



DIVISION SAFETY AND
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Case study: IMO minimum propulsion
power to maintain the manoeuvrability of
KVLCC2 tanker in adverse conditions

Frederik Gerhardt

RISE Report : 2024:18

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Abstract

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In order to reduce greenhouse gas emissions, the International Maritime Organization (IMO) has passed a resolution on the Energy Efficiency Design Index (EEDI). The index is a measure of the amount of carbon dioxide a ship emits in relation to its transport work. It is required that most newbuilds have an EEDI smaller than a prescribed value, which in turn is based on statistics and will gradually be lowered over time.

One obvious way to reduce CO₂ emissions is “slow steaming” and the installation of a smaller engine. To avoid vessels becoming underpowered and thus unsafe, the IMO has implemented rules regarding the “Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions”. IMO “Interim Guideline” MEPC.1/Circ.850/Rev.3 outlines the details of how to determine this “Minimum power”.

Using the well know KVLCC2 tanker as an example the current report presents a case study that follows the latest IMO-Rev.3 guideline step by step. Results from the simple Level 1 assessment from the IMO-guideline as well as the more advanced Level 2 assessment are shown and discussed. Some issues and apparent inconsistencies in the IMO guideline are discussed at the end of the report.

Key words: Energy Efficiency Design Index (EEDI), Minimum Propulsion Power, Adverse Conditions, slow steaming, KVLCC2

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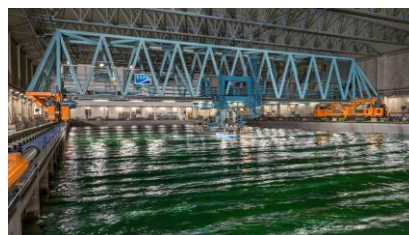
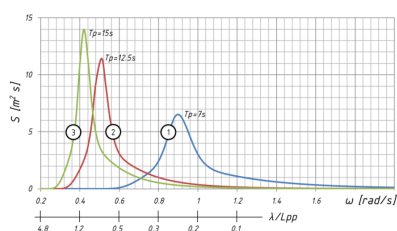
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Summary

The introduction of the EEDI more than a decade ago, slow steaming, and the wish to reduce bunkering costs have resulted in a trend to install less powerful engines in ships. To avoid vessels becoming underpowered and thus unsafe, the International Maritime Organization (IMO) has published a guideline regarding the “Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions”.

This report presents a case study that follows the IMO-guideline step by step and works out the minimum engine size for the KVLCC2 tanker. Using a combination of Computational Fluid Dynamics and model tests, the parameters and assumptions behind the guideline are discussed in some detail. Results show that it is particularly important to determine the added resistance in waves correctly because it dominates the power prediction. It becomes clear, that the selection of the propulsive factors, particularly the “thrust deduction factor” has a significant influence on results.

The work summarised here is part of a wider project that aims to provide experimental benchmarking data for added resistance predictions. It has been sponsored by the Swedish Transport Administration (Trafikverket) under grant number TRV 2021/53938.

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1 Introduction

In order to reduce greenhouse gas emissions, the International Maritime Organization (IMO) has passed a resolution on the Energy Efficiency Design Index (EEDI). The index is a measure of the amount of carbon dioxide a ship emits in relation to its transport work. It is required that most newbuilds have an EEDI smaller than a prescribed value, which in turn is based on statistics and will gradually be lowered over time.

One obvious way to reduce CO₂ emissions is “slow steaming” and the installation of a smaller engine. To avoid vessels becoming underpowered and thus unsafe, the IMO has implemented rules regarding the “Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions”. An IMO “Interim Guideline” first published in 2013 outlines the details of how to determine this “Minimum power”.

In 2017, suggestions for modification of the resolutions on minimum power were submitted to IMO as a result of two research projects, SHOPERA (European Union) and JASNAOE (Japan), [1]. These proposals were later criticised, i.a. for limiting the possibilities for hydrodynamic design improvements and for being too conservative.

Subsequent discussions within IMO did not result in consensus and it was therefore recommended that a slightly modified “Interim Guideline” be kept and published as MEPC.1/Circ.850/Rev.2 [2].

In June 2021 IMO’s Marine Environment Protection Committee, at its seventy-sixth session approved amendments to the Interim Guidelines and published these as MEPC.1/Circ.850/Rev.3 [3]. The most significant change from Rev.2 to Rev.3 is dropping the required speed for safe manoeuvring from in between 4 and 9 knots (depending on relative size of the rudder) to just 2 knots, while simultaneously prescribing slightly harsher weather conditions.

The current report presents a case study that follows the latest IMO-Rev.3 guideline step by step and works out the minimum engine size for the KVLCC2 tanker.

A similar exercise has previously been carried out for the (now superseded) Rev.2 guideline and was published in 2020 as [4].

