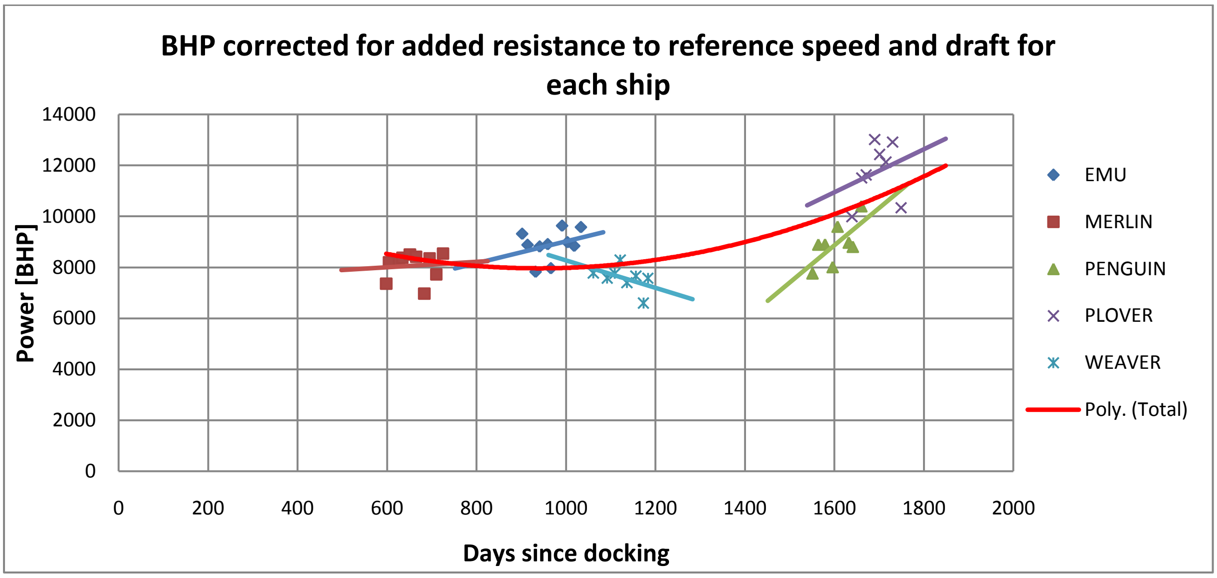


Figure 10-1: Corrected BHP, each measured point in days since last dry dock

The fouling on the hull is found by these corrections to have a small linear increase the first 2-3 years. After three years the fouling trend gets exponential. This linear increase, which is assumed to be from day one to approximately three years, is found on the basis of the numbers calculated in this thesis to have a slope number of **0.39 BHP/day**.

After 1500 days the slope of the exponential curve is found to be **5.529 BHP/day** and after 1800 days the increase of resistance is **8.469 BHP/day.**

The percentage of power increase after the first three years is then roughly estimated to be 4.7 %. This corresponds well to numbers estimated by ITTC.

10.1 Further work

Due to the limited time in this thesis the corrections have a high probability of being inaccurate. The number of measurements is small. Small amounts of measurements involves that the calculated trend of the fouling can change a large amount with each new measurement. Therefore, the most important effort to make the fouling trend more accurate is to continue the corrections for longer time periods.

Also if the amount of ships had been increased, the accuracy of the result would be better.

To increase the accuracy of the corrections further, the water temperature and the salinity of the water should be included in the corrections. The ship has water temperature measurement system on board. The salinity can be found from ocean statistics from the coordinates the ship has sailed in.

Since the results from the ships vary from one measurement to another, it is assumed that the crew does not follow the instructions of stable conditions. To improve the validity of the numbers from the ship, the crew must be more aware of the importance of these stable conditions.

To simplify the work amount needed in the Excel spreadsheet it is possible to, instead of reading the wind coefficients from Figure 5-14, make a mathematical function of the graph. This function can be implemented in the Excel spreadsheet and the wind corrections would be fully automatically done after the inputs from the ship form is inserted.

In principal, an equivalent function could have been made for the added wave resistance coefficients as well. However, this is much more complicated than a formula for the wind coefficients would have been. The added wave resistance coefficients consist of many graphs and therefore the function would have been much more comprehensive.

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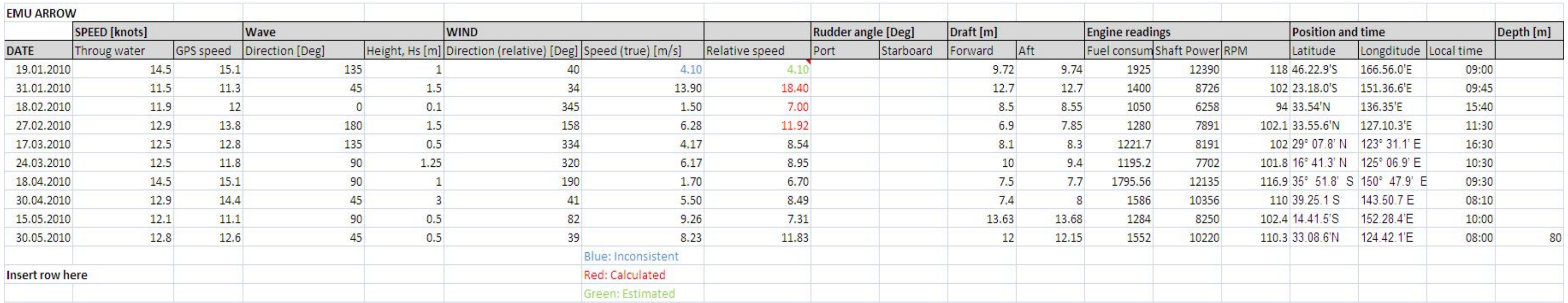
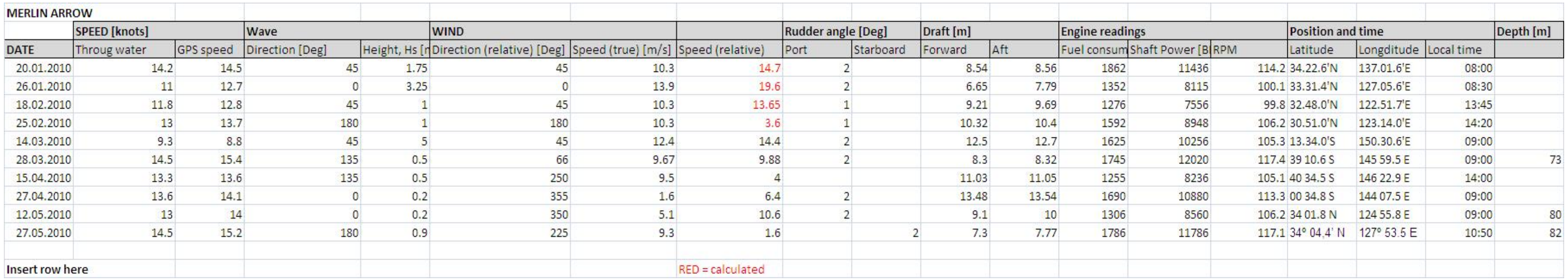
Appendix 1 - Measurements from Emu Arrow



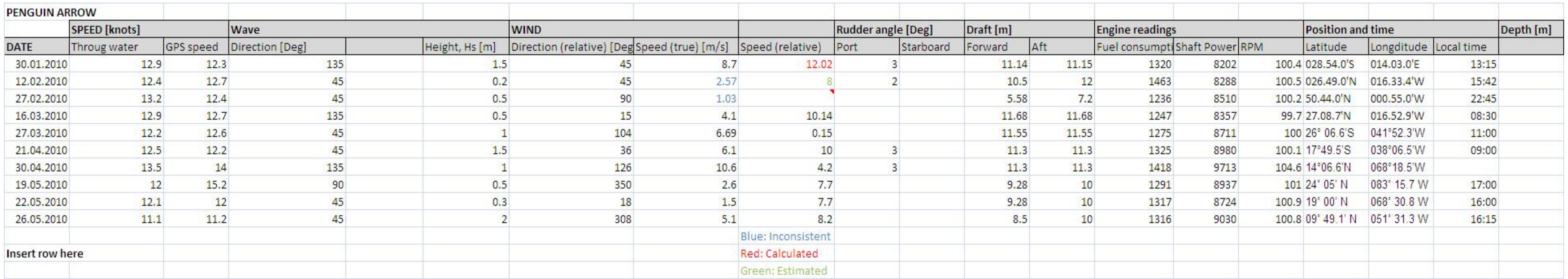
EMU ARROW																		
	SPEED [knots]		Wave		WIND			Rudder angle [Deg]		Draft [m]		Engine readings			Position and time			Depth [m]
DATE	Throug water	GPS speed	Direction [Deg]	Height, Hs [m]	Direction (relative) [Deg]	Speed (true) [m/s]	Relative speed	Port	Starboard	Forward	Aft	Fuel consum	Shaft Power	RPM	Latitude	Longditude	Local time	
19.01.2010	14.5	15.1	135	1	40	4.10	4.10			9.72	9.74	1925	12390	118	46.22.9'S	166.56.0'E	09:00	
31.01.2010	11.5	11.3	45	1.5	34	13.90	18.40			12.7	12.7	1400	8726	102	23.18.0'S	151.36.6'E	09:45	
18.02.2010	11.9	12	0	0.1	345	1.50	7.00			8.5	8.55	1050	6258	94	33.54'N	136.35'E	15:40	
27.02.2010	12.9	13.8	180	1.5	158	6.28	11.92			6.9	7.85	1280	7891	102.1	33.55.6'N	127.10.3'E	11:30	
17.03.2010	12.5	12.8	135	0.5	334	4.17	8.54			8.1	8.3	1221.7	8191	102	29° 07.8' N	123° 31.1' E	16:30	
24.03.2010	12.5	11.8	90	1.25	320	6.17	8.95			10	9.4	1195.2	7702	101.8	16° 41.3' N	125° 06.9' E	10:30	
18.04.2010	14.5	15.1	90	1	190	1.70	6.70			7.5	7.7	1795.56	12135	116.9	35° 51.8' S	150° 47.9' E	09:30	
30.04.2010	12.9	14.4	45	3	41	5.50	8.49			7.4	8	1586	10356	110	39.25.1 S	143.50.7 E	08:10	
15.05.2010	12.1	11.1	90	0.5	82	9.26	7.31			13.63	13.68	1284	8250	102.4	14.41.5'S	152.28.4'E	10:00	
30.05.2010	12.8	12.6	45	0.5	39	8.23	11.83			12	12.15	1552	10220	110.3	33.08.6'N	124.42.1'E	08:00	80
						Blue: Inconsistent												
Insert row here						Red: Calculated												
						Green: Estimated												

Appendix 2 - Measurements from Merlin Arrow



MERLIN ARROW																		
	SPEED [knots]		Wave		WIND			Rudder angle [Deg]		Draft [m]		Engine readings			Position and time			Depth [m]
DATE	Throug water	GPS speed	Direction [Deg]	Height, Hs [r	Direction (relative) [Deg]	Speed (true) [m/s]	Speed (relative)	Port	Starboard	Forward	Aft	Fuel consum	Shaft Power [B	RPM	Latitude	Longditude	Local time	
20.01.2010	14.2	14.5	45	1.75	45	10.3	14.7	2		8.54	8.56	1862	11436	114.2	34.22.6'N	137.01.6'E	08:00	
26.01.2010	11	12.7	0	3.25	0	13.9	19.6	2		6.65	7.79	1352	8115	100.1	33.31.4'N	127.05.6'E	08:30	
18.02.2010	11.8	12.8	45	1	45	10.3	13.65	1		9.21	9.69	1276	7556	99.8	32.48.0'N	122.51.7'E	13:45	
25.02.2010	13	13.7	180	1	180	10.3	3.6	1		10.32	10.4	1592	8948	106.2	30.51.0'N	123.14.0'E	14:20	
14.03.2010	9.3	8.8	45	5	45	12.4	14.4	2		12.5	12.7	1625	10256	105.3	13.34.0'S	150.30.6'E	09:00	
28.03.2010	14.5	15.4	135	0.5	66	9.67	9.88	2		8.3	8.32	1745	12020	117.4	39 10.6 S	145 59.5 E	09:00	73
15.04.2010	13.3	13.6	135	0.5	250	9.5	4			11.03	11.05	1255	8236	105.1	40 34.5 S	146 22.9 E	14:00	
27.04.2010	13.6	14.1	0	0.2	355	1.6	6.4	2		13.48	13.54	1690	10880	113.3	00 34.8 S	144 07.5 E	09:00	
12.05.2010	13	14	0	0.2	350	5.1	10.6	2		9.1	10	1306	8560	106.2	34 01.8 N	124 55.8 E	09:00	80
27.05.2010	14.5	15.2	180	0.9	225	9.3	1.6		2	7.3	7.77	1786	11786	117.1	34° 04.4' N	127° 53.5 E	10:50	82
Insert row here							RED = calculated											

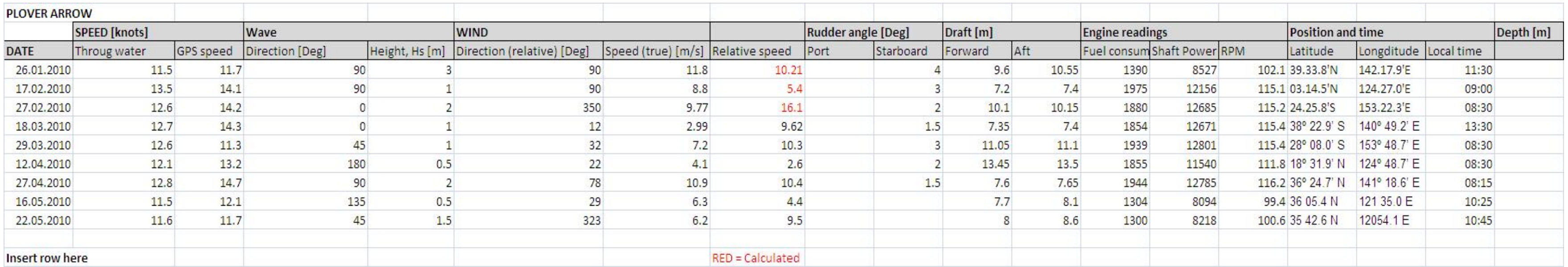
Appendix 3 - Measurements from Penguin Arrow



PENGUIN ARROW

	SPEED [knots]		Wave			WIND			Rudder angle [Deg]		Draft [m]		Engine readings			Position and time			Depth [m]
DATE	Throug water	GPS speed	Direction [Deg]		Height, Hs [m]	Direction (relative) [Deg	Speed (true) [m/s]	Speed (relative)	Port	Starboard	Forward	Aft	Fuel consumpti	Shaft Power	RPM	Latitude	Longditude	Local time	
30.01.2010	12.9	12.3	135		1.5	45	8.7	12.02	3		11.14	11.15	1320	8202	100.4	028.54.0'S	014.03.0'E	13:15	
12.02.2010	12.4	12.7	45		0.2	45	2.57	8	2		10.5	12	1463	8288	100.5	026.49.0'N	016.33.4'W	15:42	
27.02.2010	13.2	12.4	45		0.5	90	1.03				5.58	7.2	1236	8510	100.2	50.44.0'N	000.55.0'W	22:45	
16.03.2010	12.9	12.7	135		0.5	15	4.1	10.14			11.68	11.68	1247	8357	99.7	27.08.7'N	016.52.9'W	08:30	
27.03.2010	12.2	12.6	45		1	104	6.69	0.15			11.55	11.55	1275	8711	100	26° 06.6'S	041°52.3'W	11:00	
21.04.2010	12.5	12.2	45		1.5	36	6.1	10	3		11.3	11.3	1325	8980	100.1	17°49.5'S	038°06.5'W	09:00	
30.04.2010	13.5	14	135		1	126	10.6	4.2	3		11.3	11.3	1418	9713	104.6	14°06.6'N	068°18.5'W		
19.05.2010	12	15.2	90		0.5	350	2.6	7.7			9.28	10	1291	8937	101	24° 05' N	083° 15.7 W	17:00	
22.05.2010	12.1	12	45		0.3	18	1.5	7.7			9.28	10	1317	8724	100.9	19° 00' N	068° 30.8 W	16:00	
26.05.2010	11.1	11.2	45		2	308	5.1	8.2			8.5	10	1316	9030	100.8	09° 49.1' N	051° 31.3 W	16:15	
								Blue: Inconsistent											
Insert row here								Red: Calculated											
								Green: Estimated											

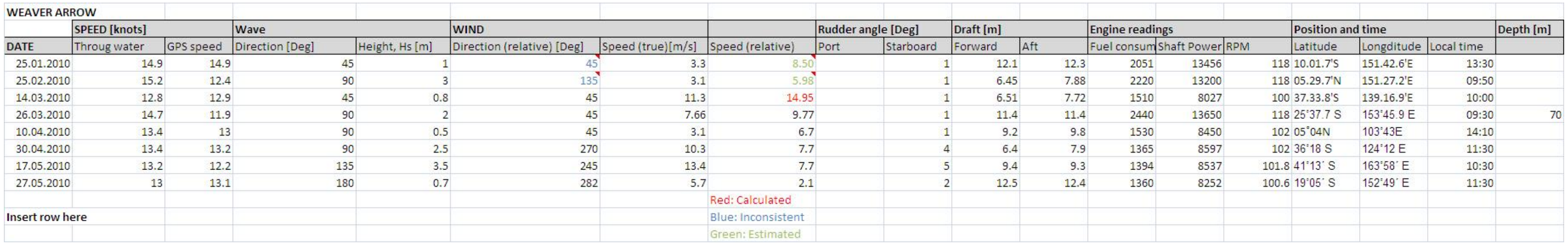
Appendix 4 - Measurements from Plover Arrow



PLOVER ARROW

	SPEED [knots]		Wave		WIND			Rudder angle [Deg]		Draft [m]		Engine readings			Position and time			Depth [m]
DATE	Throug water	GPS speed	Direction [Deg]	Height, Hs [m]	Direction (relative) [Deg]	Speed (true) [m/s]	Relative speed	Port	Starboard	Forward	Aft	Fuel consum	Shaft Power	RPM	Latitude	Longditude	Local time	
26.01.2010	11.5	11.7	90	3	90	11.8	10.21		4	9.6	10.55	1390	8527	102.1	39.33.8'N	142.17.9'E	11:30	
17.02.2010	13.5	14.1	90	1	90	8.8	5.4		3	7.2	7.4	1975	12156	115.1	03.14.5'N	124.27.0'E	09:00	
27.02.2010	12.6	14.2	0	2	350	9.77	16.1		2	10.1	10.15	1880	12685	115.2	24.25.8'S	153.22.3'E	08:30	
18.03.2010	12.7	14.3	0	1	12	2.99	9.62		1.5	7.35	7.4	1854	12671	115.4	38° 22.9' S	140° 49.2' E	13:30	
29.03.2010	12.6	11.3	45	1	32	7.2	10.3		3	11.05	11.1	1939	12801	115.4	28° 08.0' S	153° 48.7' E	08:30	
12.04.2010	12.1	13.2	180	0.5	22	4.1	2.6		2	13.45	13.5	1855	11540	111.8	18° 31.9' N	124° 48.7' E	08:30	
27.04.2010	12.8	14.7	90	2	78	10.9	10.4		1.5	7.6	7.65	1944	12785	116.2	36° 24.7' N	141° 18.6' E	08:15	
16.05.2010	11.5	12.1	135	0.5	29	6.3	4.4			7.7	8.1	1304	8094	99.4	36 05.4 N	121 35.0 E	10:25	
22.05.2010	11.6	11.7	45	1.5	323	6.2	9.5			8	8.6	1300	8218	100.6	35 42.6 N	12054.1 E	10:45	
Insert row here							RED = Calculated											

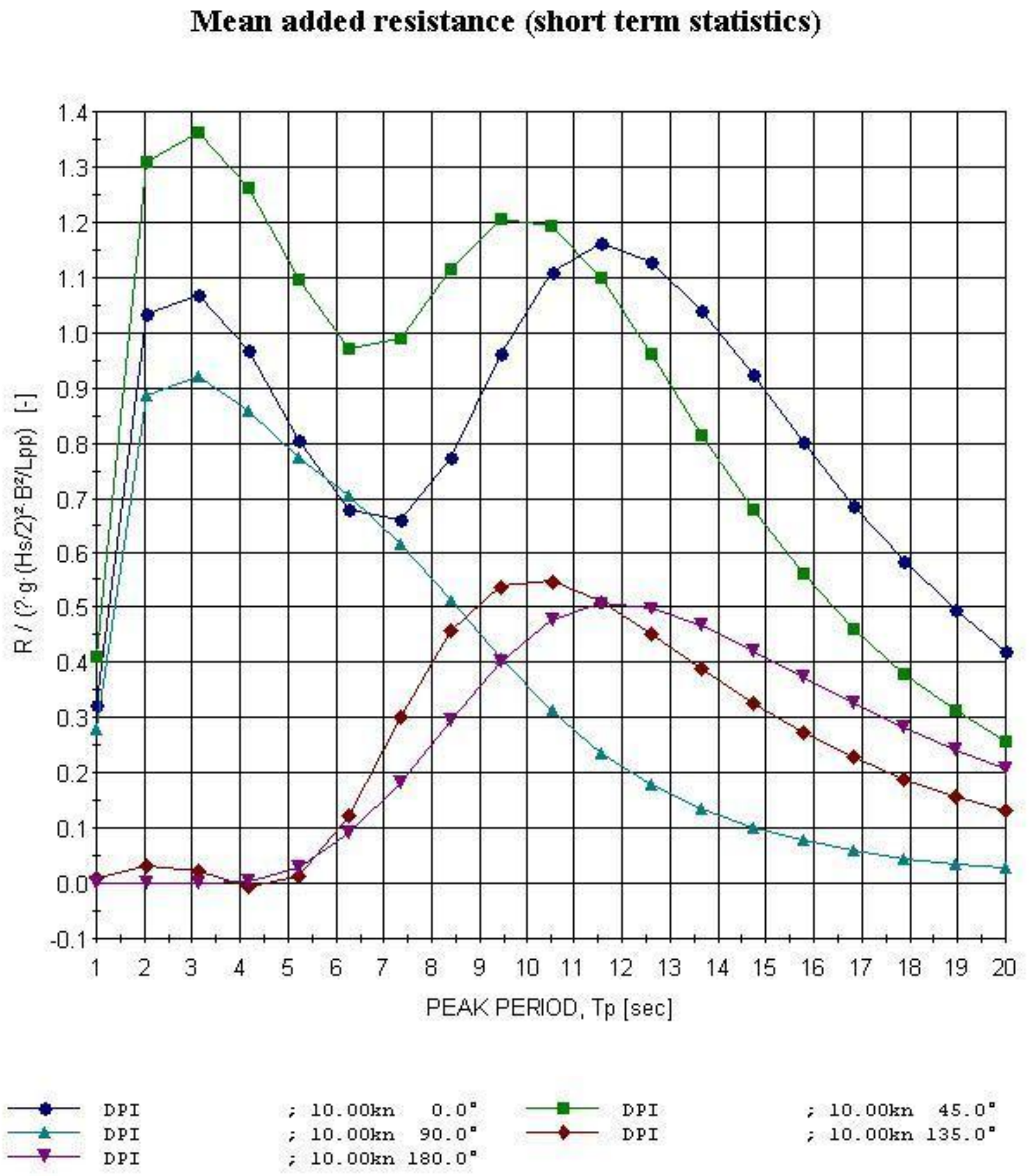
Appendix 5 - Measurements from Weaver Arrow