2 Notation

A_R	Rudder Area (m ²)
A_{FW}	Frontal wind area (m ²)
A_{LW}	Lateral wind area (m ²)
B	Beam of hull (m)
C_{AW}	Added resistance coefficient (-)
C_F	Frictional resistance coefficient (-)
D	Propeller diameter (m)
$D(\mu)$	Wave energy spreading function
DWT	Deadweight (t)
H_s	Significant wave height (m)
IMO	International Maritime Organisation
J	Advance ratio of propeller (-)
K_T	Thrust coefficient of propeller (-)
K_Q	Torque coefficient of propeller (-)
k	Form factor (-)
k_{yy}	Pitch gyradius (m)
L_{pp}	Length between perpendiculars (m)
n	Rate of revolution (1/s)
$P_{D \min}$	Minimum Propulsion Power (W)
RANSE	Reynolds Averaged Navier Stokes Eq.
R_{AW}	Added resistance in waves (N)
R_{CW}	Calm water resistance (N)
R_{air}	Air/wind resistance (N)
rpm	Rate of revolution (1/min)
S	Wetted surface area (m ²)
MCR	Maximum continuous rating (W)
T	Draft (m)
T_p	Spectral peak (modal) period (s)
t	Thrust deduction factor (-)
V_s	Required ship speed (m/s or knots)
V_w	Mean wind speed (m/s)
w	Wake fraction coefficient
ζ_A	Wave amplitude (m)
μ, μ'	angle between ship speed vector and waves, direction of wave component
∇	Volume displacement (m ³)
ρ	Density of sea water (kg/ m ³)

3 The IMO Guideline

The minimum power requirements from IMO guideline MEPC.1/Circ.850/Rev.3 [3] (for simplicity 'The IMO-guideline' for the rest of this report) currently apply to all new tankers, bulk carriers and combination carriers required to comply with regulations on energy efficiency for ships according to regulation 21 of MARPOL Annex VI. However, the guidelines should not be applied to ships with non-conventional propulsion systems, such as pod propulsion. The guidelines are intended for ships in unrestricted navigation and are applied in the maximum summer load condition.

3.1 Two assessment levels

The IMO-guideline presently gives two alternative methods to determine minimum propulsion power. Firstly, a "Level 1 assessment" using generic "minimum power lines" and secondly a "Level 2 assessment" that is based on individually calculating ship resistance components which are then used as input to a power prediction.

3.1.1 Level 1 assessment

The "minimum power line" method is simple, conservative, and based on installed power of existing ships. It uses deadweight and ship type as the only input. Minimum power is calculated as:

$$P_{D \min} = a \cdot DWT + b$$

Where *DWT* is the deadweight of the ship in metric tons and *a* and *b* are taken from the table below:

Table 1: Parameters *a* and *b*

Ship type	a [kW/t]	b [kW]
Bulk carrier DWT < 145 000 t	0.0763	3374.3
Bulk carrier DWT ≥ 145 000 t	0.0490	7329.0
Tankers and combination carriers	0.0652	5960.2

3.1.2 Level 2 assessment

The second method is more advanced and based on the solution of a one degree-of-freedom manoeuvring equation in longitudinal direction to demonstrate that the ship can move with the speed of 2.0 knots through water in wind and wave directions from head to 30 degrees off-bow for a situation of weather vaning.

The assessment assumes relatively harsh weather conditions (6m waves) for ships above 250 m and somewhat milder conditions for smaller ships, compare section 5.1.

The main part of the assessment procedure involves a speed-power prediction in wind and waves and requires detailed knowledge of the various resistance components, namely calm water, wind, and added wave resistance. Figure 1 illustrates the assessment schematically.