WEAVER ARROW																		
	SPEED [knots]		Wave		WIND			Rudder angle [Deg]		Draft [m]		Engine readings			Position and time			Depth [m]
DATE	Throug water	GPS speed	Direction [Deg]	Height, Hs [m]	Direction (relative) [Deg]	Speed (true)[m/s]	Speed (relative)	Port	Starboard	Forward	Aft	Fuel consum	Shaft Power	RPM	Latitude	Longditude	Local time	
25.01.2010	14.9	14.9	45	1	45	3.3	8.50		1	12.1	12.3	2051	13456	118	10.01.7'S	151.42.6'E	13:30	
25.02.2010	15.2	12.4	90	3	135	3.1	5.98		1	6.45	7.88	2220	13200	118	05.29.7'N	151.27.2'E	09:50	
14.03.2010	12.8	12.9	45	0.8	45	11.3	14.95		1	6.51	7.72	1510	8027	100	37.33.8'S	139.16.9'E	10:00	
26.03.2010	14.7	11.9	90	2	45	7.66	9.77		1	11.4	11.4	2440	13650	118	25°37.7 S	153°45.9 E	09:30	70
10.04.2010	13.4	13	90	0.5	45	3.1	6.7		1	9.2	9.8	1530	8450	102	05°04N	103°43E	14:10	
30.04.2010	13.4	13.2	90	2.5	270	10.3	7.7		4	6.4	7.9	1365	8597	102	36°18 S	124°12 E	11:30	
17.05.2010	13.2	12.2	135	3.5	245	13.4	7.7		5	9.4	9.3	1394	8537	101.8	41°13´ S	163°58´ E	10:30	
27.05.2010	13	13.1	180	0.7	282	5.7	2.1		2	12.5	12.4	1360	8252	100.6	19°05´ S	152°49´ E	11:30	
							Red: Calculated											
Insert row here							Blue: Inconsistent											
							Green: Estimated											

Appendix 6 - RAW coefficients, V = 10 knots

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	10 knots
	DATE	2010-06-07
	REF	T = 7 m



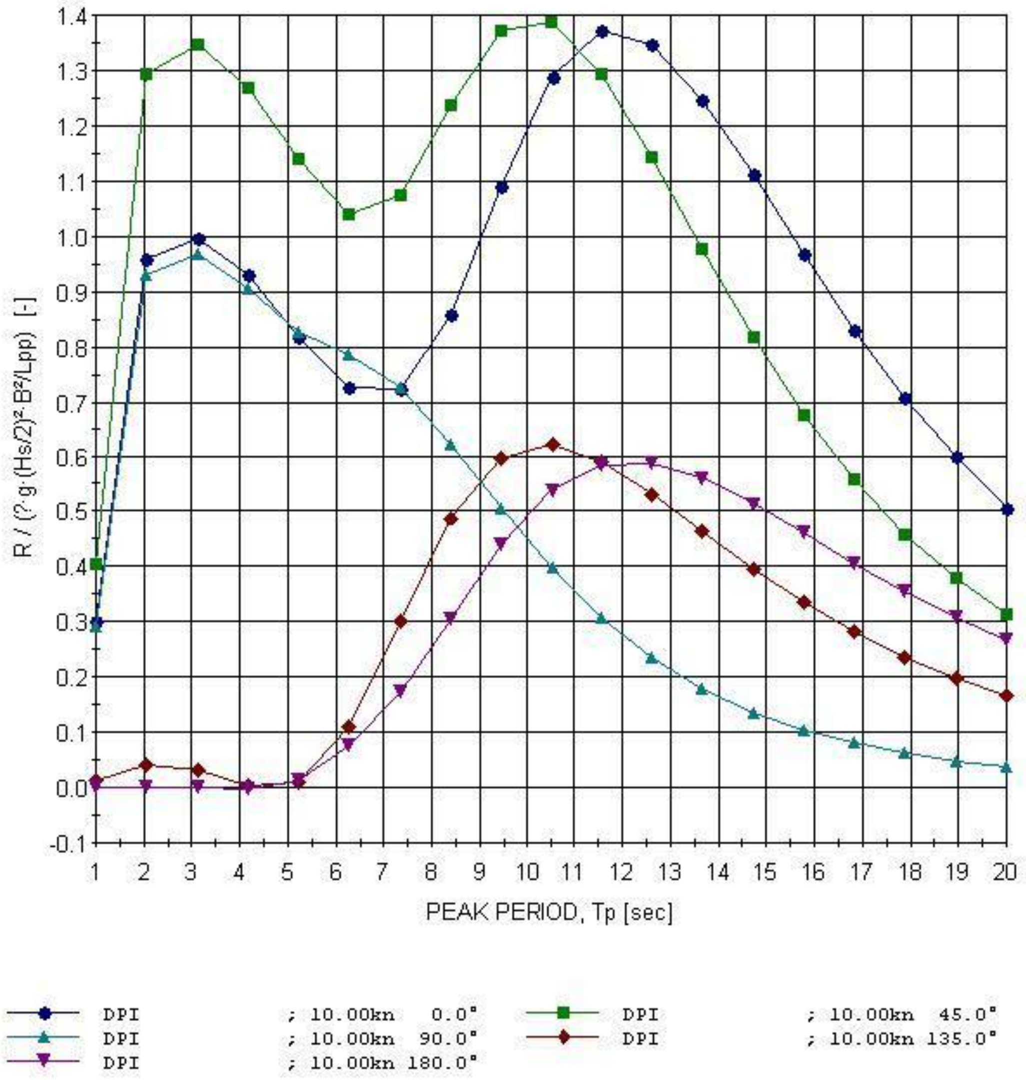
Project: DPI, T = 7 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 10:52:32 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	10 knots
DATE	2010-06-07
REF	T = 8 m

Mean added resistance (short term statistics)

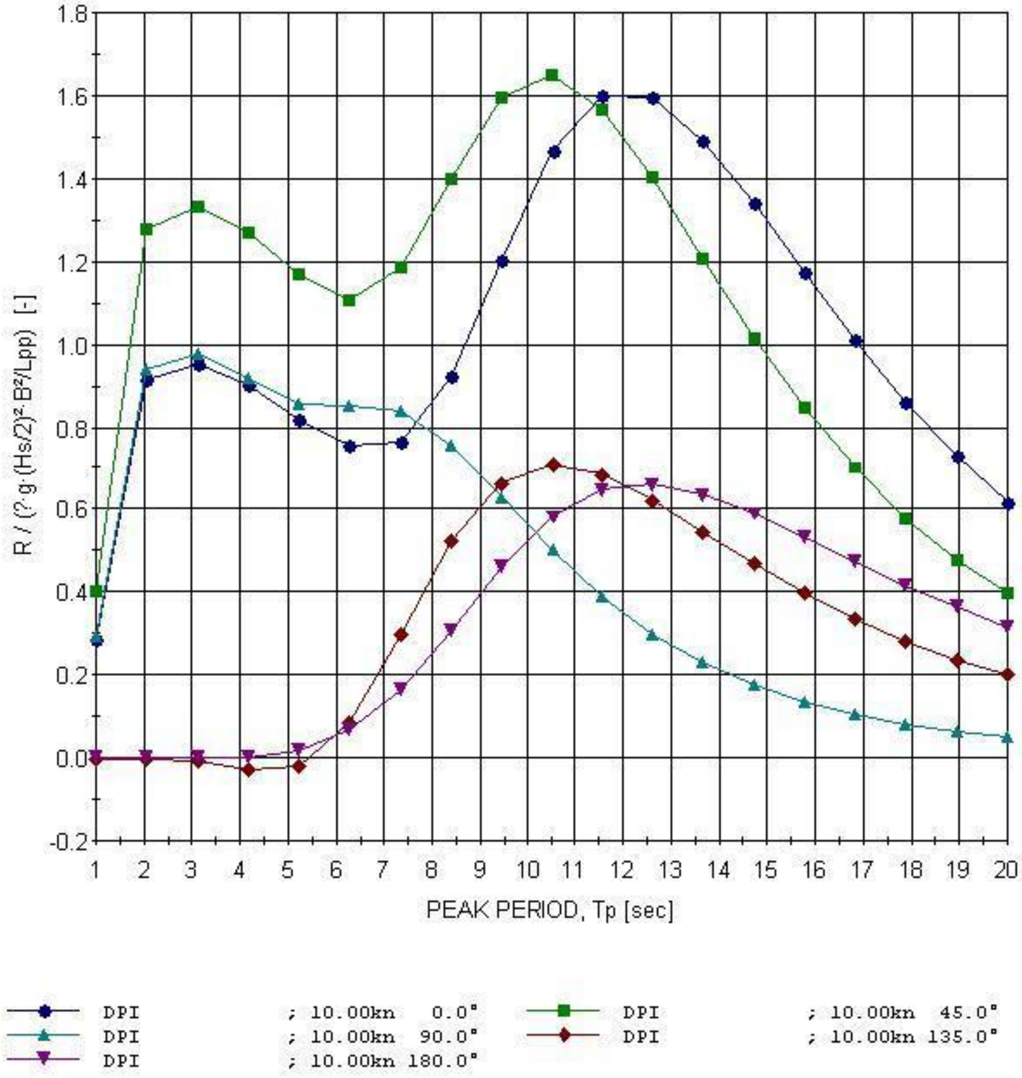


Project: DPI, T= 8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 10:53:35 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS		
	ENCL.	1)
	REPORT	10 knots
	DATE	2010-06-07
	REF	T = 9 m

Mean added resistance (short term statistics)

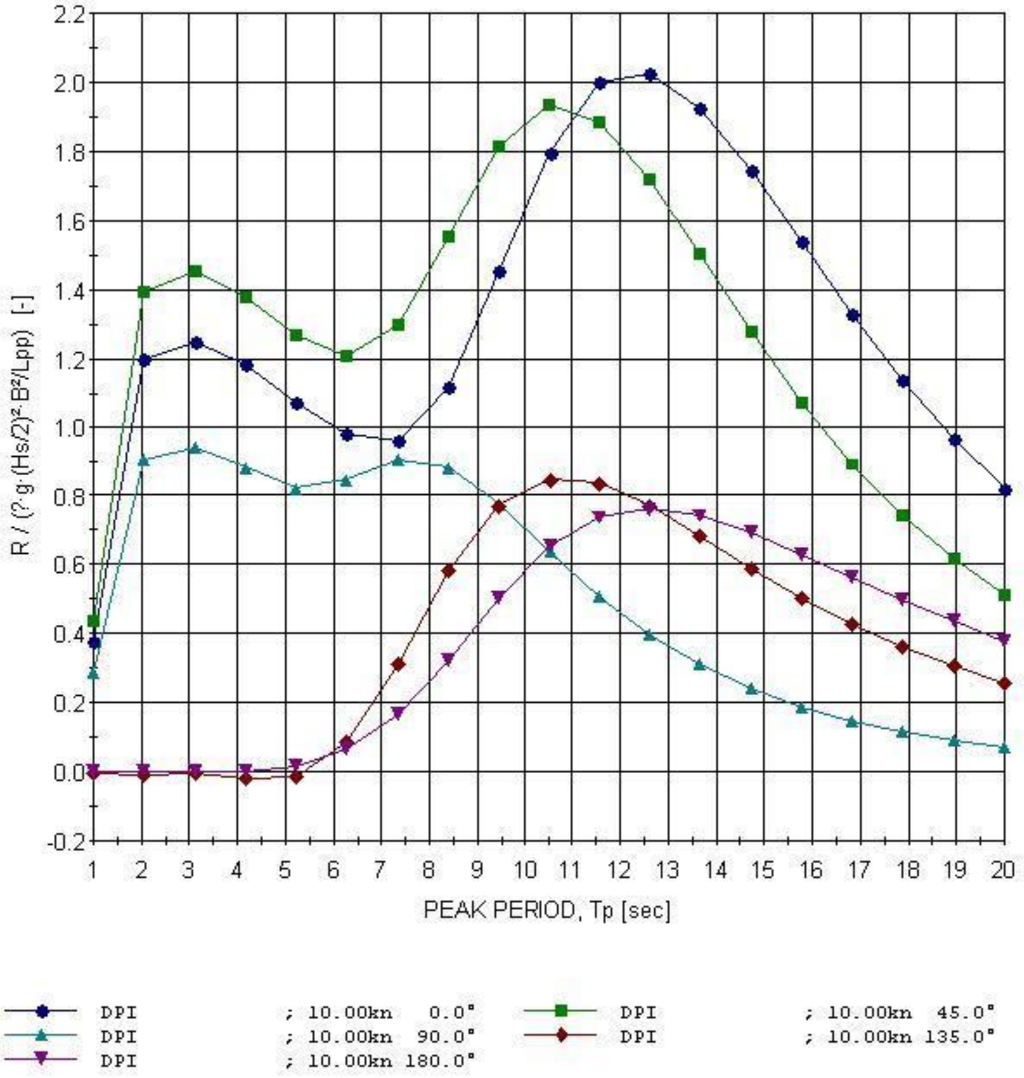


Project: DPI, T = 9 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 10:54:45 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	10 knots
	DATE	2010-06-07
	REF	T = 10 m

Mean added resistance (short term statistics)



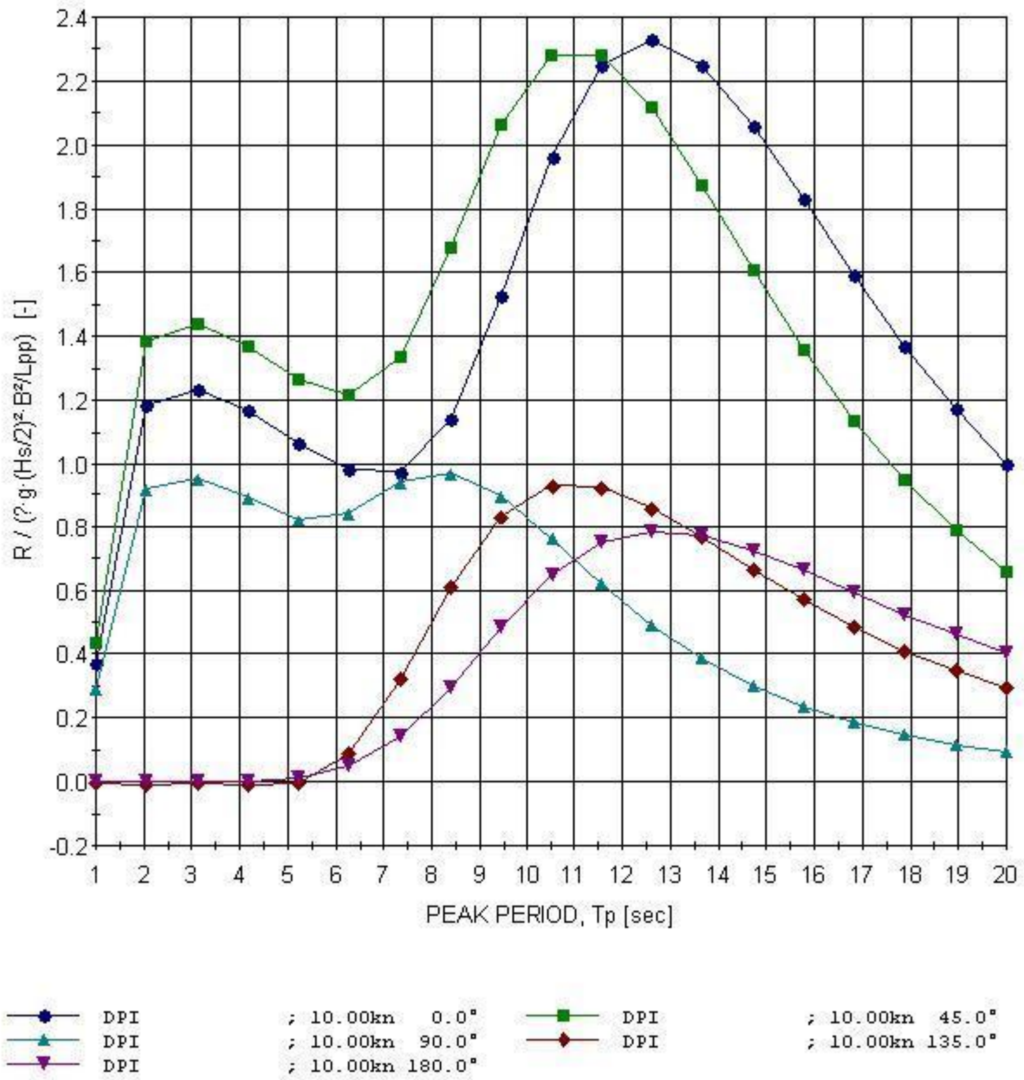
Project: DPI, T = 10 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 10:55:38 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	10 knots
DATE	2010-06-07
REF	T = 11 m

Mean added resistance (short term statistics)



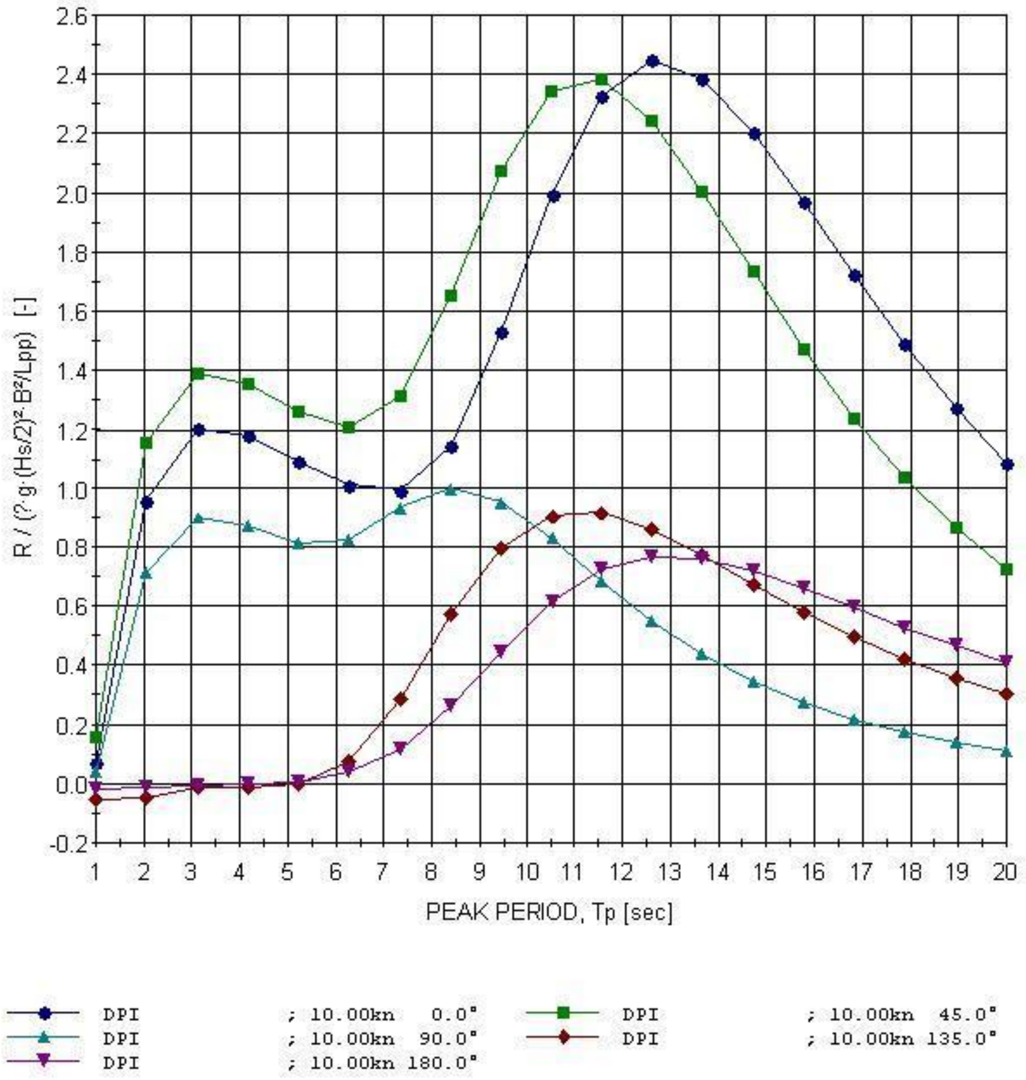
Project: DPI, T = 11 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 10:56:31 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	10 knots
DATE	2010-06-07
REF	T = 11.8 m

Mean added resistance (short term statistics)