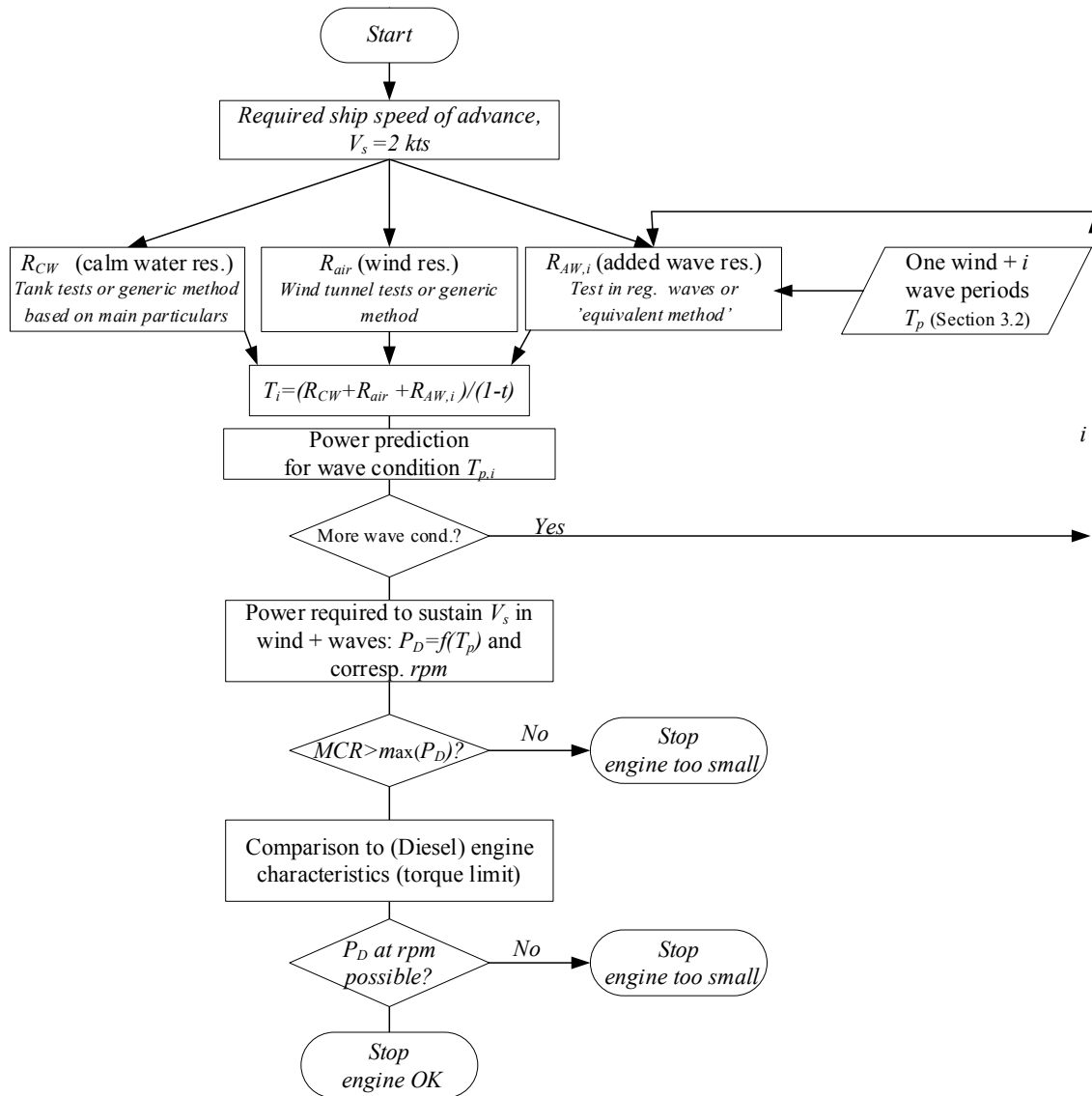


Figure 1: Flow diagram interpreting the Level 2 assessment from MEPC.1/Circ.850/Rev.3 [3]

3.2 Example ship and case study

In this report both, Level 1 and Level 2 assessments are discussed. Using the well-known KVLCC2 tanker [5] as a case study, minimum propulsion power is calculated in the (alternative) ways described in the IMO-guideline.

The KVLCC2 is the second variant of a generic Very Large Crude Carrier (VLCC) developed at the Korea Research Institute of Ships and Ocean Engineering (KRISO). Although the tanker has never been built, it has been used extensively for CFD and experimental studies. In practice VLCCs are usually unproblematic in terms of minimum power but due to the availability of data and the usefulness as a benchmark case it was decided to use the KVLCC2 for the present case study.

On similar note the more common design draft, not scantling as required by EEDI, is used here.

The main particulars of the ship and the two models used for the case study are summarised in Table 2. A photograph of the 1:68 seakeeping model is shown in Figure 2 and further details can be found in [6].

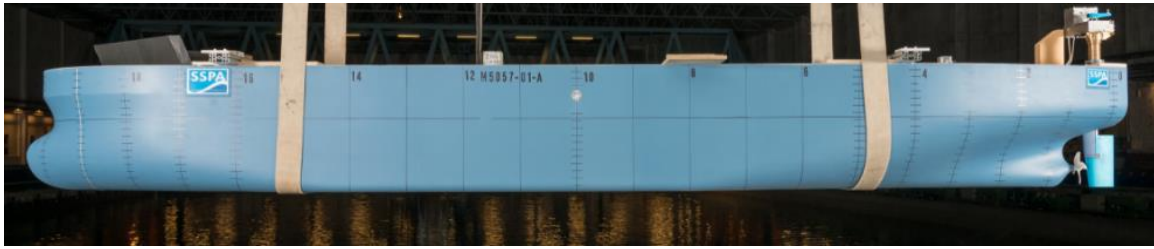


Figure 2: KVLCC2 model used for seakeeping tests

Table 2: Main particular of KVLCC2 [5], [7]

	Ship	Resistance model	Seakeeping model
Scale	1	45.714	68
HULL			
Lpp [m]	320	7.0	4.706
Beam, B [m]	58	1.269	0.853
Draft, T [m]	20.8	0.455	0.306
Displ ∇ [m ³]	312 784	3.274	0.995
Wetted surface (hull+rudder) [m ²]	S 27 249+ 275.3 = 27524.3	13.171	5.952
Block coeff., C_B	0.810	0.810	0.810
Deadweight, DWT [t]	300 000	NA	NA
Frontal wind area A_{FW} [m ²]	1200	NA	NA
Lateral wind area A_{LW} [m ²]	3600	NA	NA
Pitch gyradius k_{yy}	NA	NA	0.25*Lpp
PROPELLER KP458 [4]			
No. blades	4	NA, towed models	
D [m]	9.86		
P/D (0.7R)	0.721		
A_e/A_0	0.431		

4 Level 1 assessment of KVLCC2

With the “tanker values” of $a = 0.0652$ kW/t and $b = 5960.2$ kW (Table 1) and an estimated deadweight of 300 000 t [6] the minimum power according to the Level 1 assessment becomes:

$$P_{D,min} = a \cdot DWT + b$$

$$P_{D,min} = 25.5 \text{ MW}$$

5 Level 2 assessment of KVLCC2

The Level 2 assessment procedure is based on the principle that, if the ship has sufficient installed power to move with an advance speed of $V_s=2$ kts in wind and wave directions from head to 30 degrees off-bow, the ship will also be able to keep course in waves and wind from any other direction.

5.1 Adverse weather conditions

The IMO-guideline defines the “adverse conditions”, under which the ship should be able to sustain the advance speed V_s , by means of JONSWAP wave spectra and the mean wind speed V_w . Some of the parameters that define the environmental conditions depend on ship length, see Table 3.

Table 3: Parameters defining “adverse conditions” [3]

Ship length	V_w	H_s	T_p
$L_{pp} < 200\text{m}$	19 m/s	4.5 m	7s-15s
$200\text{m} \leq L_{pp} \leq 250\text{m}$	Linearly interpolated		
$L_{pp} > 250\text{m}$	22.6 m/s	6.0 m	

It is important to note, that the environmental conditions are therefore not defined by one single sea state but by a range of sea states with spectral peak periods varying from 7s to 15s. As a result, not one but several predictions of minimum power need to be carried out, compare Figure 1. The highest power value calculated during this process determines the engine size.