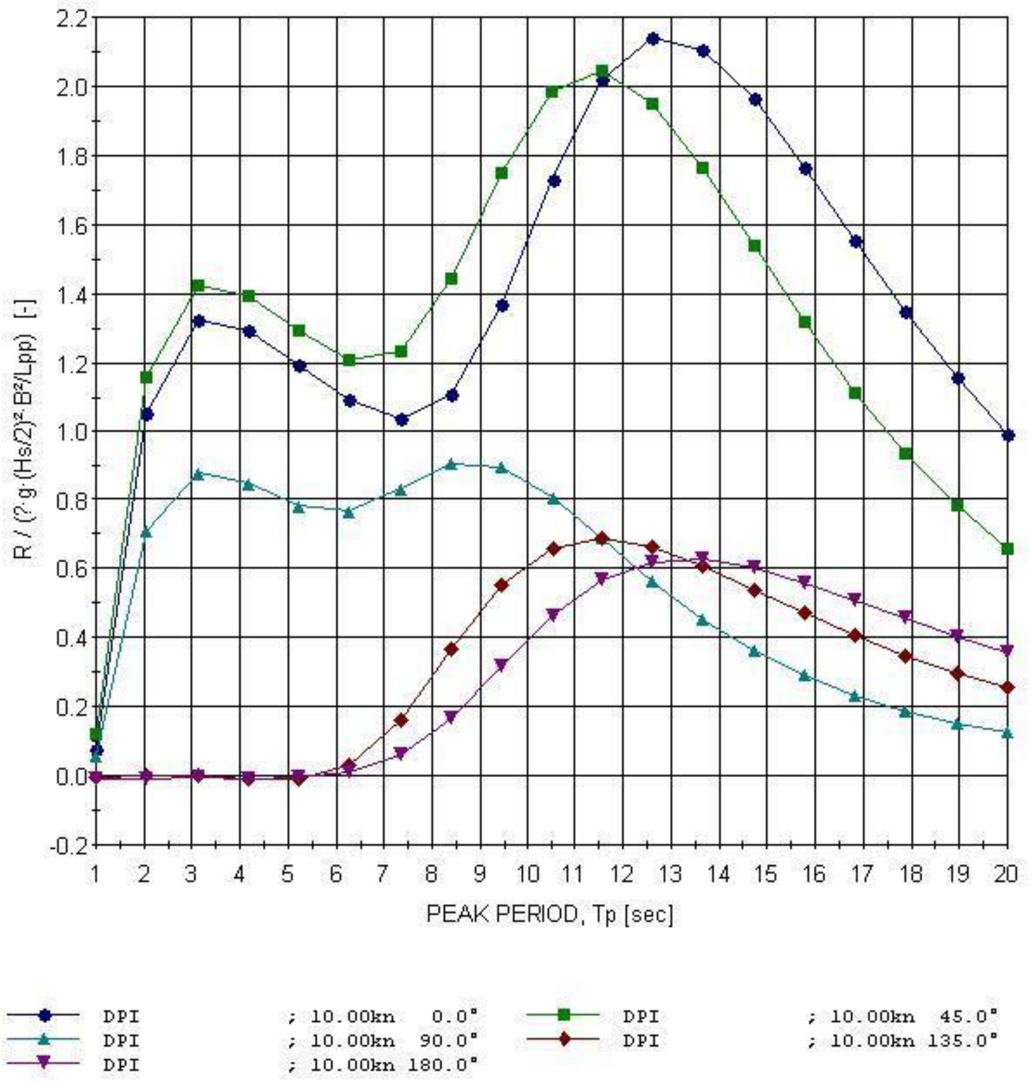


Project: DPI, T = 11.8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 10:57:14 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	10 knots
	DATE	2010-06-07
	REF	T = 13.5 m

Mean added resistance (short term statistics)



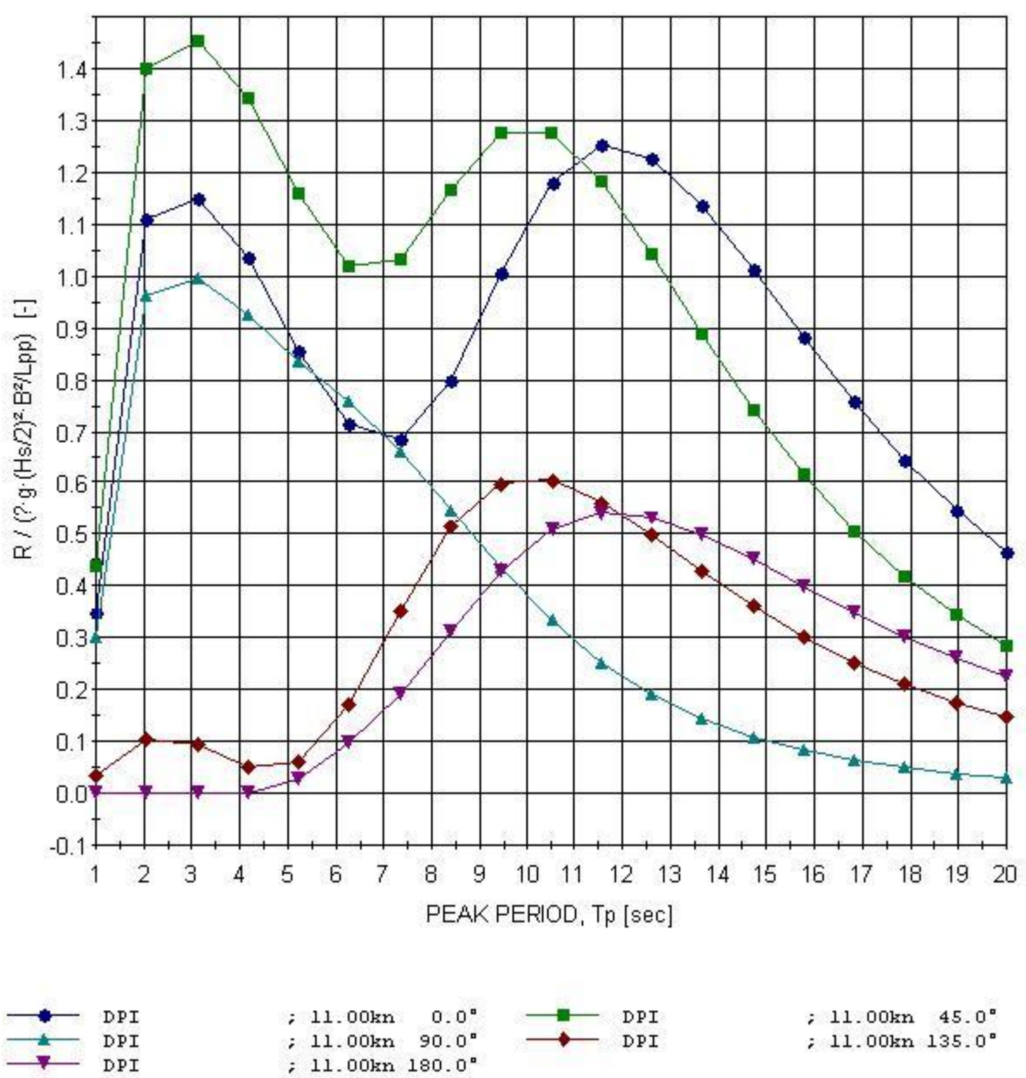
Project: DPI, T = 13.5 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 10:58:24 - Licensed to: Mads (NTNU)

Appendix 7 - RAW coefficients, V = 11 knots

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	11 knots
	DATE	2010-06-07
	REF	T = 7 m

Mean added resistance (short term statistics)

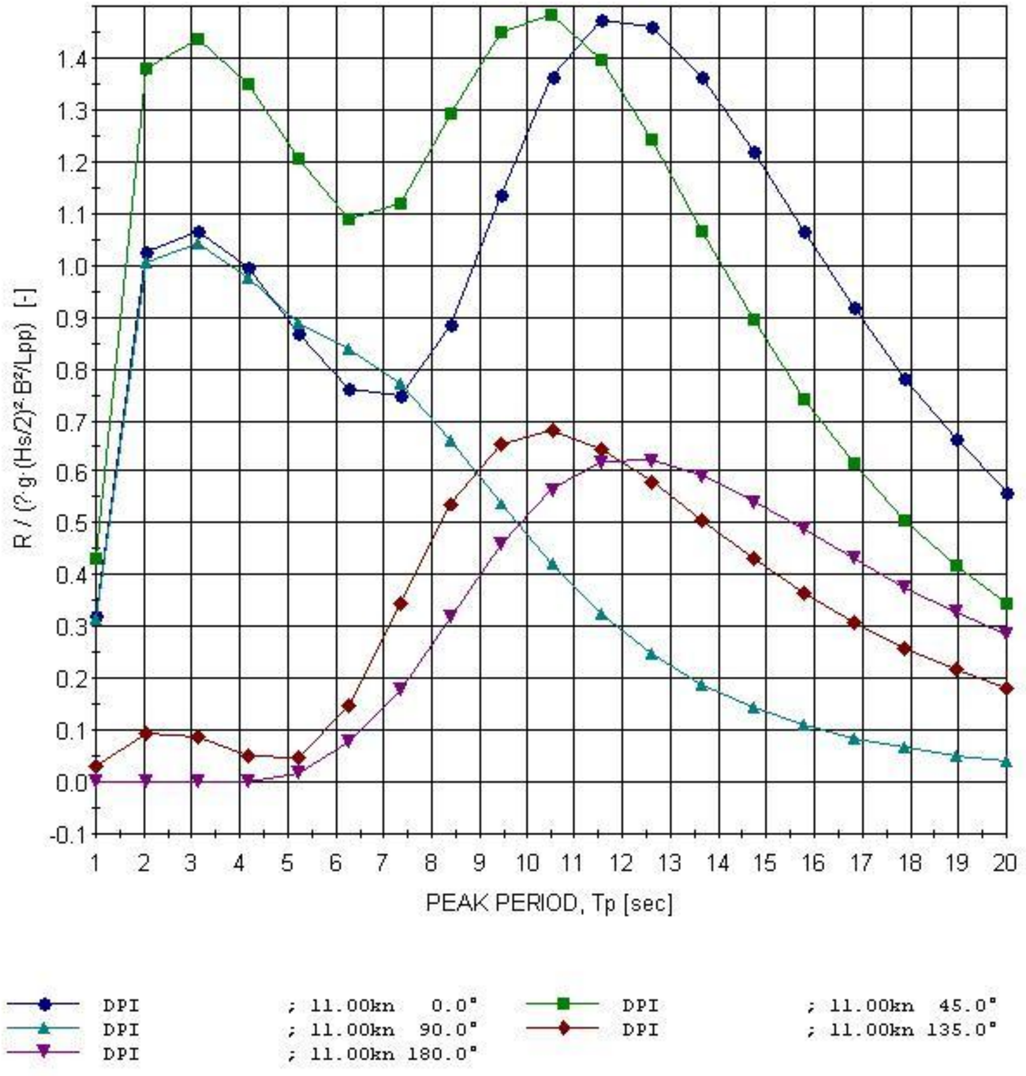


Project: DPI, T = 7 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:08:04 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	11 knots
	DATE	2010-06-07
	REF	T = 8 m

Mean added resistance (short term statistics)

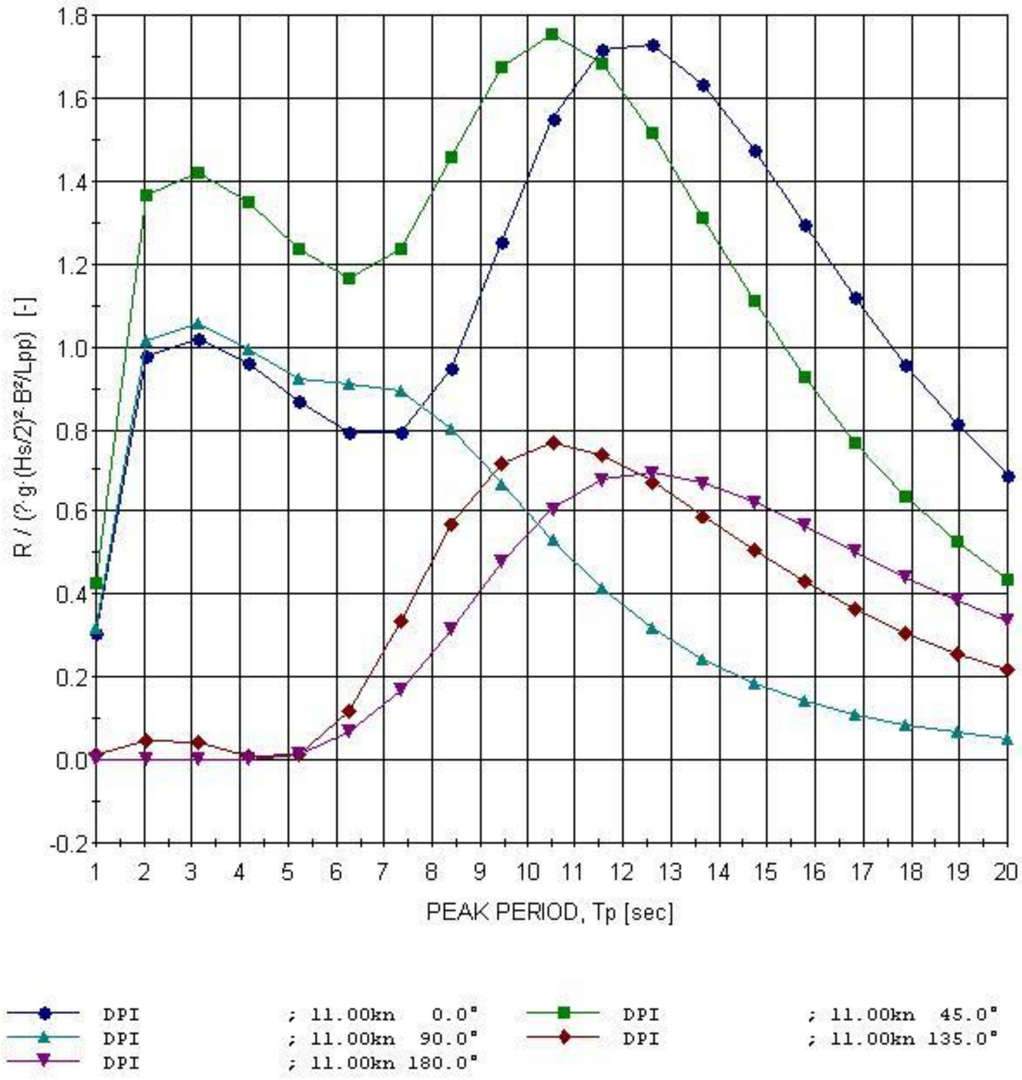


Project: DPI, T= 8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:08:36 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	11 knots
	DATE	2010-06-07
	REF	T = 9 m

Mean added resistance (short term statistics)

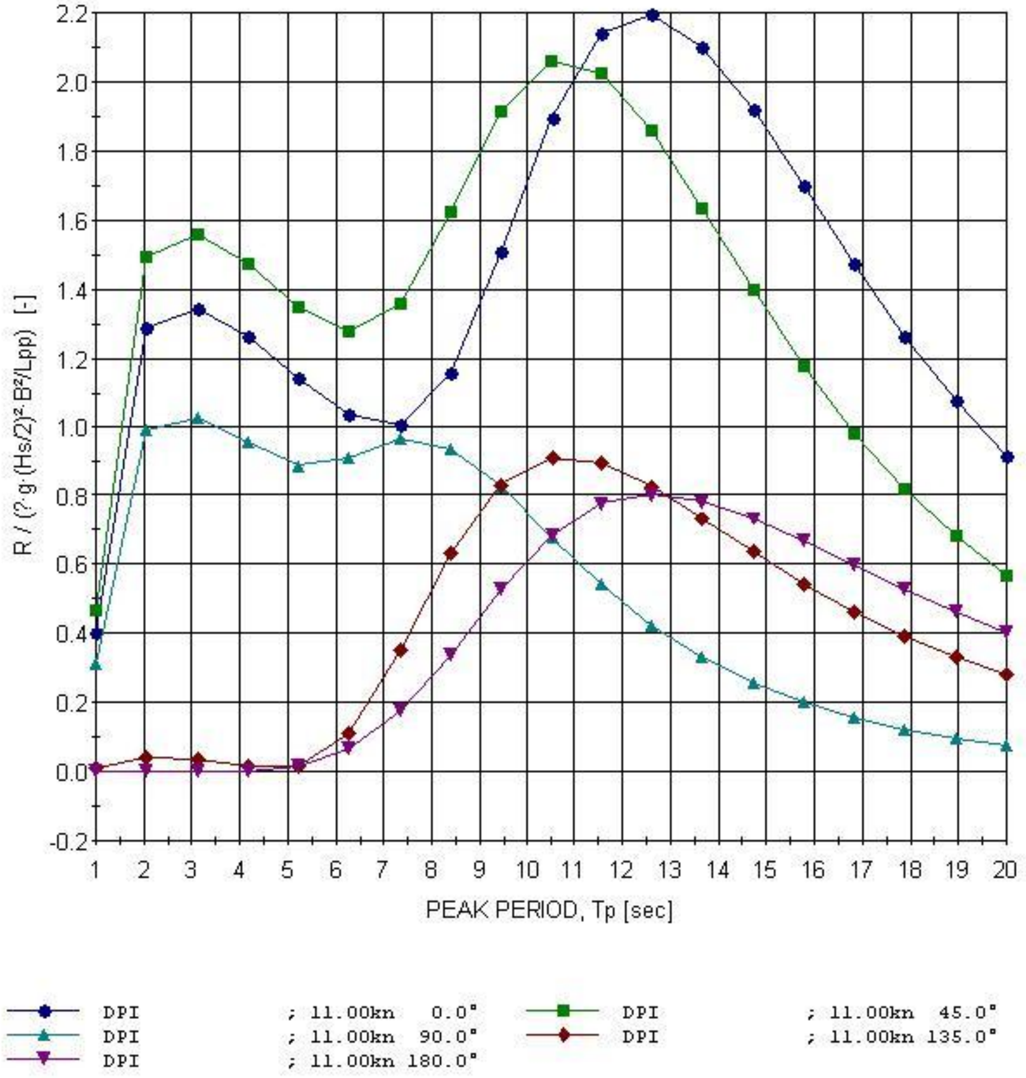


Project: DPI, T = 9 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:09:06 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS		
	ENCL.	1)
	REPORT	11 knots
	DATE	2010-06-07
	REF	T = 10 m

Mean added resistance (short term statistics)



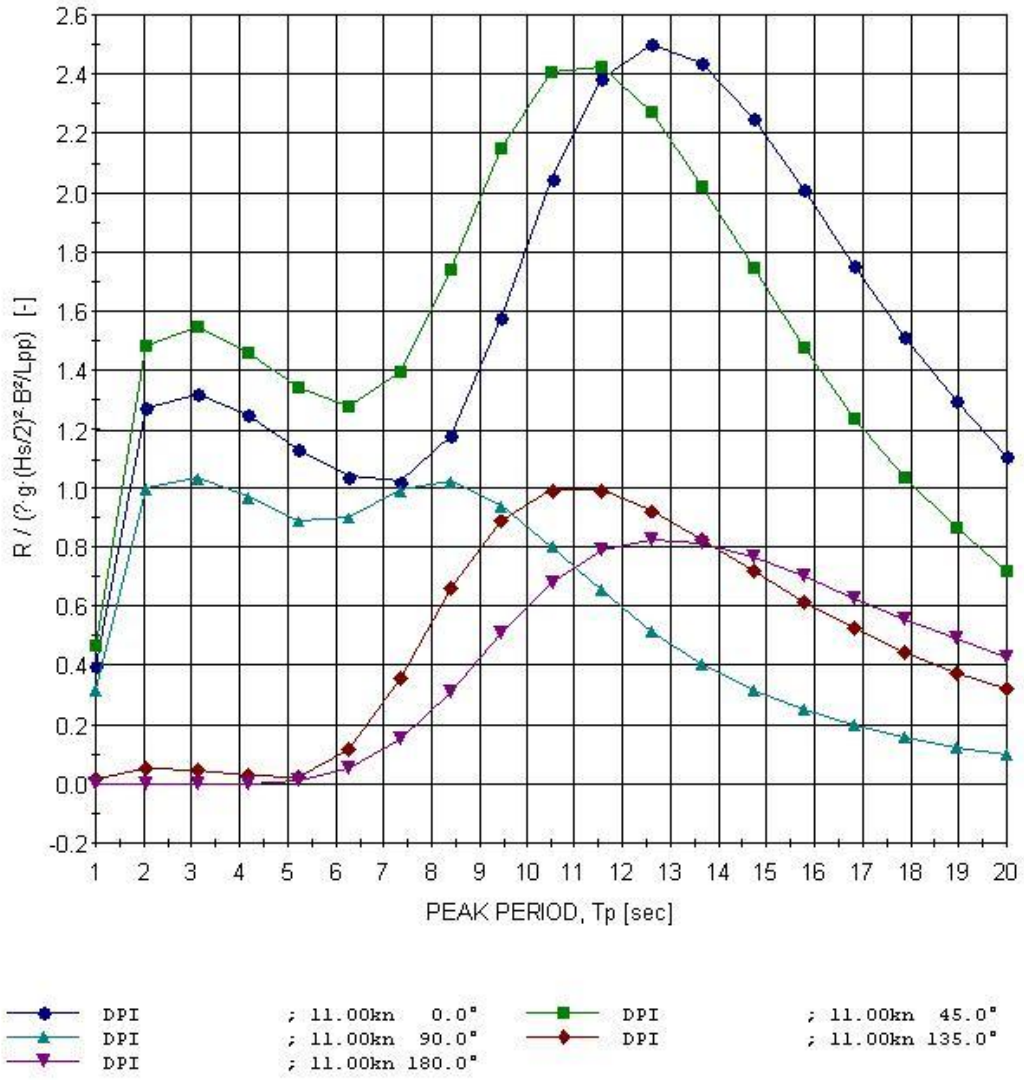
Project: DPI, T = 10 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:09:41 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	11 knots
DATE	2010-06-07
REF	T = 11 m

Mean added resistance (short term statistics)



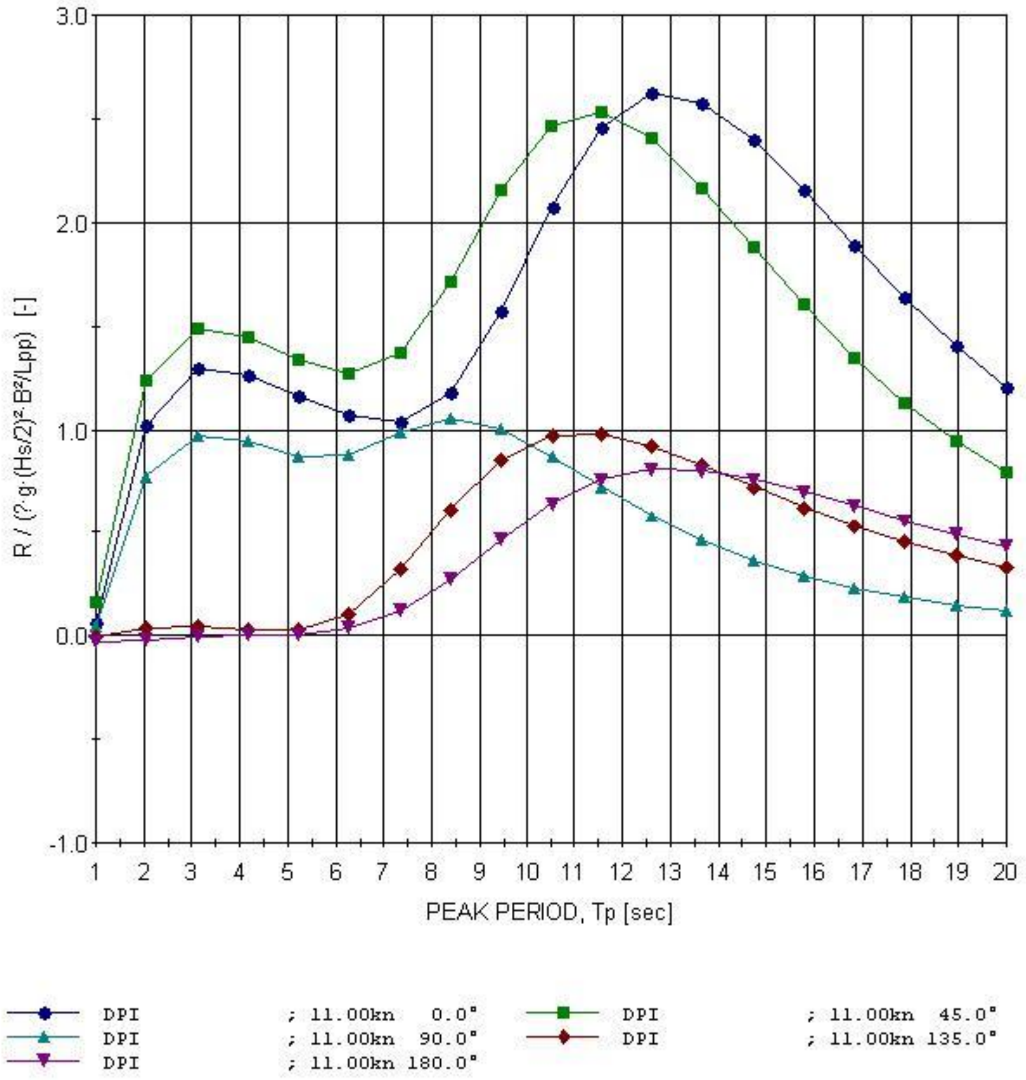
Project: DPI, T = 11 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:10:06 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	11 knots
DATE	2010-06-07
REF	T = 11.8 m

Mean added resistance (short term statistics)

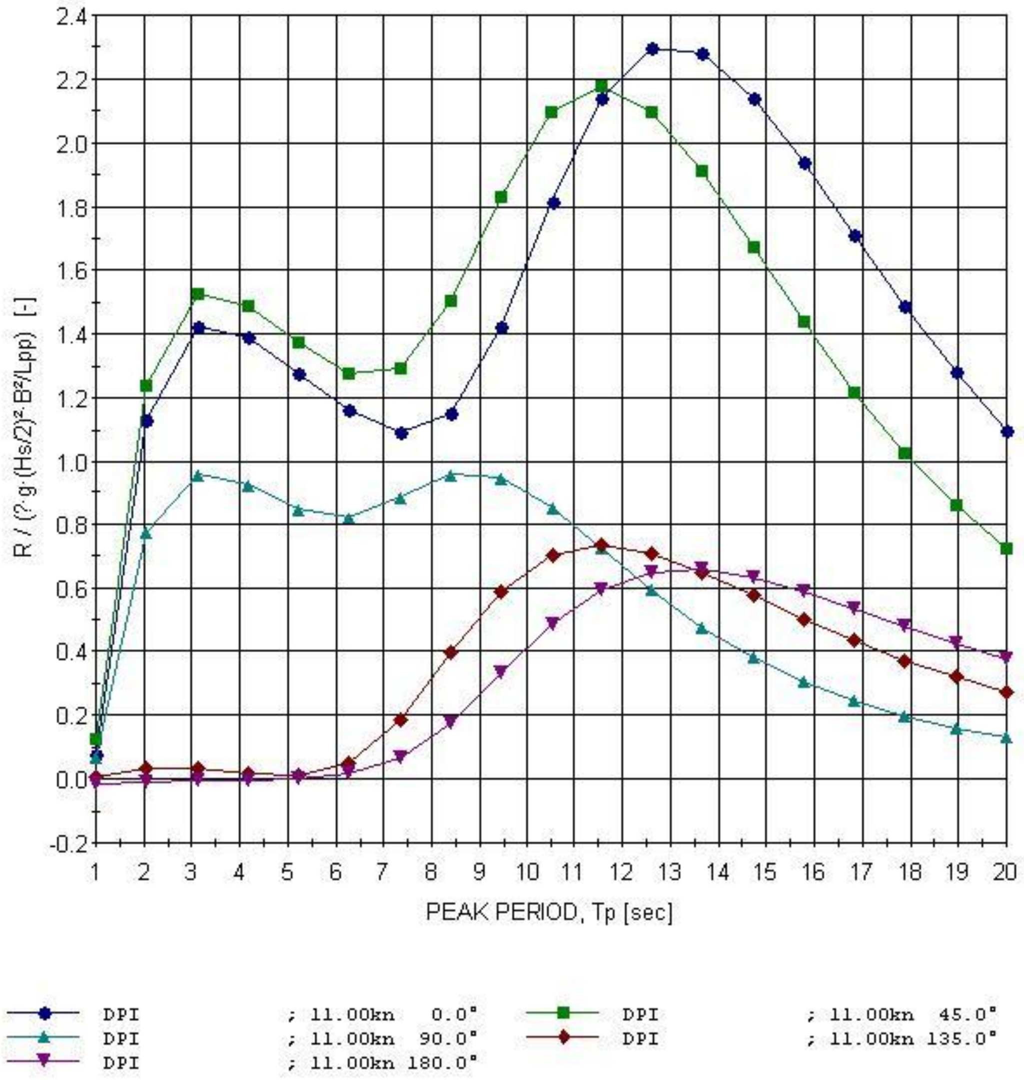


Project: DPI, T = 11.8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:10:43 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	11 knots
	DATE	2010-06-07
	REF	T = 13.5 m

Mean added resistance (short term statistics)



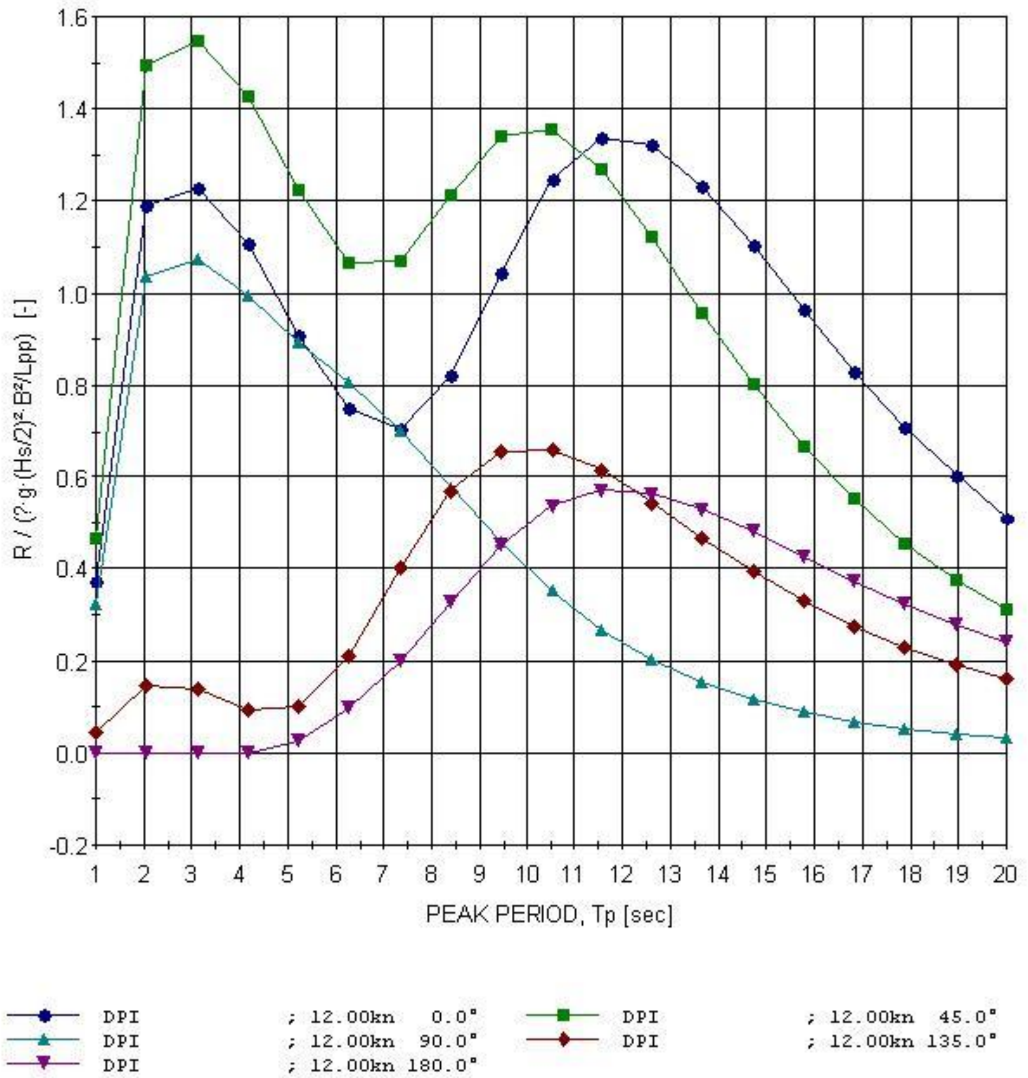
Project: DPI, T = 13.5 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:11:14 - Licensed to: Mads (NTNU)

Appendix 8 - RAW coefficients, V = 12 knots

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	12 knots
	DATE	2010-06-07
	REF	T = 7 m

Mean added resistance (short term statistics)

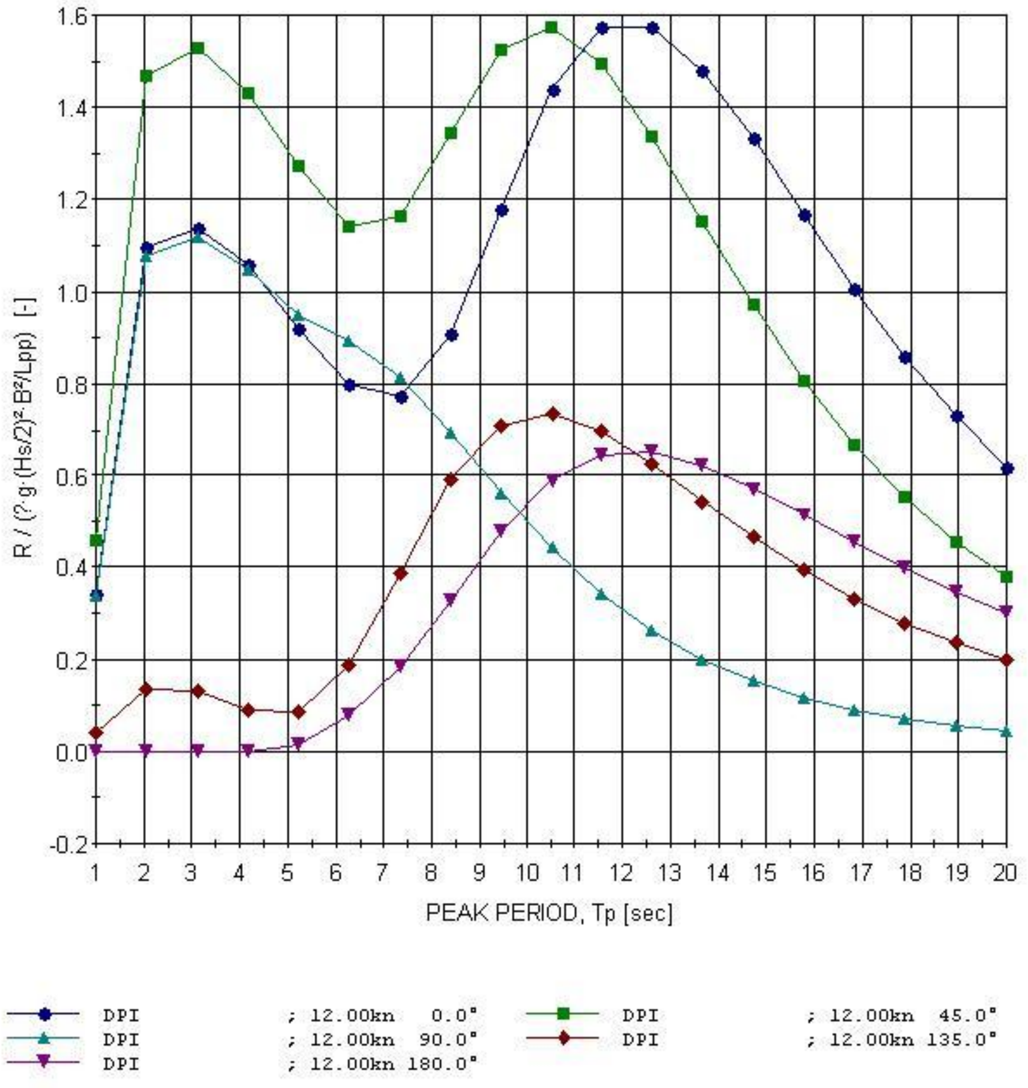


Project: DPI, T = 7 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:15:45 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS		
	ENCL.	1)
	REPORT	12 knots
	DATE	2010-06-07
	REF	T = 8 m

Mean added resistance (short term statistics)

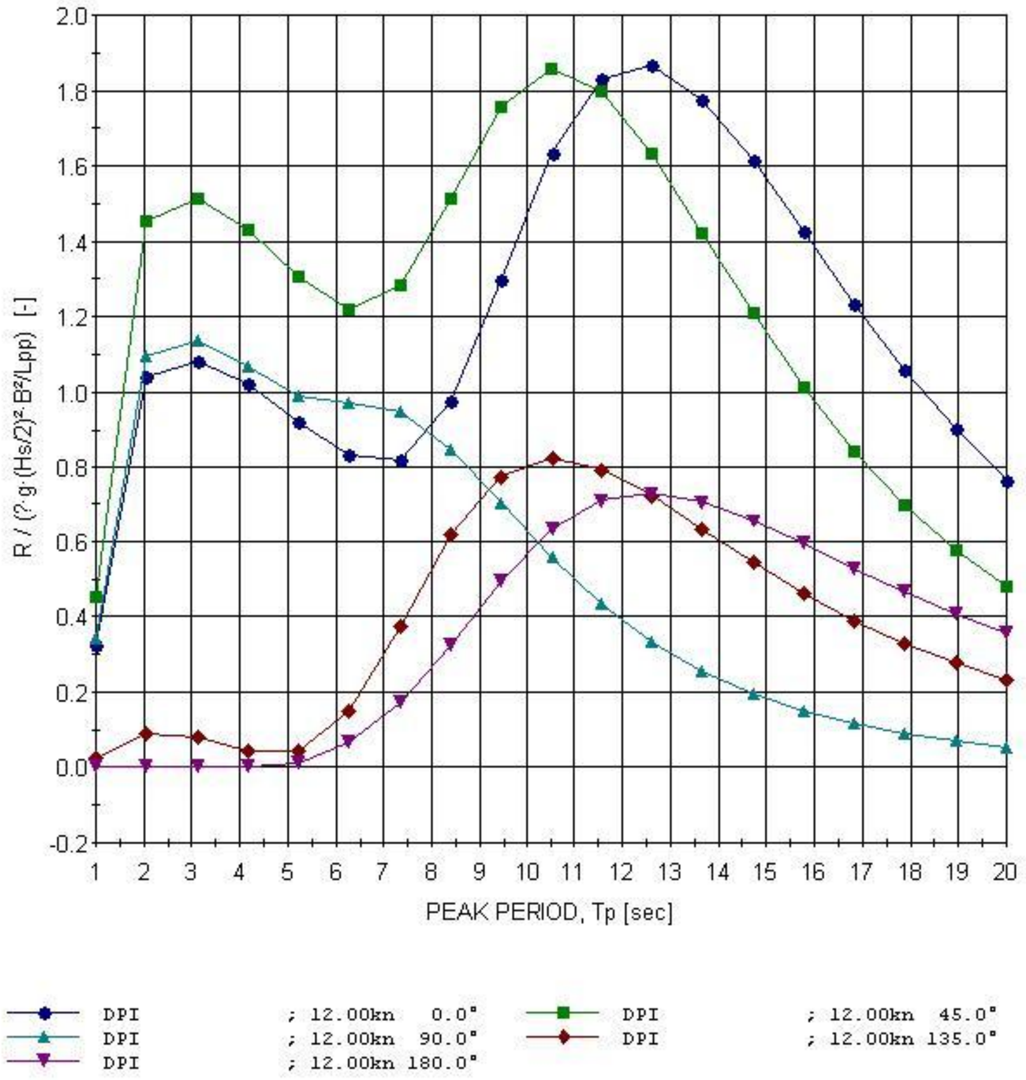


Project: DPI, T= 8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:16:10 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	12 knots
	DATE	2010-06-07
	REF	T = 9 m

Mean added resistance (short term statistics)



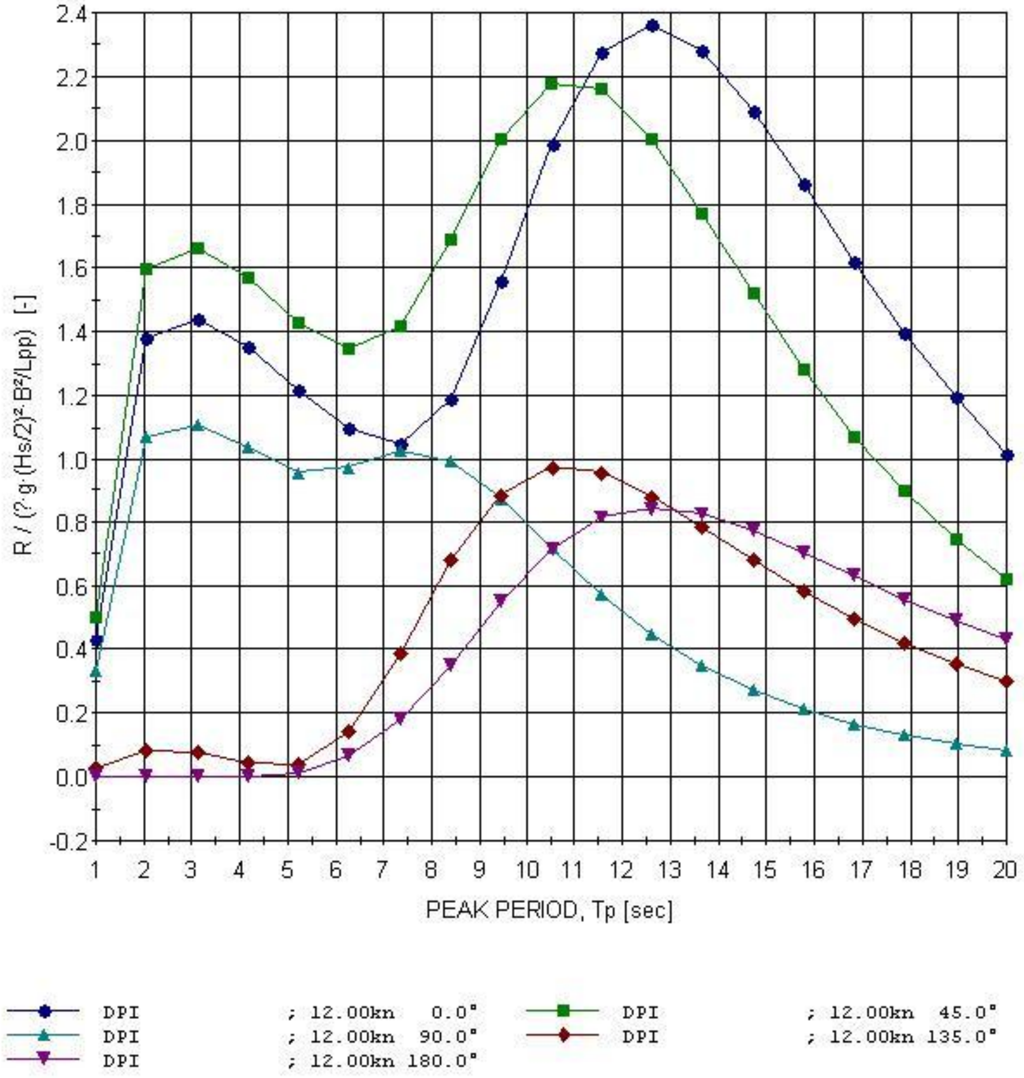
Project: DPI, T = 9 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:16:31 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	12 knots
DATE	2010-06-07
REF	T = 10 m

Mean added resistance (short term statistics)

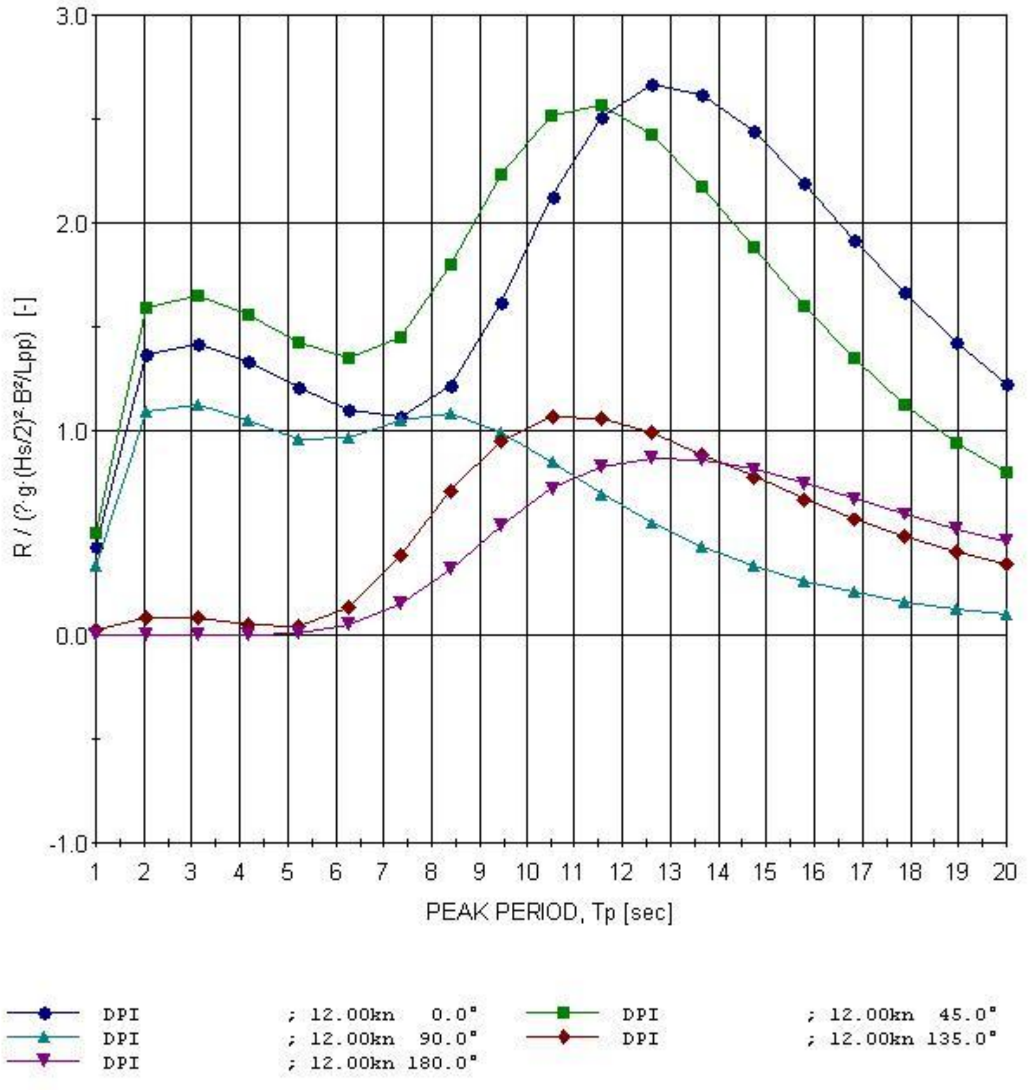


Project: DPI, T = 10 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:17:00 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	12 knots
	DATE	2010-06-07
	REF	T = 11 m