For a large ship like the KVLCC2 ($L_{pp} > 250\text{m}$) three example spectra according to Table 3 are plotted in Figure 3.

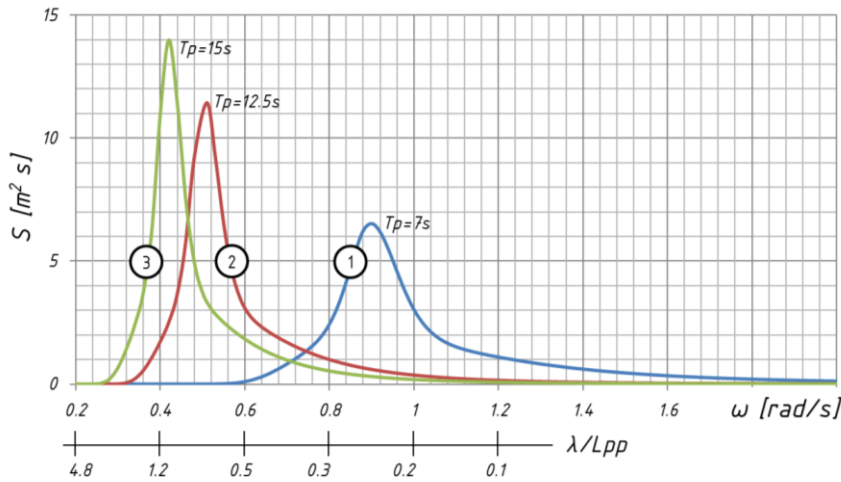


Figure 3: JONSWAP spectra [8] with a significant wave height of $H_s=6$ m and three different modal periods T_p

5.2 Calm water resistance

5.2.1 The IMO-guideline

Section 10 of the IMO-guideline explains how to determine calm water resistance for bulk carriers, tankers and combination carriers. The calm-water characteristics used for the assessment, such as calm-water resistance, self-propulsion factors and propeller open-water characteristics should be obtained by the methods approved for EEDI verification. In the first instance this means model tests.

The IMO guidelines also gives the following default estimates for thrust deduction factor and wave fraction; $t=0.1$ and $w=0.15$ respectively.

5.2.2 Case study KVLCC2

In order to also experimentally determine the calm water resistance, towing tank tests with the large 7 metre model (Table 2) were conducted at RISE.

Neglecting the wave-making resistance and hull roughness, the calm water resistance is expressed as:

$$R_{CW} = (1 + k) \cdot C_F \cdot \frac{1}{2} \rho S \cdot V_s^2$$

Where k is the experimentally determined form factor, C_F the frictional resistance coefficient, S the wetted surface area of the ship and ρ the density of water.

C_F is calculated from the ITTC 1957 correlation line [9] as:

$$C_F = \frac{0.075}{[\log_{10}(Re) - 2]^2}$$

Where Re denotes the L_{pp} -based Reynolds number.

The experimental results for the form factor determination are illustrated by the circular symbols in the Prohaska-plot below (Figure 4) and the form factor becomes

$$k = 0.232$$

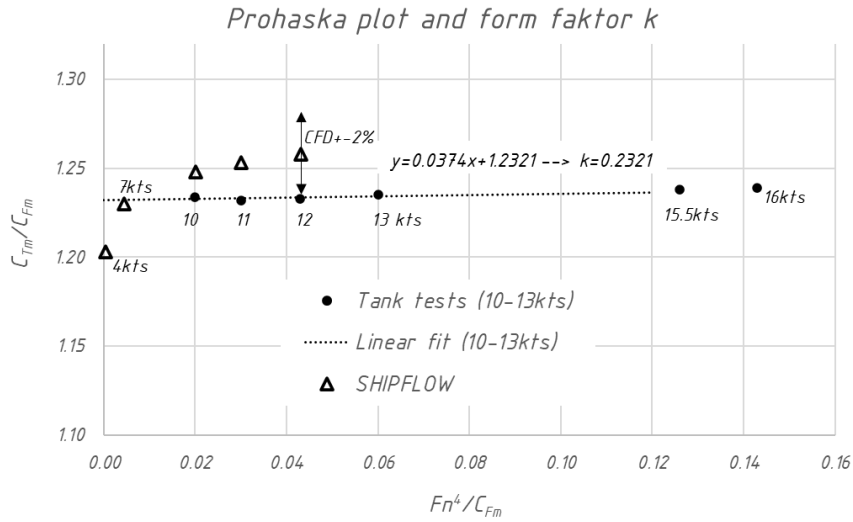


Figure 4: Determination of form factor k using Prohaska's method for analysis of towing tank results [11].

The figure also shows results from combined potential flow, thin boundary layer, and RANSE calculations with the CFD code SHIPFLOW [10].

At a seawater temperature of 15° the frictional resistance coefficient C_F from the above equation is:

$$C_F = \frac{0.075}{[\log_{10}(4.19 \cdot 10^8) - 2]^2} = 1.71 \cdot 10^{-3}$$

Based on the experimental results the calm water resistance therefore becomes:

$$R_{CW} = (1 + 0.232) \cdot C_F \cdot \frac{1}{2} \rho S \cdot V_s^2 = 31.4 \text{ kN}$$

5.3 Added wind resistance

5.3.1 The IMO-guideline

Added resistance due to wind resistance is calculated in steps 12-13 of the IMO-guideline:

$$R_{air} = C_{air} \cdot \frac{1}{2} \rho_{air} \cdot A_{FW} \cdot V_{w,rel}^2$$

where C_{air} is the aerodynamic resistance coefficient, ρ_{air} is the density of air (here 1.2 kg/m³), A_{FW} is the frontal windage area of the hull and superstructure and $V_{w,rel}$ is the relative or “apparent” wind speed (vector sum of ship speed and true wind speed from Table 3).