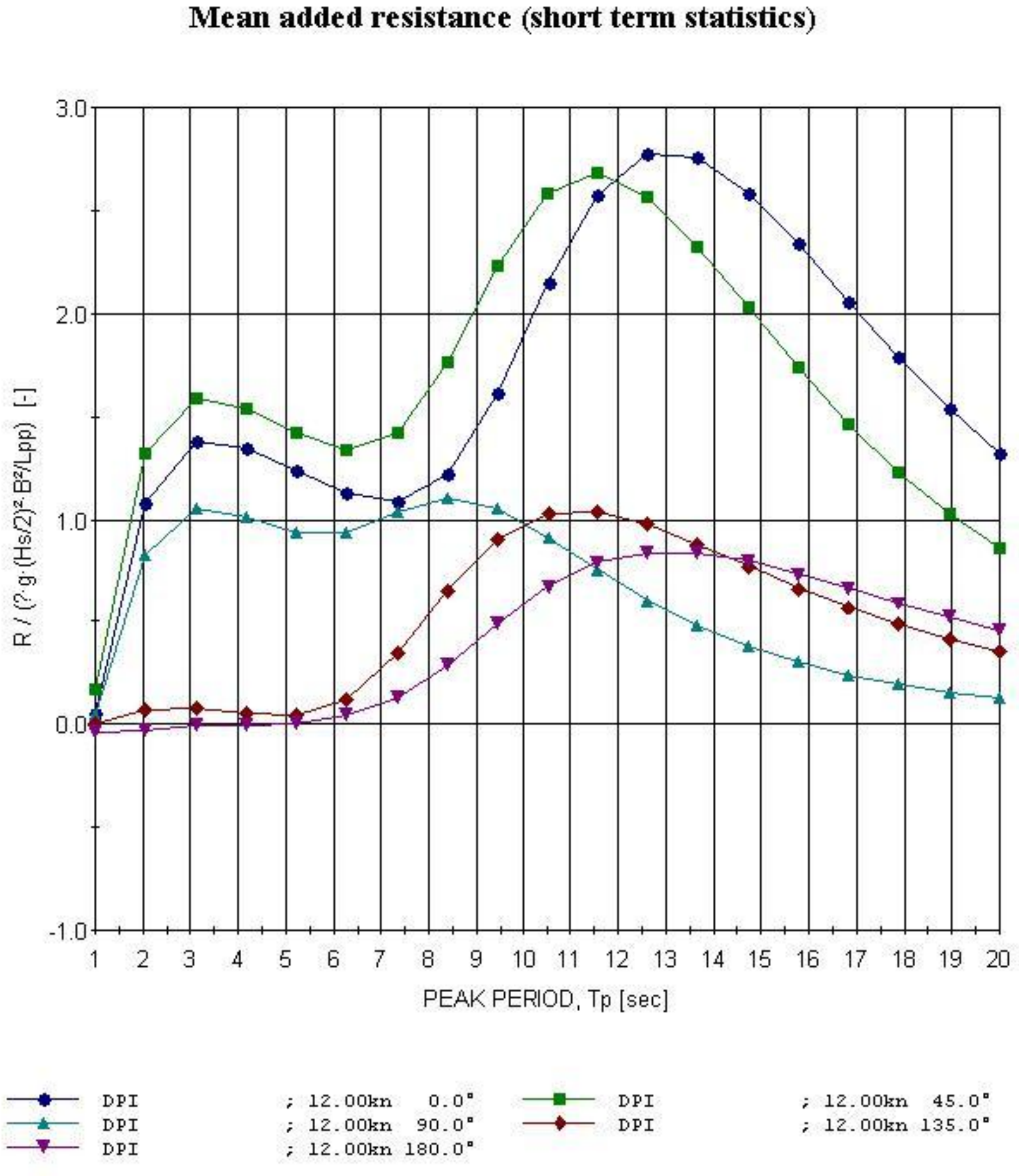
Mean added resistance (short term statistics)



Project: DPI, T = 11 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:17:26 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	12 knots
	DATE	2010-06-07
	REF	T = 11.8 m



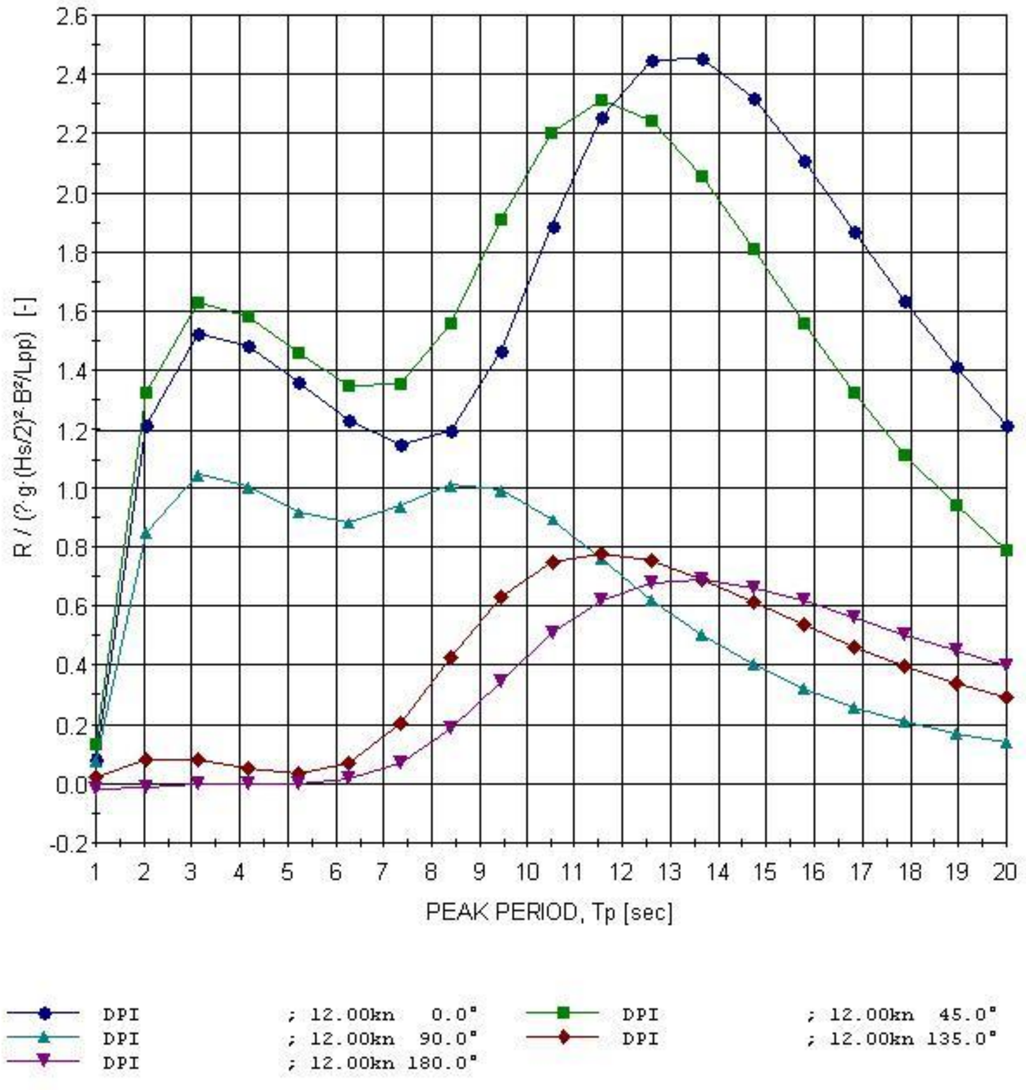
Project: DPI, T = 11.8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:17:47 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	12 knots
DATE	2010-06-07
REF	T = 13.5 m

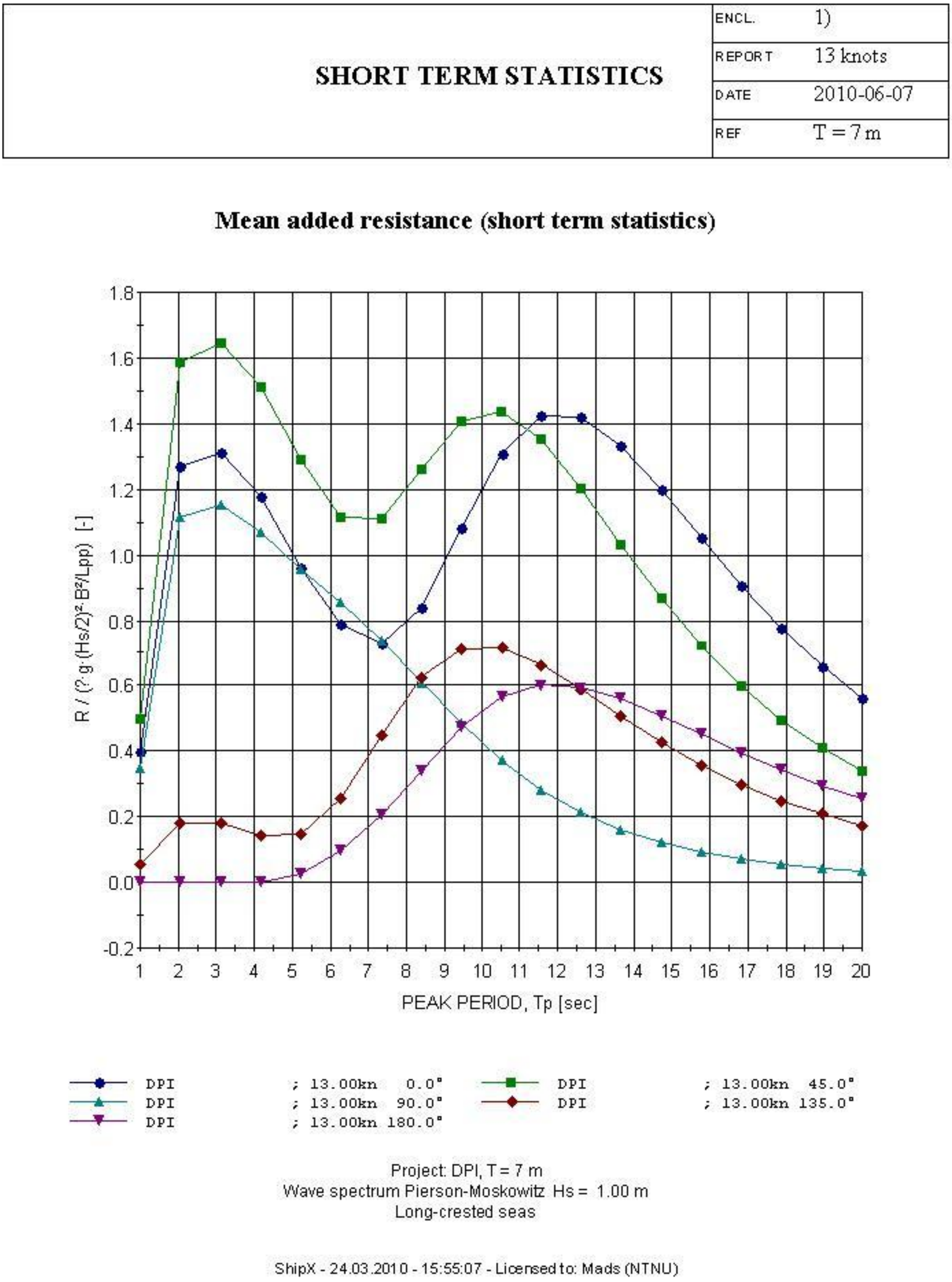
Mean added resistance (short term statistics)



Project: DPI, T = 13.5 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:18:16 - Licensed to: Mads (NTNU)

Appendix 9 - RAW coefficients, V = 13 knots



SHORT TERM STATISTICS		
	ENCL.	1)
	REPORT	13 knots
	DATE	2010-06-07
	REF	T = 7 m

Mean added resistance (short term statistics)

●	DPI	; 13.00kn 0.0°	■	DPI	; 13.00kn 45.0°
▲	DPI	; 13.00kn 90.0°	◆	DPI	; 13.00kn 135.0°
▼	DPI	; 13.00kn 180.0°			

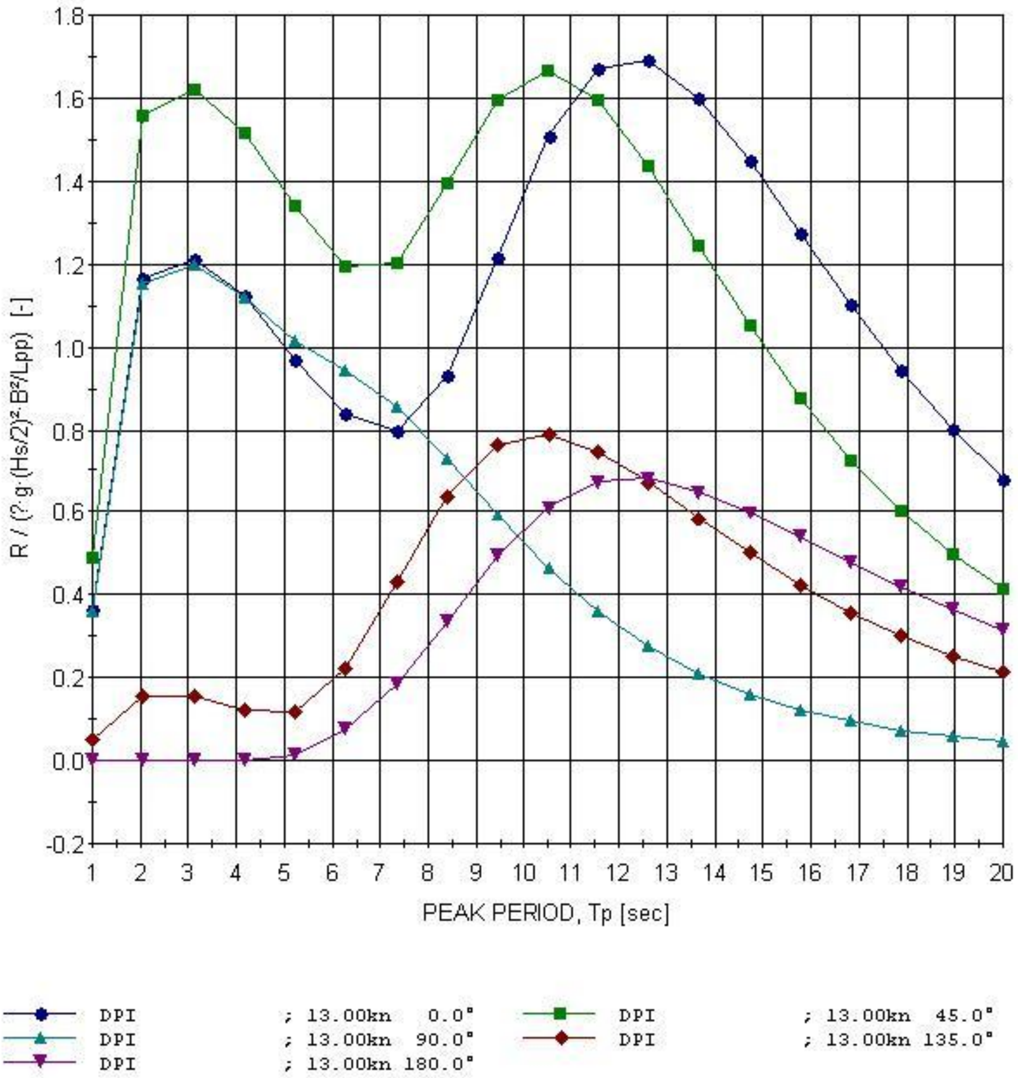
Project: DPI, T = 7 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 24.03.2010 - 15:55:07 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	13 knots
DATE	2010-06-07
REF	8 m

Mean added resistance (short term statistics)



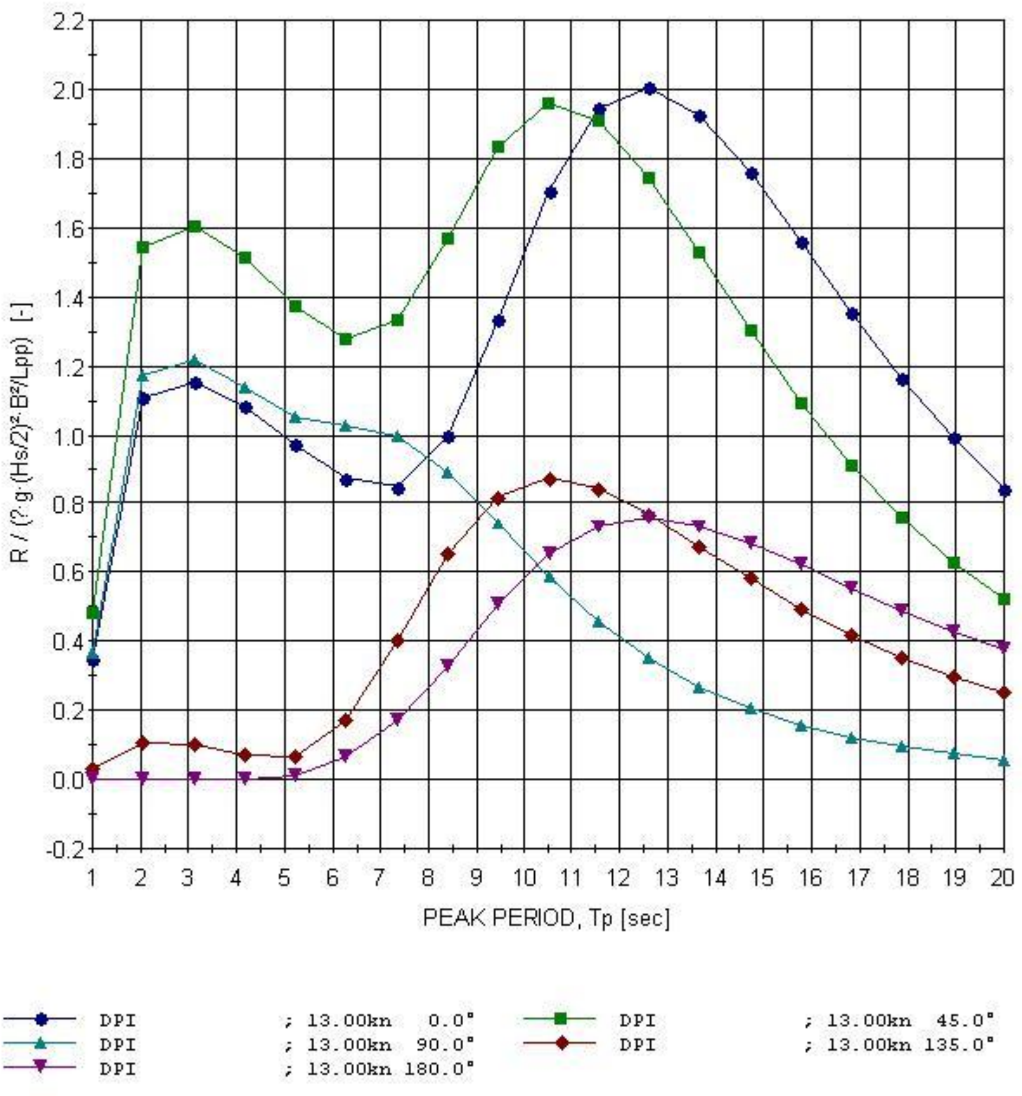
Project: DPI, T= 8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 24.03.2010 - 15:56:35 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	13 knots
DATE	2010-06-07
REF	9 m

Mean added resistance (short term statistics)

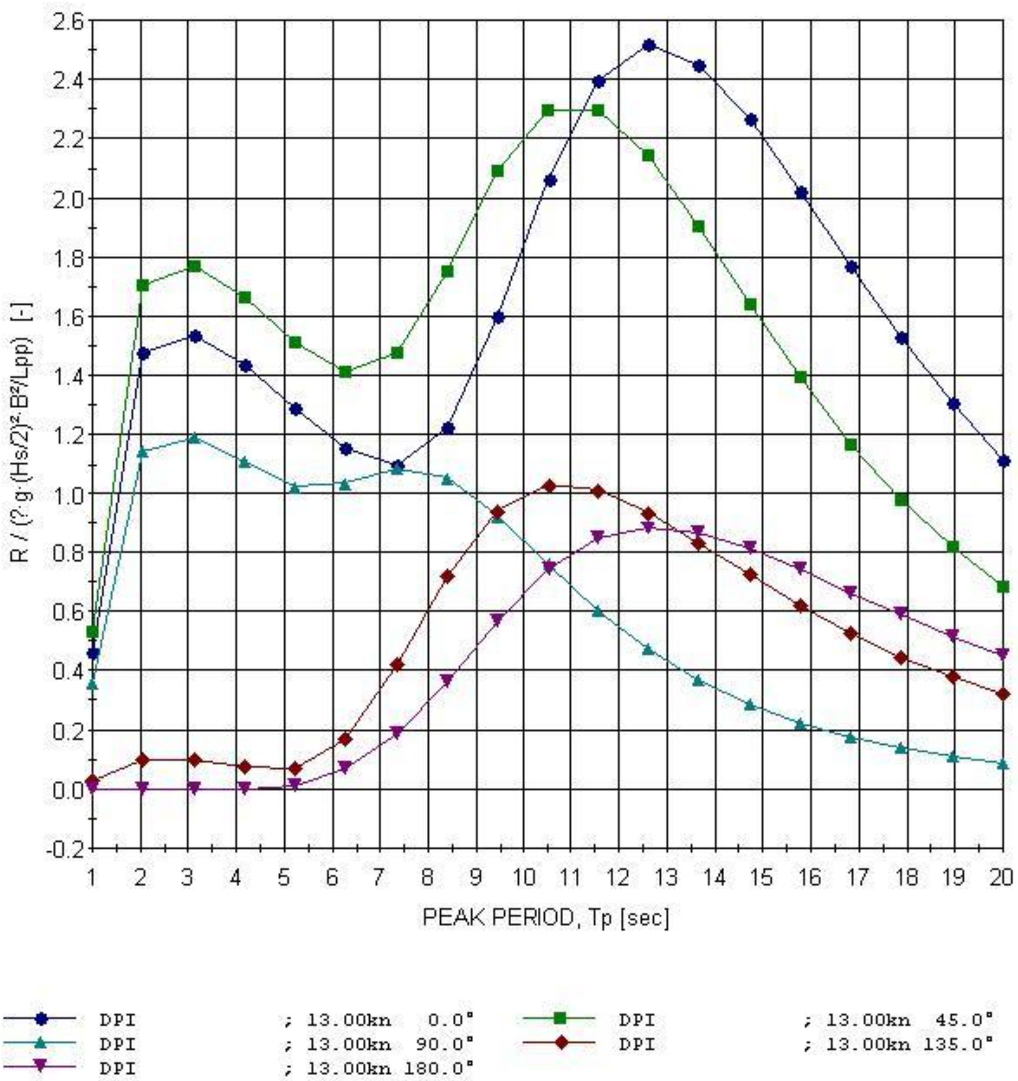


Project: DPI, T = 9 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 24.03.2010 - 15:58:00 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	13 knots
	DATE	2010-06-07
	REF	10 m

Mean added resistance (short term statistics)



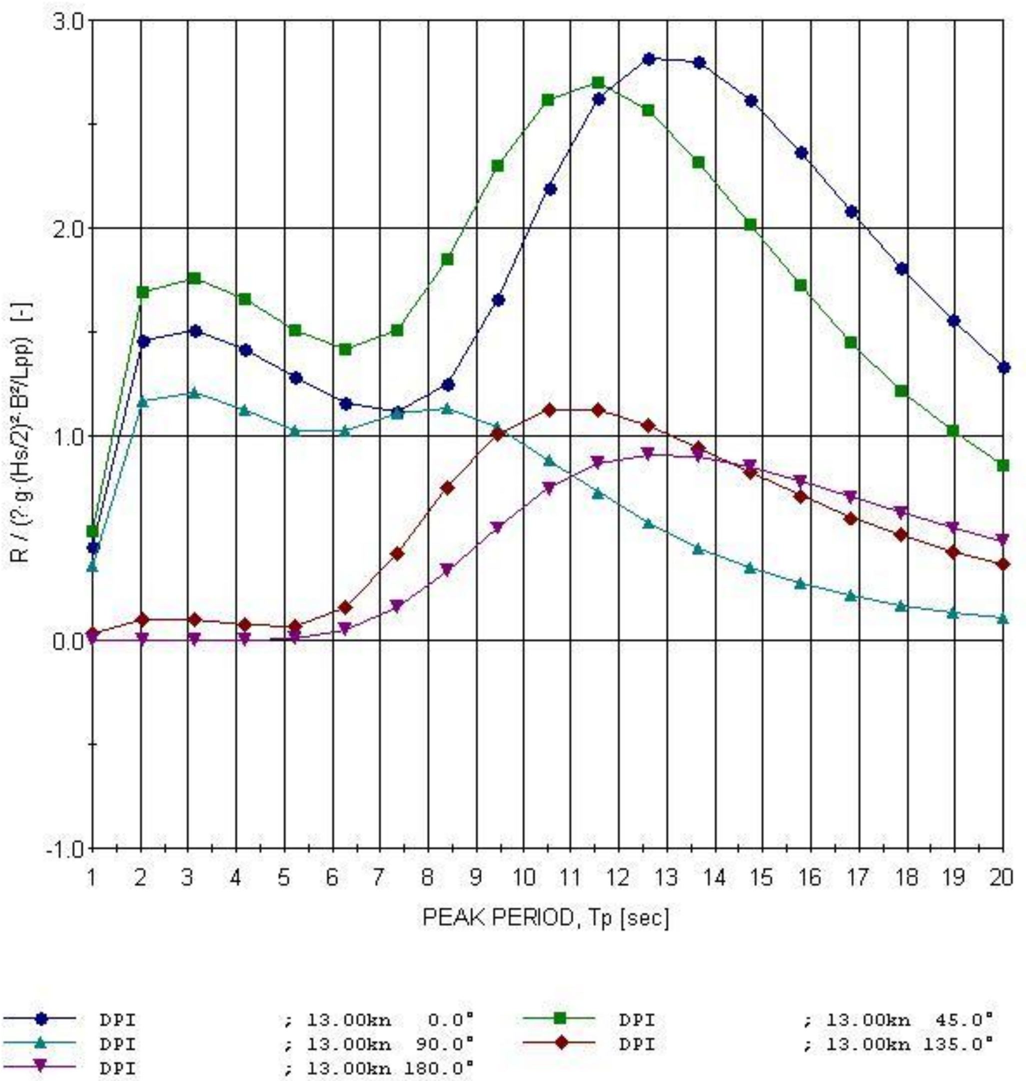
Project: DPI, T = 10 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 24.03.2010 - 16:10:17 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	13 knots
DATE	2010-06-07
REF	11 m

Mean added resistance (short term statistics)

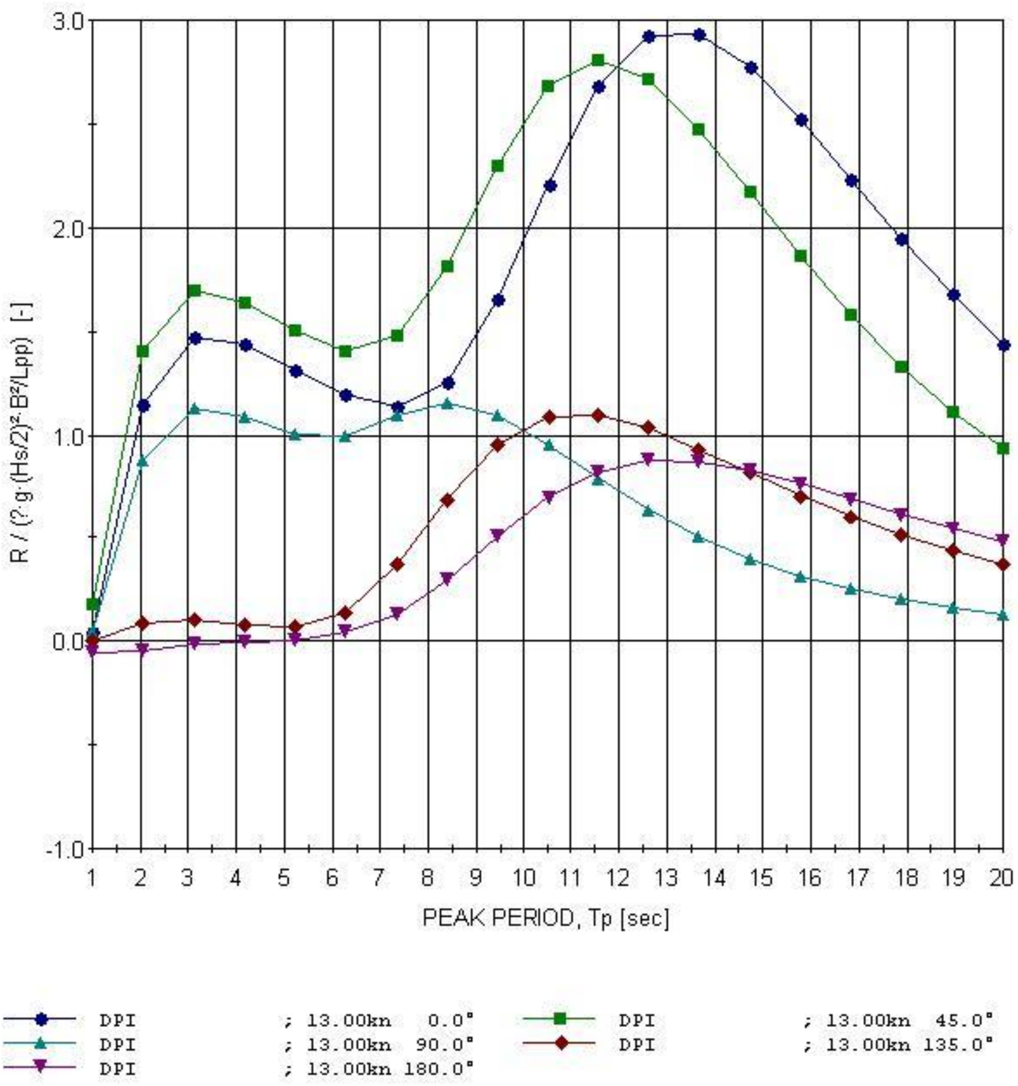


Project: DPI, T = 11 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 24.03.2010 - 16:10:57 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	13 knots
	DATE	2010-06-07
	REF	11.8 m

Mean added resistance (short term statistics)



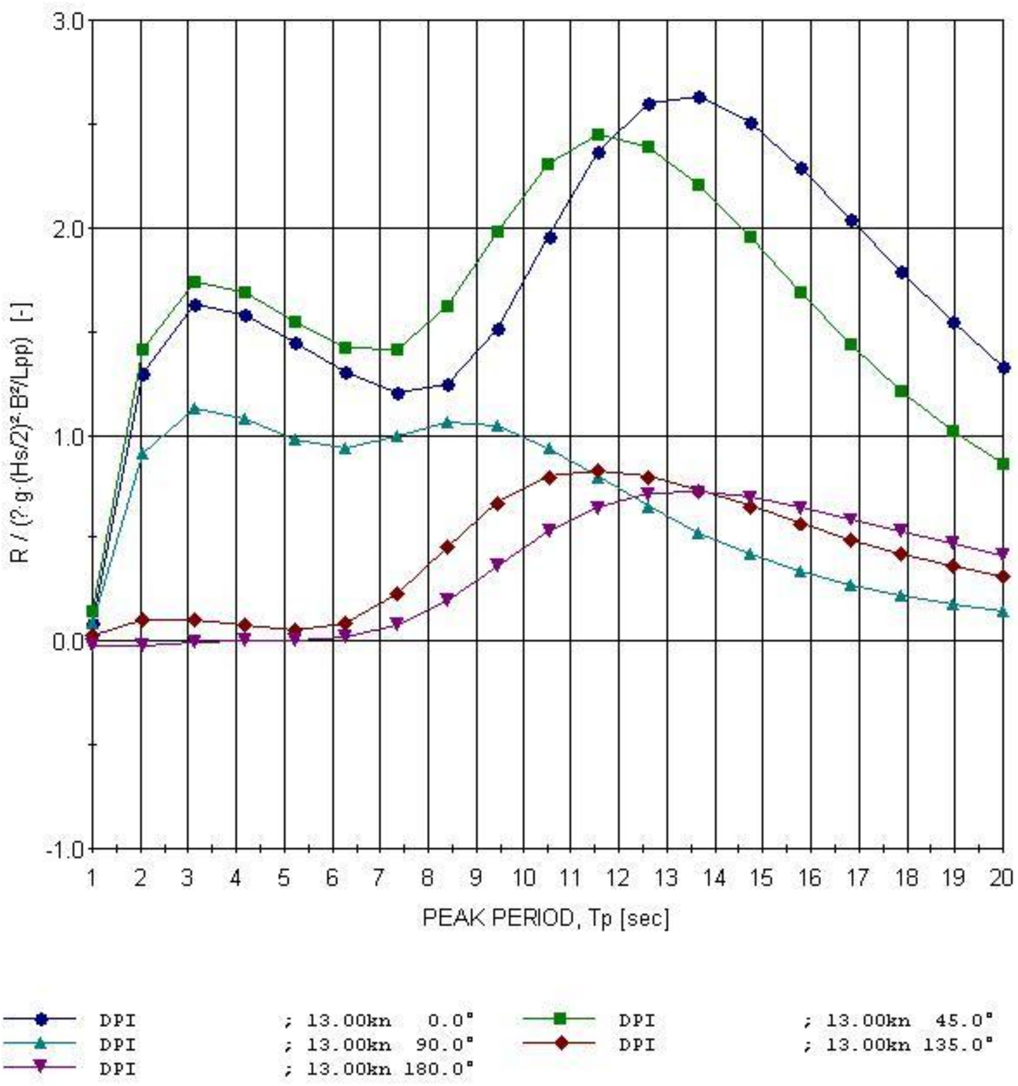
Project: DPI, T = 11.8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 24.03.2010 - 16:11:54 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	13 knots
DATE	2010-06-07
REF	13.5 m

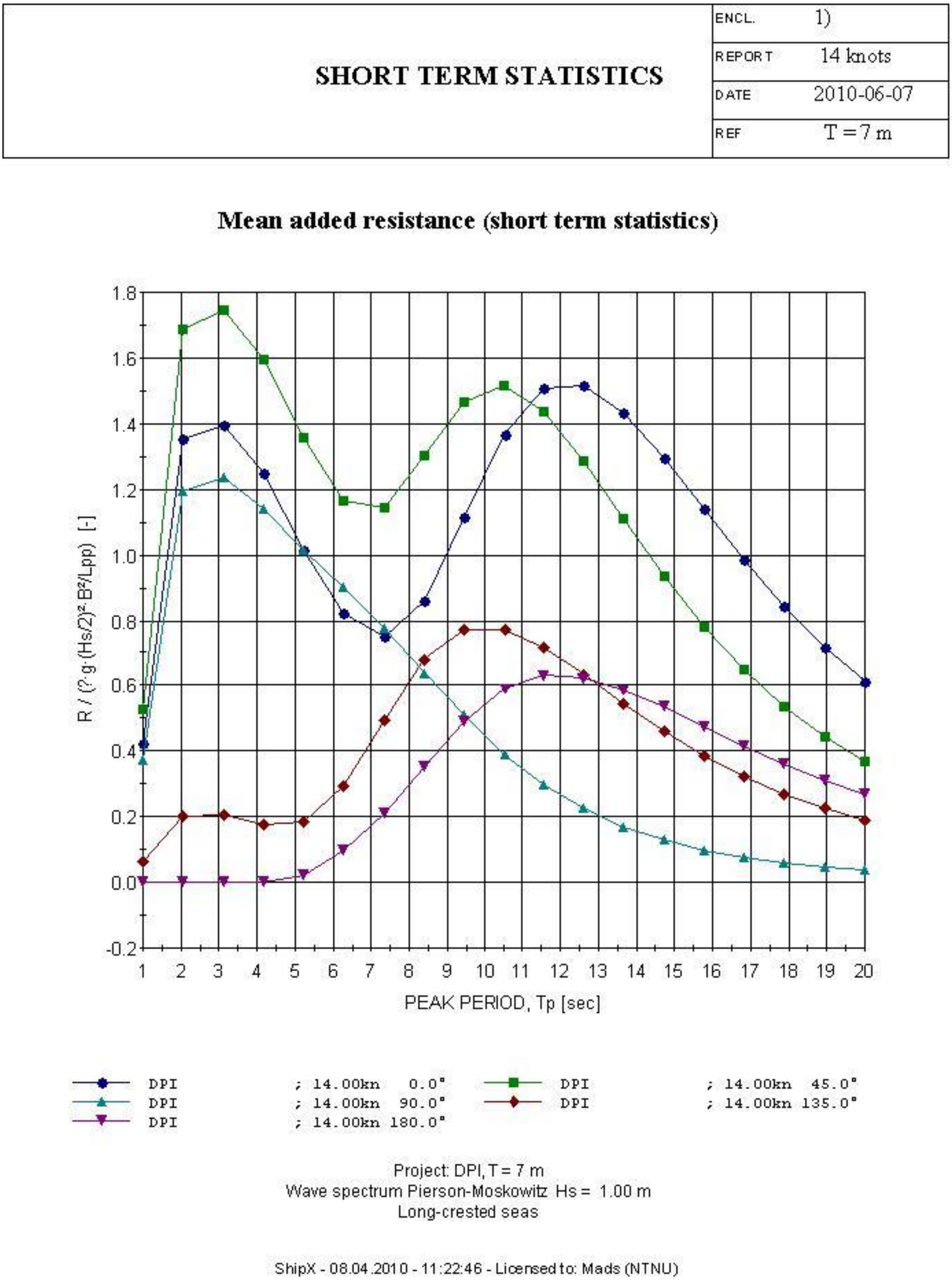
Mean added resistance (short term statistics)



Project: DPI, T = 13.5 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 24.03.2010 - 16:12:32 - Licensed to: Mads (NTNU)

Appendix 10 - RAW coefficients, V = 14 knots



SHORT TERM STATISTICS	ENCL.	1)
	REPORT	14 knots
	DATE	2010-06-07
	REF	T = 7 m

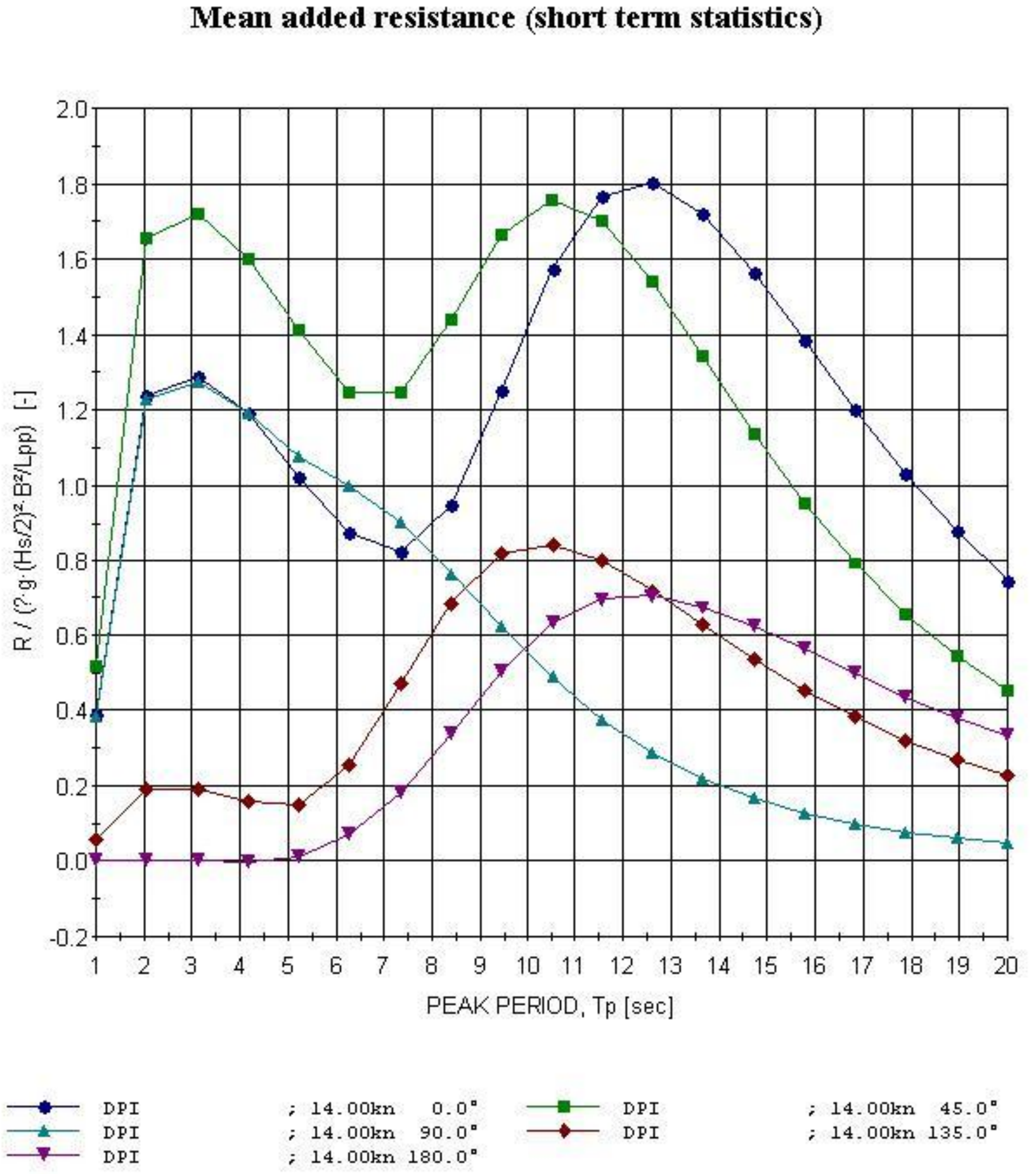
Mean added resistance (short term statistics)

DPI ; 14.00kn 0.0°
DPI ; 14.00kn 45.0°
DPI ; 14.00kn 90.0°
DPI ; 14.00kn 135.0°
DPI ; 14.00kn 180.0°

Project: DPI, T = 7 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:22:46 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	14 knots
	DATE	2010-06-07
	REF	T = 8 m

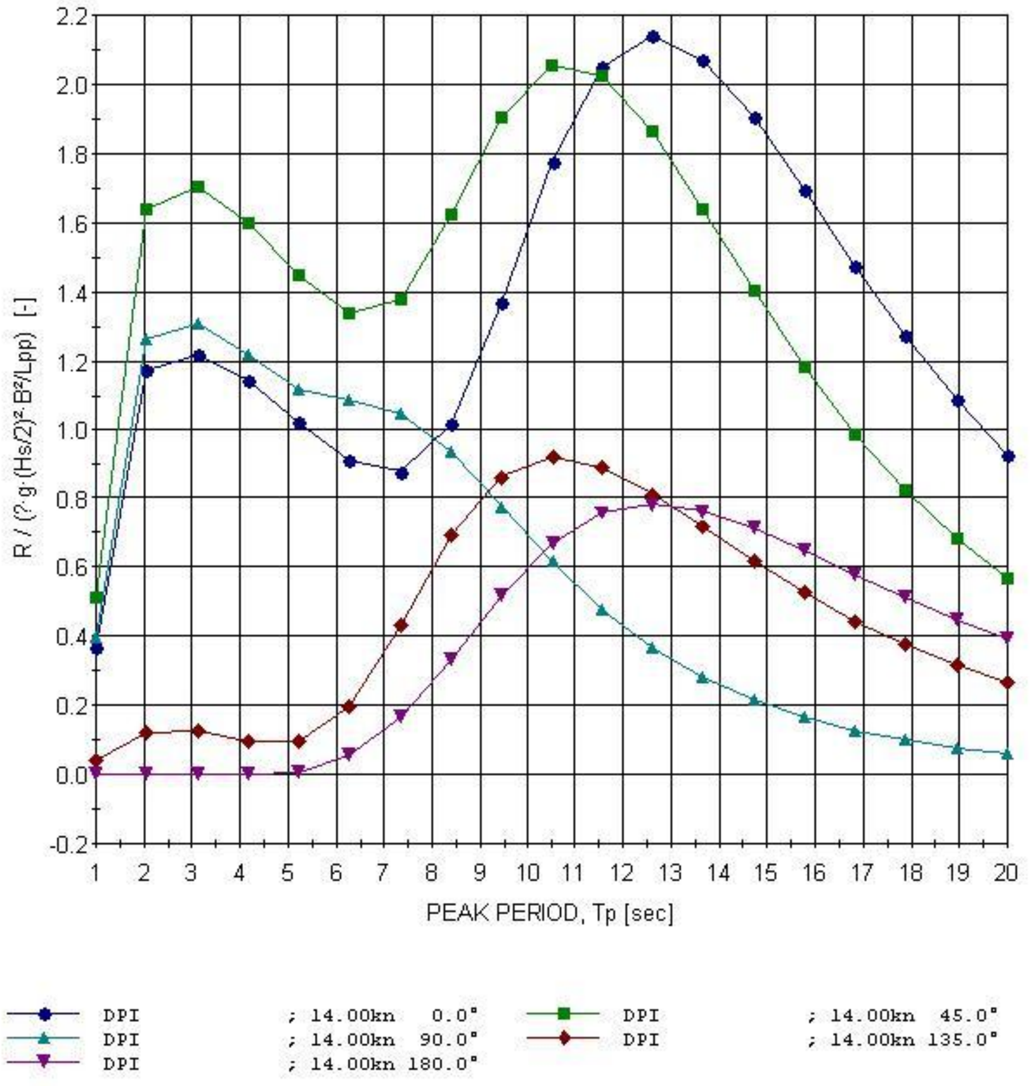


Project: DPI, T= 8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:23:09 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	14 knots
	DATE	2010-06-07
	REF	T = 9 m