The IMO-guideline recommends finding the coefficient C_{air} by wind tunnel testing, alternatively the generic value of 1.1 can be used. For ships with large deck cranes (projected lateral area of cranes equal to or exceeding 10% of total lateral projected area) this value should be set to 1.4 instead of 1.1.

According to the guideline wind resistance should be investigated for apparent [!] wind directions from head wind to 30 degrees off the bow. For power prediction purposes the maximum value over this interval is to be used.

5.3.2 Case study KVLCC2

Based on the above generic aerodynamic resistance coefficient of $C_{air} = 1.1$, the wind area from Table 2 and the true wind speed of $V_w = 22.6$ m/s (Table 3) the wind resistance of the KVLCC2 sailing at 2 knots in head wind becomes:

$$R_{air} = 442.2 \text{ kN}$$

For comparison Figure 4 also shows wind forces based on data from other sources. As can be seen the IMO assumption of $C_{air} = 1.1$ appears to be conservative.

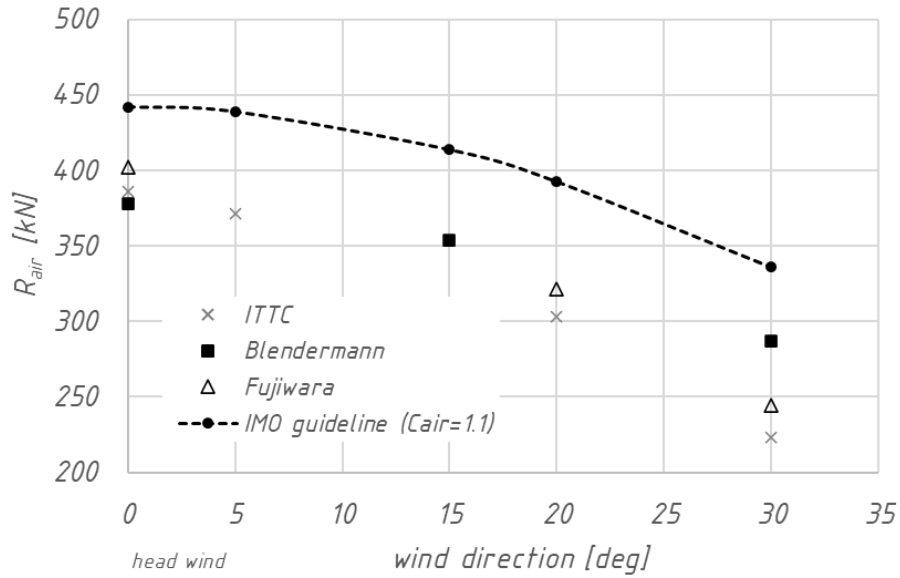


Figure 4: Added wind resistance as function of apparent wind angle. Comparison of IMO values and wind coefficients from ITTC [12], Blendermann [13] and Fujiwara et al. [14].

5.4 Added resistance in waves

5.4.1 The IMO-guideline

The IMO-guideline give two alternative methods to determine added resistance in waves (R_{aw}):

1. A generic expression based on main parameters of the ship
2. Superposition based on the wave spectra from section and a ship-specific quadratic transfer function (QTF).

In the first, generic, method R_{aw} is determined according to:

$$R_{AW,generic} = 1336 (5.3 + V_s) \left(\frac{B \cdot T}{L_{pp}} \right)^{0.75} H_S^2 \quad (1)$$

The second method is more evolved and calculates added resistance based on model tests in long-crested regular (i.e. harmonic) waves or “equivalent methods verified by the Administrations or the Recognized Organizations”.

$$R_{AW,superposition} = 2 \int_0^{2\pi} \int_0^{\infty} \frac{R_{AW,reg}(Vs, \omega)}{\zeta_A^2} S_{\zeta}(\omega) D(\mu) d\omega d\mu \quad (2)$$

Here $R_{AW,reg}(Vs, \omega)$ denotes the added resistance values from model tests in regular waves at discrete different wave frequencies ω , $S_{\zeta}(\omega)$ is the wave energy density spectrum and ζ_A is the wave amplitude. As an alternative to model testing the guideline suggests finding the added resistance QTF based on the semi-empirical “SNNM method”, see e.g. [12].

Finally, the parameter $D(\mu)$ in Equation 2 denotes the wave spreading function of the wave energy (assumed as \cos^2 spreading according to the IMO guideline). According to the IMO guideline the maximum added resistance in short crested waves is defined as maximum over mean wave directions from head waves ($\mu = 0$) to 30 degrees off-bow ($\mu=30^\circ$).

As an alternative the added resistance value in long-crested head waves can be multiplied by a correction factor of 1.3 to consider that the maximum value in long-crested waves does not always occur in head waves:

$$R_{AW,superposition} = 1.3 \cdot 2 \int_0^{\infty} \frac{R_{AW,reg}(Vs, \omega)}{\zeta_A^2} S_{\zeta}(\omega) d\omega \quad (3)$$

From a practical perspective this expression is useful because it avoids (expensive) seakeeping tests in multiple oblique wave directions.

Lastly, the IMO guideline appears to be contradictory on what range of peak wave periods T_P should be used in the assessment (step 16 of the IMO assessment contradicts the T_P values reproduced in Table 3). In this report values from Table 3 are used.

5.4.2 Case study KVLCC2

According to the first, generic, expression above (Equation 1) and with $Vs= 1.03$ m/s (2 kts) we obtain:

$$R_{AW,generic} = 823.7 \text{ kN}$$

Application of the second, more evolved method (Equations 2 and 3), requires determining the quadratic transfer function of the added resistance. To this end tests in long-crested regular head waves were conducted. Because of the low speeds involved (2 knots) such tests cannot be carried out in ordinary towing tanks. To “outrun” wave reflections from the walls the facility needs to be about 35 m wide [8]. Consequently, tests with the smaller of the two KVLCC2 models were conducted in SSPA’s 40 m wide seakeeping basin.

The experiments were carried out by towing the model via long lines and soft springs. Figure 5 shows the setup used to tow the KVLCC2 in waves. It consists of plywood “wings” at deck level either side of the model. Stiff tow wires are attached to these wings and meet forward of the bow and aft of the transom. These lines are let through blocks and connect to soft vertical springs that allow the model to surge in a more or less unrestricted way, and at the same time dampen out violent wave induced jerks. Ring-type strain gauges measure the forces in all four lines. The total towing force (= resistance) is determined from the measured signals and the geometry of the setup.

The stiffness of the springs was chosen in such a way that the natural frequency of the whole system was far away from the encountered wave frequencies.

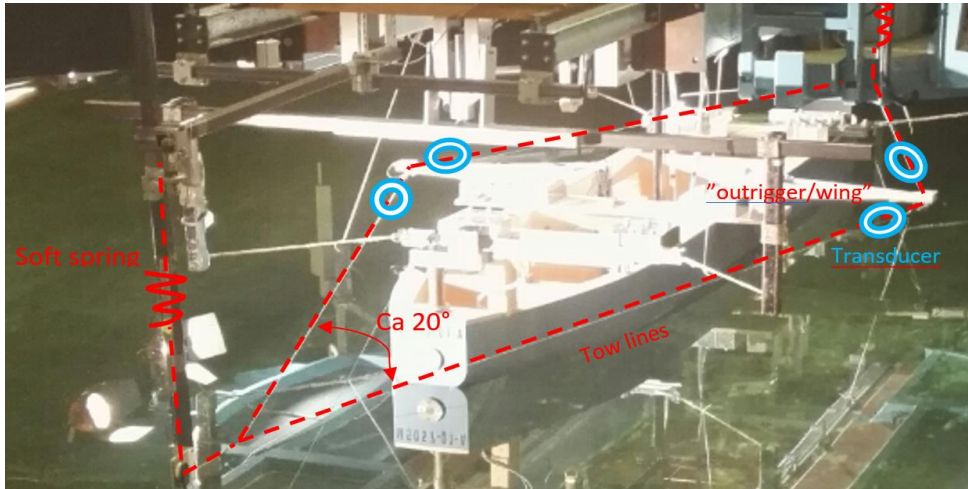


Figure 5: Setup for towing of model in waves, compare [6]

Such a towing setup can have several advantages over the traditional approaches of testing with either “captive” or “free-sailing” models, compare [6] for more details.

Figure 6 summarises the results from the added resistance tests with this setup. When analysing the experiments added resistance due to waves $R_{AW,reg}$ was determined by subtracting the mean resistance in calm water from the mean resistance in regular waves. The coefficient of added resistance due to waves plotted in Figure 6 is defined as:

$$C_{AW}(Vs, \omega) = \frac{R_{AW,reg}(Vs, \omega)}{\rho g B^2 \zeta_A^2 / L_{pp}}$$

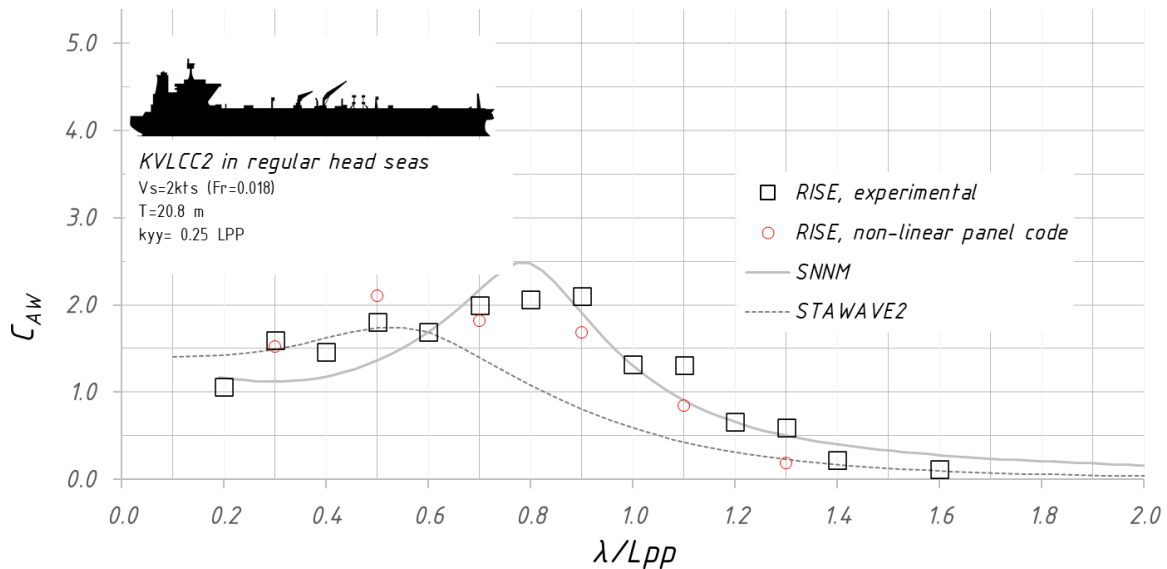


Figure 6: Transfer functions for added resistance of KVLCC2 at 2 knots. Regular, long-crested head waves. Wave steepness in experiments $H/\lambda = 2\%$ for $\lambda/LPP \leq 0.6$; else $H/\lambda = 1\%$.