Mean added resistance (short term statistics)

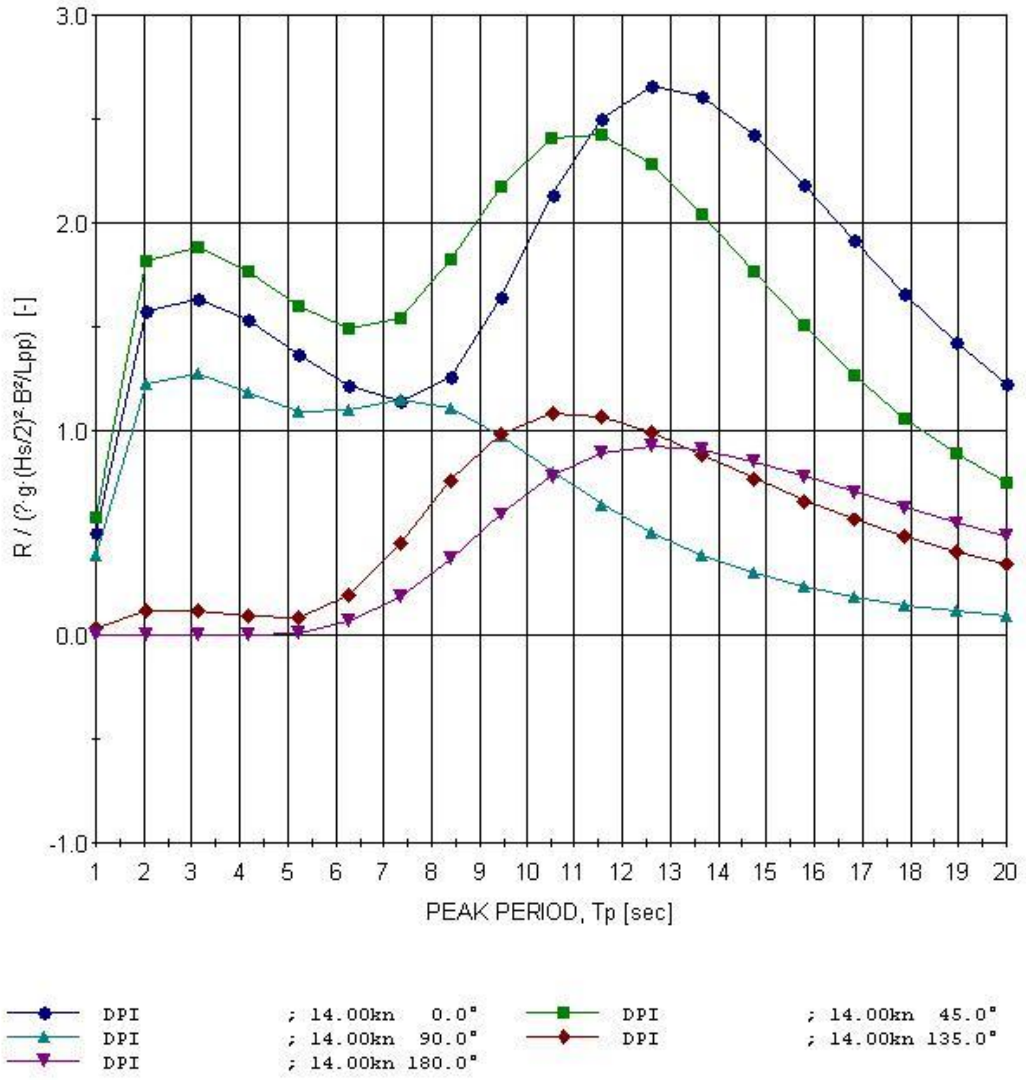


Project: DPI, T = 9 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:23:28 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	14 knots
	DATE	2010-06-07
	REF	T = 10 m

Mean added resistance (short term statistics)

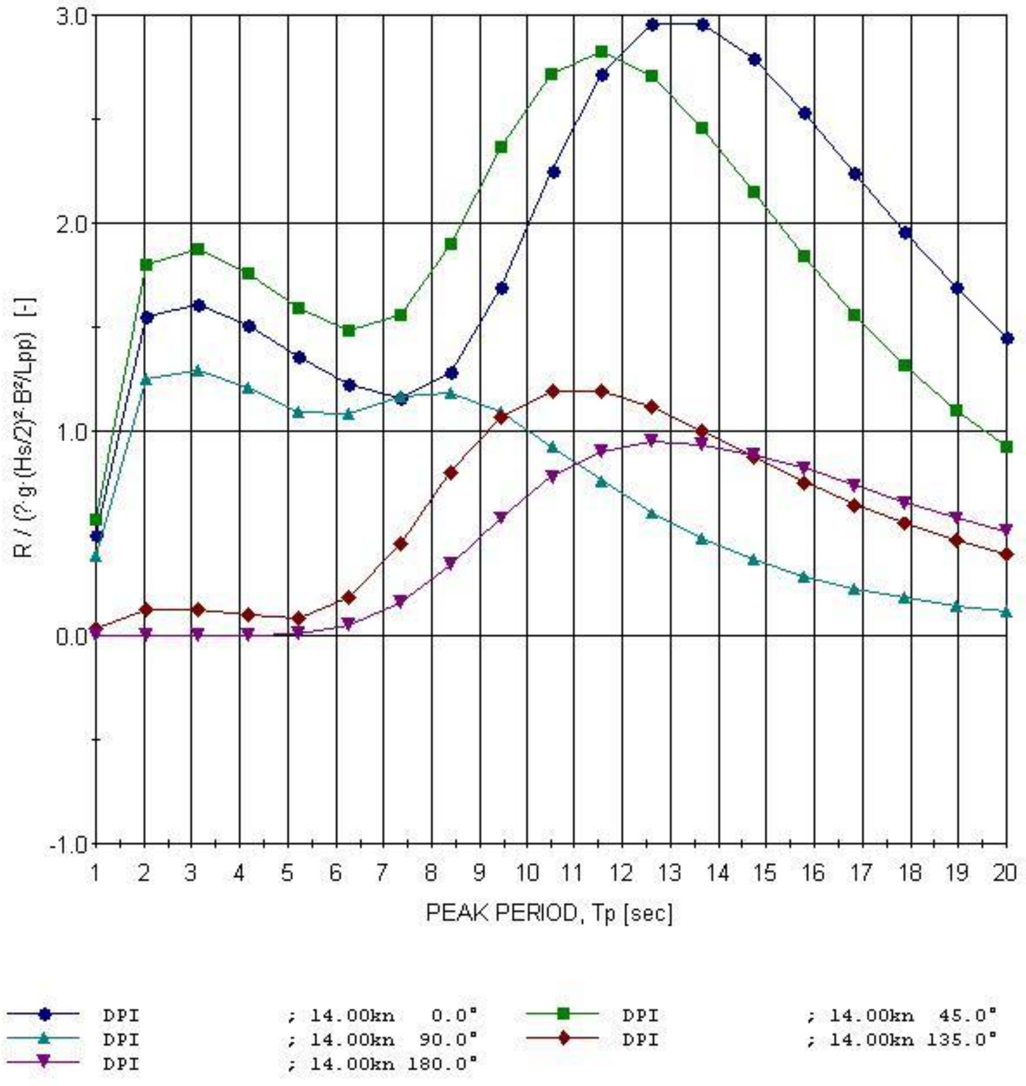


Project: DPI, T = 10 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:24:01 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	14 knots
	DATE	2010-06-07
	REF	T = 11 m

Mean added resistance (short term statistics)



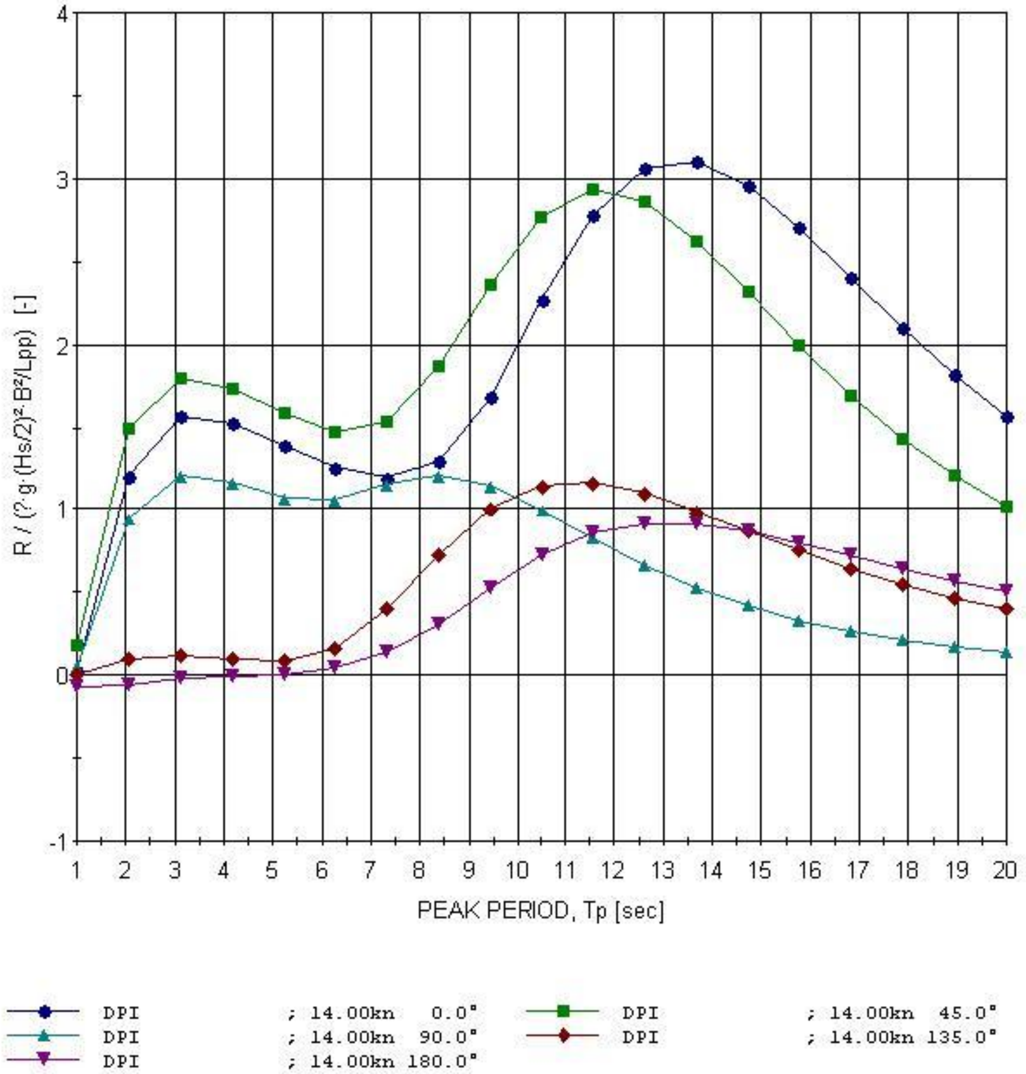
Project: DPI, T = 11 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:24:21 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	14 knots
DATE	2010-06-07
REF	T = 11.8 m

Mean added resistance (short term statistics)



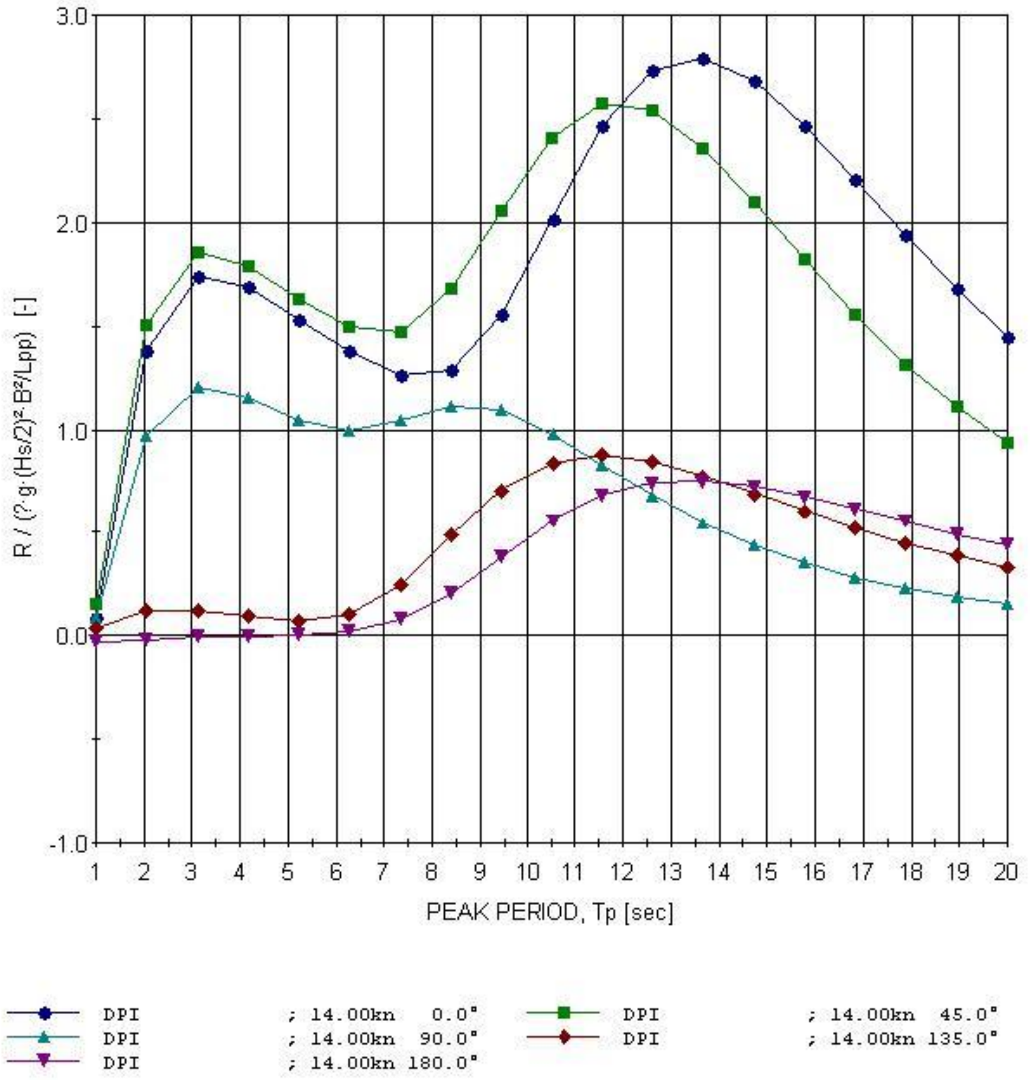
Project: DPI, T = 11.8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:24:51 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	14 knots
DATE	2010-06-07
REF	T = 13.5 m

Mean added resistance (short term statistics)



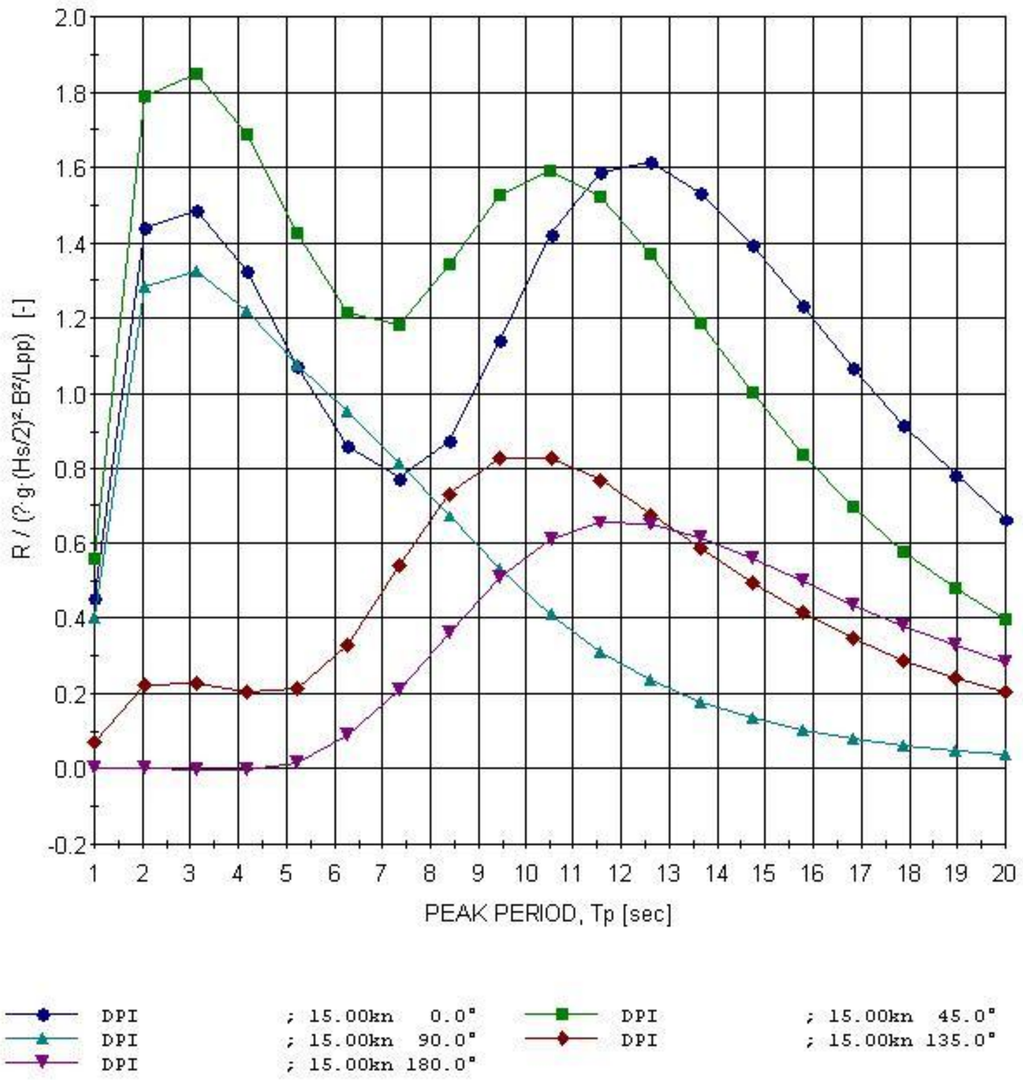
Project: DPI, T = 13.5 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:25:16 - Licensed to: Mads (NTNU)

Appendix 11 - RAW coefficients, V = 15 knots

SHORT TERM STATISTICS		
	ENCL.	1)
	REPORT	15 knots
	DATE	2010-06-07
	REF	T = 7 m

Mean added resistance (short term statistics)



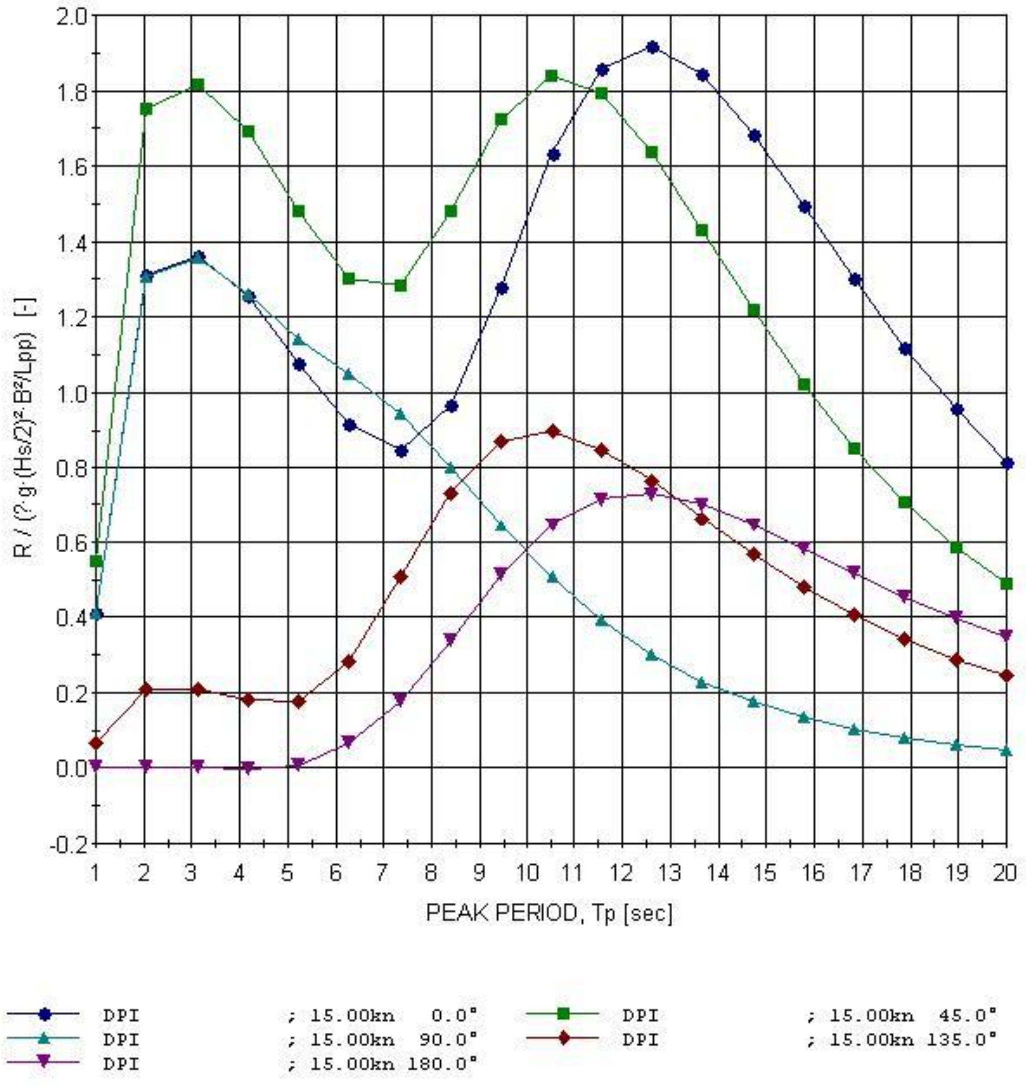
Project: DPI, T = 7 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:28:05 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL.	1)
REPORT	15 knots
DATE	2010-06-07
REF	T = 8 m

Mean added resistance (short term statistics)

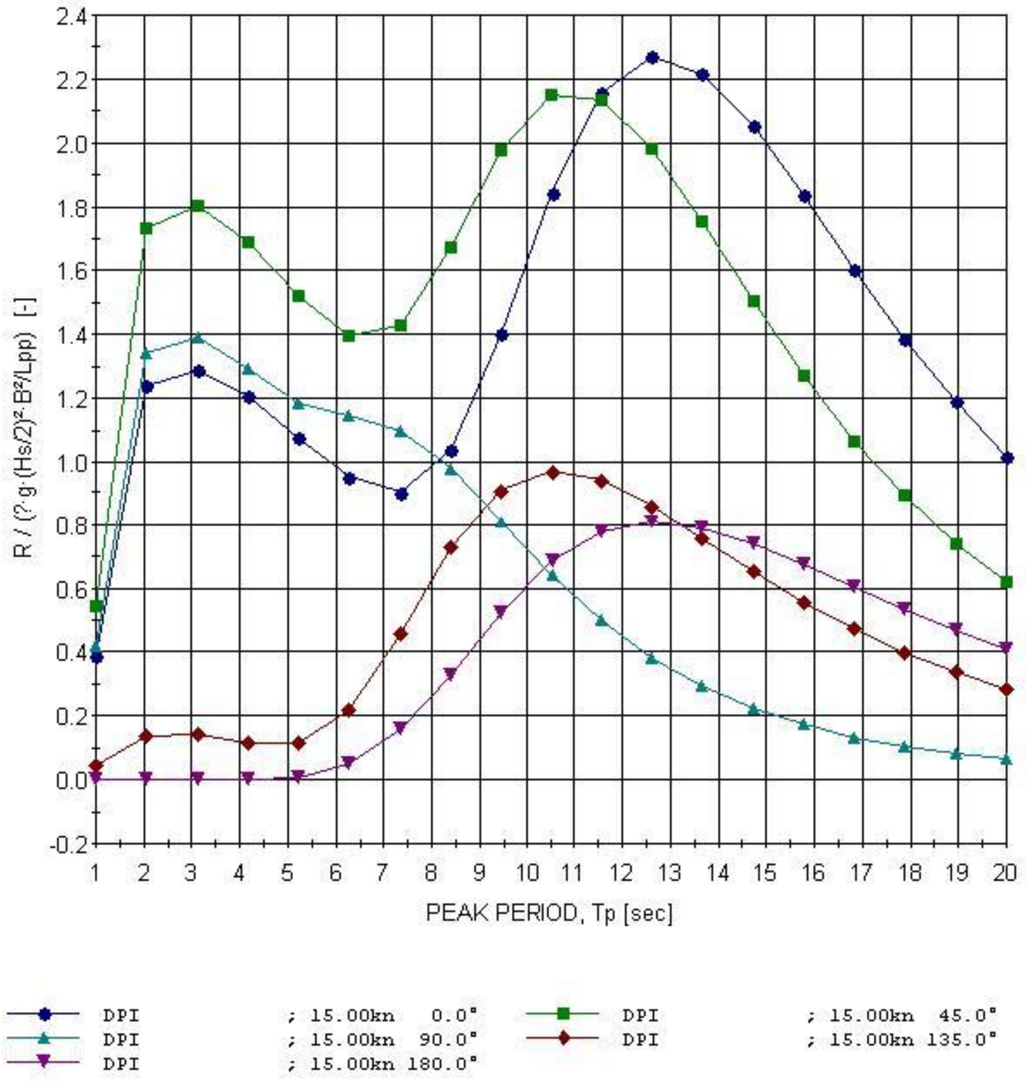


Project: DPI, T= 8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:28:27 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	15 knots
	DATE	2010-06-07
	REF	T = 9 m

Mean added resistance (short term statistics)



Project: DPI, T = 9 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

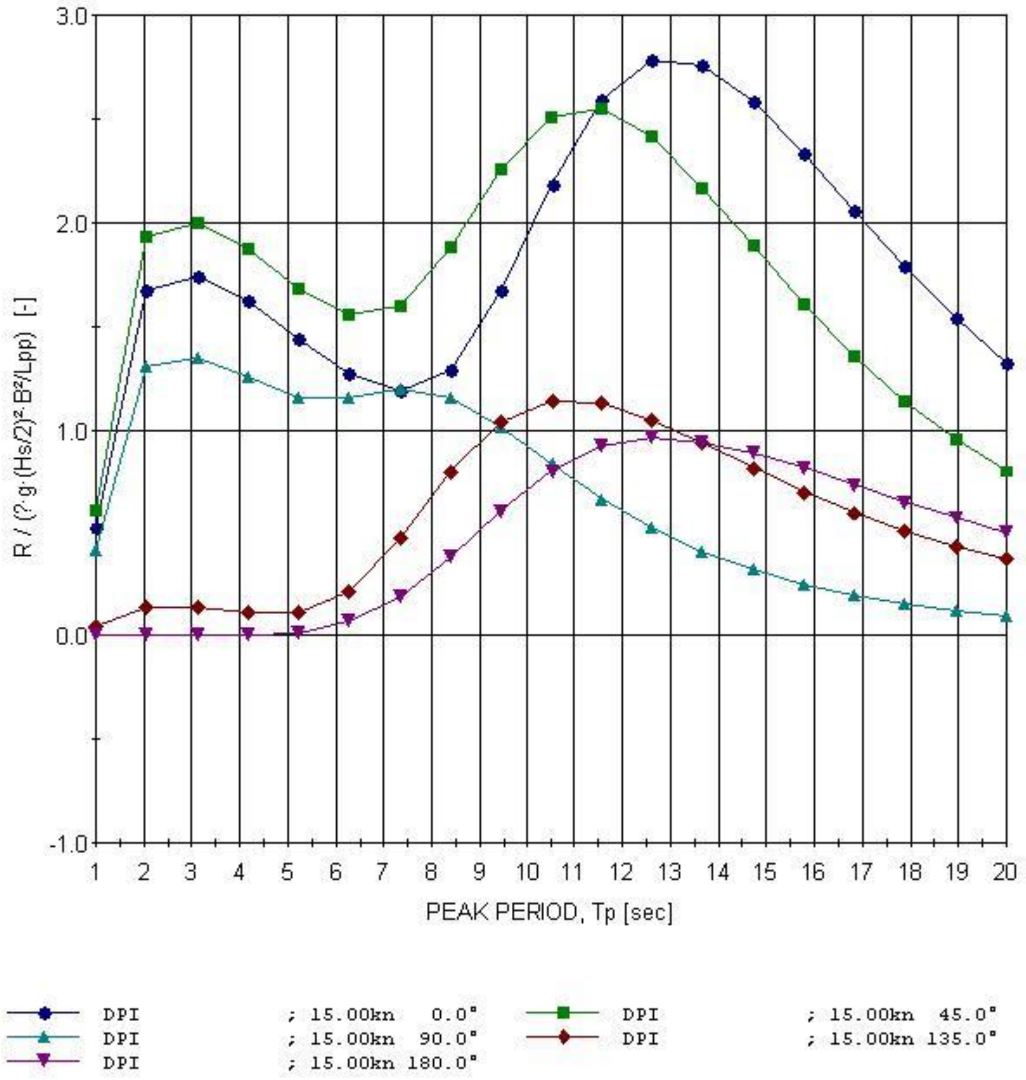
ShipX - 08.04.2010 - 11:28:56 - Licensed to: Mads (NTNU)

Appendix 11 - RAW coefficients, V = 15 knots

SHORT TERM STATISTICS

ENCL.	1)
REPORT	15 knots
DATE	2010-06-07
REF	T = 10 m

Mean added resistance (short term statistics)

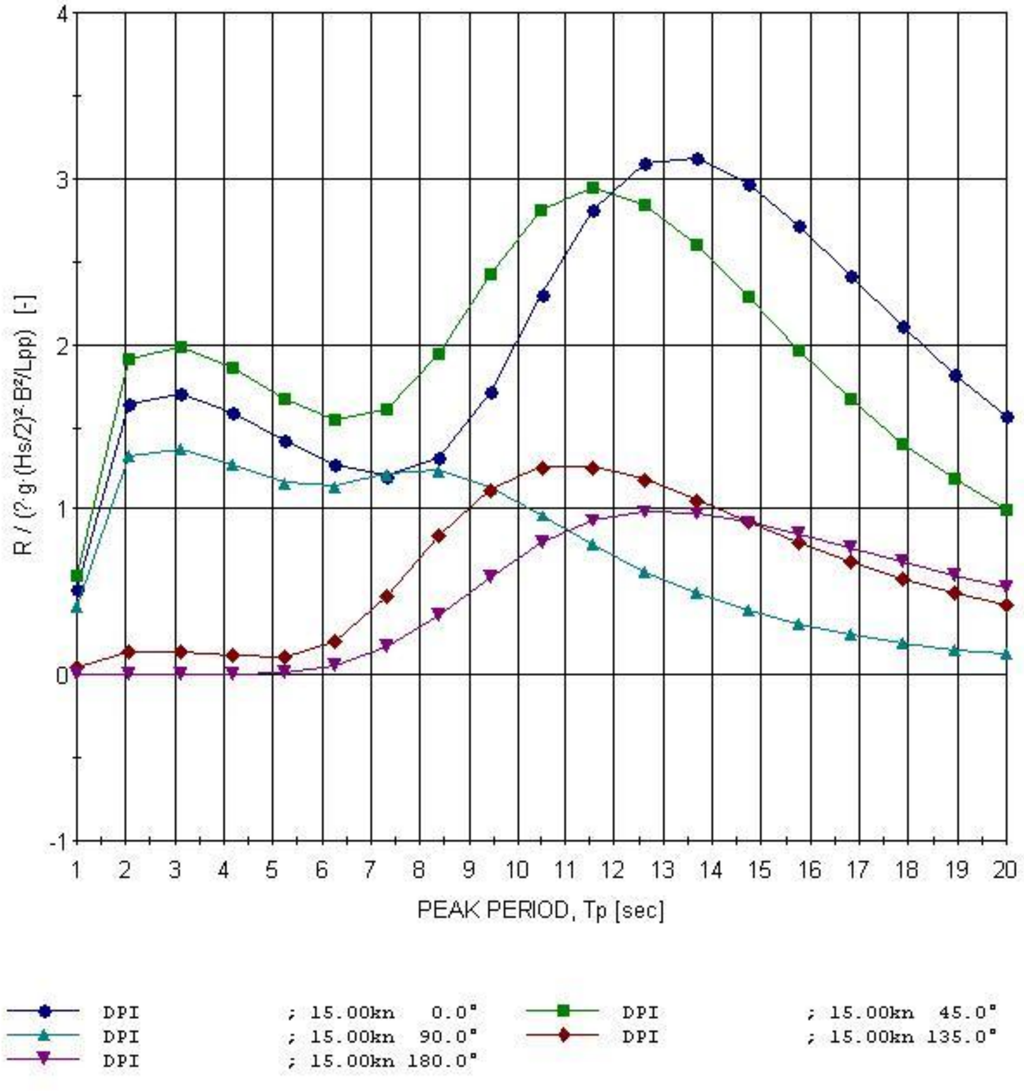


Project: DPI, T = 10 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:29:20 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS		
	ENCL.	1)
	REPORT	15 knots
	DATE	2010-06-07
	REF	T = 11 m

Mean added resistance (short term statistics)

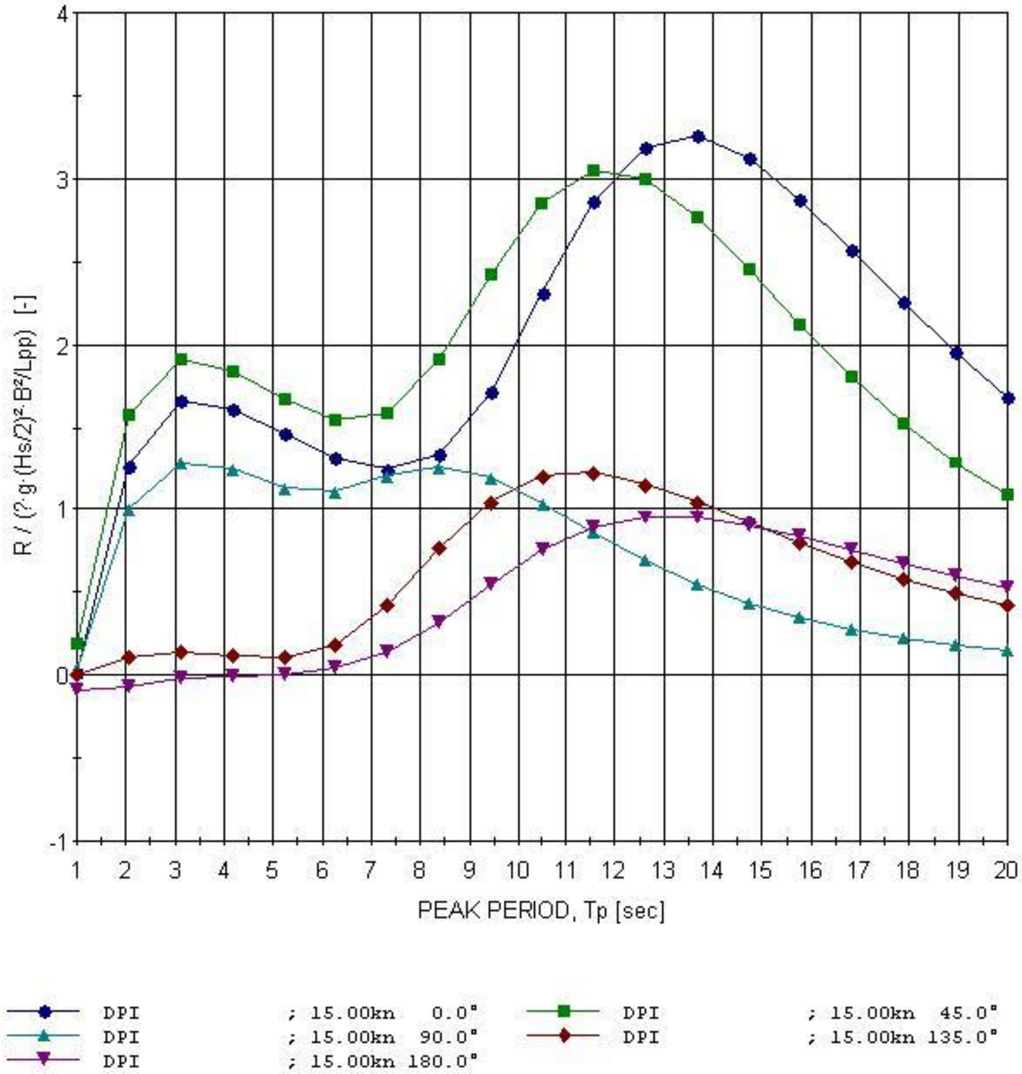


Project: DPI, T = 11 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:29:44 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS	ENCL.	1)
	REPORT	15 knots
	DATE	2010-06-07
	REF	T = 11.8 m

Mean added resistance (short term statistics)



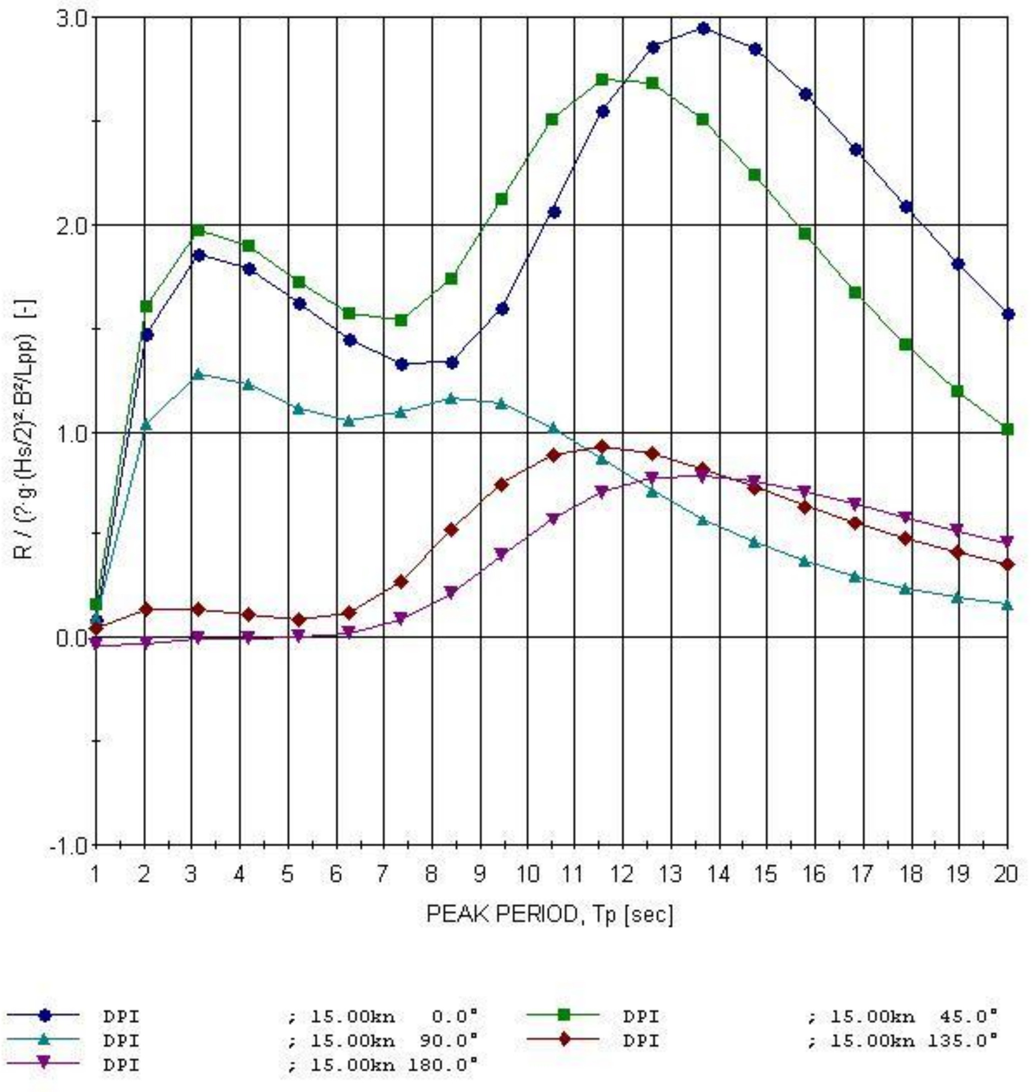
Project: DPI, T = 11.8 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:30:07 - Licensed to: Mads (NTNU)

SHORT TERM STATISTICS

ENCL. 1)
REPORT 15 knots
DATE 2010-06-07
REF T = 13.5 m

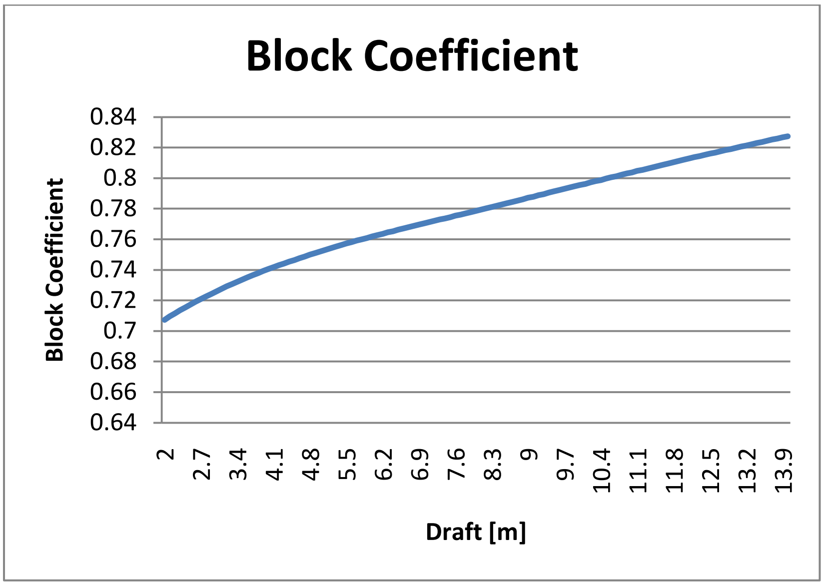
Mean added resistance (short term statistics)

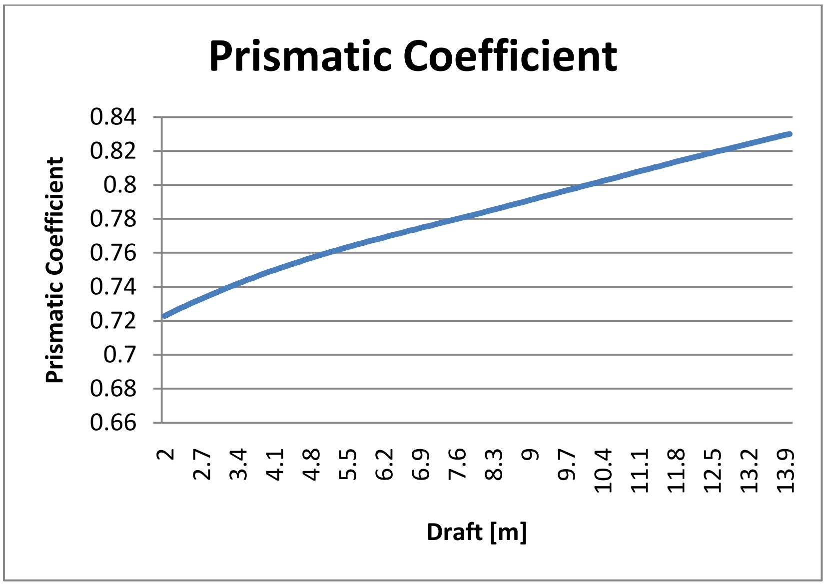


Project: DPI, T = 13.5 m
Wave spectrum Pierson-Moskowitz Hs = 1.00 m
Long-crested seas

ShipX - 08.04.2010 - 11:30:29 - Licensed to: Mads (NTNU)

Appendix 12 - C_B and C_P





Appendix 13 - CD with the complete thesis

The CD contains:

- Master thesis in pdf format
- The Excel spreadsheet for calculations
- Excel spreadsheet for digitalizing the ship to 3D
- The ShipX database