Also shown in the figure are predictions based on a panel code (Shipflow motions, [10]), the “SNNM” method from the IMO guideline, and the older STAWAVE-2 method from [12]. As can be seen agreement between SNNM predictions (grey line) and measurements (square symbols) is quite good.

Using the measured C_{AW} function (square symbols, Figure 6) as input to Equation 3 and integrating with the spectra defined in section 5.1 yields one unique R_{AW} value for each spectral peak period. Focusing on the three example spectra from Figure 3 one obtains the following added resistance forces:

$$R_{AW} \textcircled{1} = 586.6 \text{ kN}$$

$$R_{AW} \textcircled{2} = 813.3 \text{ kN}$$

$$R_{AW} \textcircled{3} = 616.2 \text{ kN}$$

Figure 7 illustrates results for the full range of spectral peak periods from the IMO-guideline.

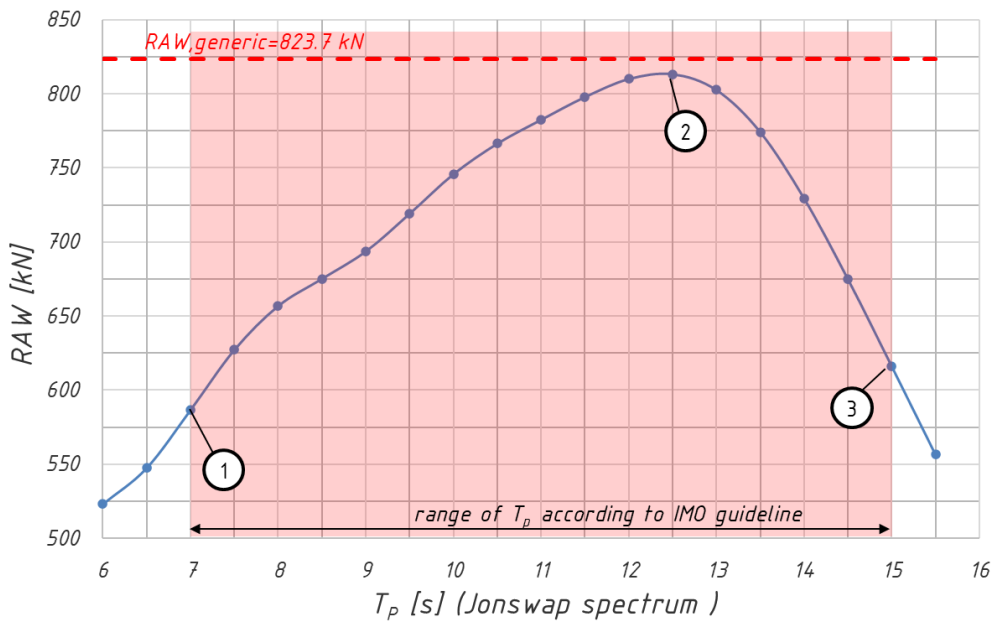


Figure 7: Added resistance of KVLCC2 sailing 2 knots in irregular waves as function of spectral peak period T_p . Based on Equation 3

5.5 Total resistance

Once calm water, wind, and added wave resistance are known, the total resistance can be calculated as the sum of these components, compare section 9 of the IMO-guideline. In the present case the calm water resistance already includes the resistance of the appendages and the total resistance for the three example spectra becomes:

$$R\textcircled{1} = 1060.2kN$$

$$R\textcircled{2} = 1286.9kN$$

$$R\textcircled{3} = 1089.8kN$$

compare also Figure 8. As can be seen the calm water resistance is negligible compared to added wind and wave resistance.

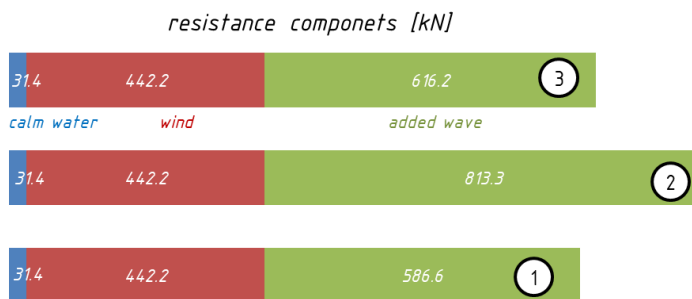


Figure 8: Comparison of resistance components for KVLCC2 at 2 knots

5.6 Power prediction

Now that the total resistance has been calculated a power prediction can be made, compare flow diagram in Figure 1.

5.6.1 The IMO-guideline

As described in sections 4-9 of the IMO-guideline such a power prediction is based on the “ K_T/J^2 method” from the “1978 ITTC Performance Prediction Method” [9]. The required advance ratio J of the propeller is found from the propeller loading K_T/J^2 :

$$\frac{K_T}{J^2} = \frac{T_S}{\rho D^2 (1-w)^2 V_S^2}$$

Where D is the propeller diameter. From the definition of the advance ratio the rate of revolution of the propeller becomes:

$$n_S = \frac{(1-w) V_S}{J \cdot D}$$

Where w is the (full-scale) wake fraction coefficient.

Finally, the shaft power to propel the ship at V_s in “adverse conditions” becomes:

$$P_{DS} = 2\pi\rho \cdot K_Q(J) \cdot D^5 n_s^3$$

Where K_Q denotes the torque coefficient of the full-scale propeller at the advance ratio J . This is calculated from the full-scale propeller open water curves [9].

5.6.2 Case study KVLCC2

Section 10 of the IMO-guideline gives “default conservative estimates” for wake fraction w and thrust deduction factor t .

$$t_{IMO} = 0.1$$

$$w_{IMO} = 0.15$$

Figure 9 compares these numbers to measured and calculated values from different sources.

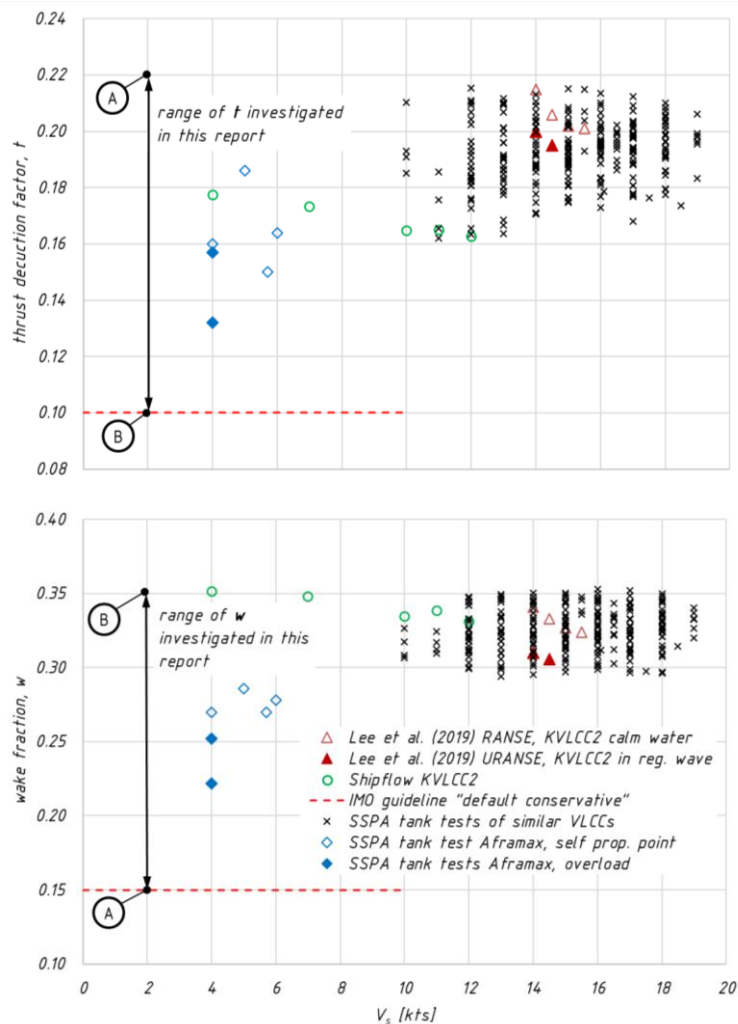


Figure 9: Wake fraction and thrust deduction for tankers

It can be noted that:

- The generic values from the guidelines (dashed red lines) are at the extremities of the experimental and CFD values.
- The IMO “default conservative estimate” of $t=0.1$ is much lower than one would expect from the “cloud” of measured points shown in Figure 9. This is of particular concern because a conservative power prediction requires a high thrust deduction factor (and a low wake fraction).
- SHIPFLOW simulations (green circles) seem to plausibly extend the experimental trend to lower speeds
- Wake values from the RANSE simulations by Lee et al. [7] are similar to the SHIPFLOW simulations. t -values from the two sources, however, differ by some 20%.
- As illustrated by the URANSE results (solid vs. light triangles) and ‘SSPA Aframax’ tests (diamonds) the effect of overloading the propeller e.g. due to waves is to reduce w and t compared to the calm water case or the self-propulsion point values.

For the present case study of the KVLCC2 values of t and w are estimated based on the SHIPFLOW calculations (circular green symbols):

$$t = 0.18$$

$$w = 0.30$$

Additionally, the influence of t and w on the minimum propulsion power was investigated by varying the two factors within the range illustrated by the circular A and B symbols in Figure 9.

Scenario A (conservative): $t=0.22$; $w=0.15$

Scenario B (optimistic): $t=0.1$; $w=0.35$

Based on these assumptions and with the resistance values calculated above, power predictions according to the IMO guidelines were made. The results are illustrated in Figure 10.

As expected, point 2 –having the largest total resistance (Figure 8)– requires the highest power, $P_D=7.1$ MW. This corresponds to ‘Spectrum 2’ with a T_p of 12.5s, see also Figure 3. Maintaining a speed of 2 knots in the other spectra requires less power.

The minimum required shaft power for the KVLCC2 the corresponding rpm therefore correspond to point 2:

$$P_{DS}=7.1 \text{ MW} \quad n_{Level 2} = 45.2 \text{ rpm}$$

It can also be seen from Figure 10, that varying thrust deduction factor and wake fraction within the A-B range from Figure 9 significantly influence the results of the power prediction. This is illustrated by the corridor between the dotted lines. Depending on the choice of w and t the power demand can differ by about ± 1 MW.

As illustrated by the green dash-dotted line, the power predictions based on the IMO “default conservative” estimate for w and t do not seem to be conservative. As discussed above the reason for this is the very low value of $t=0.1$, compare Figure 9.

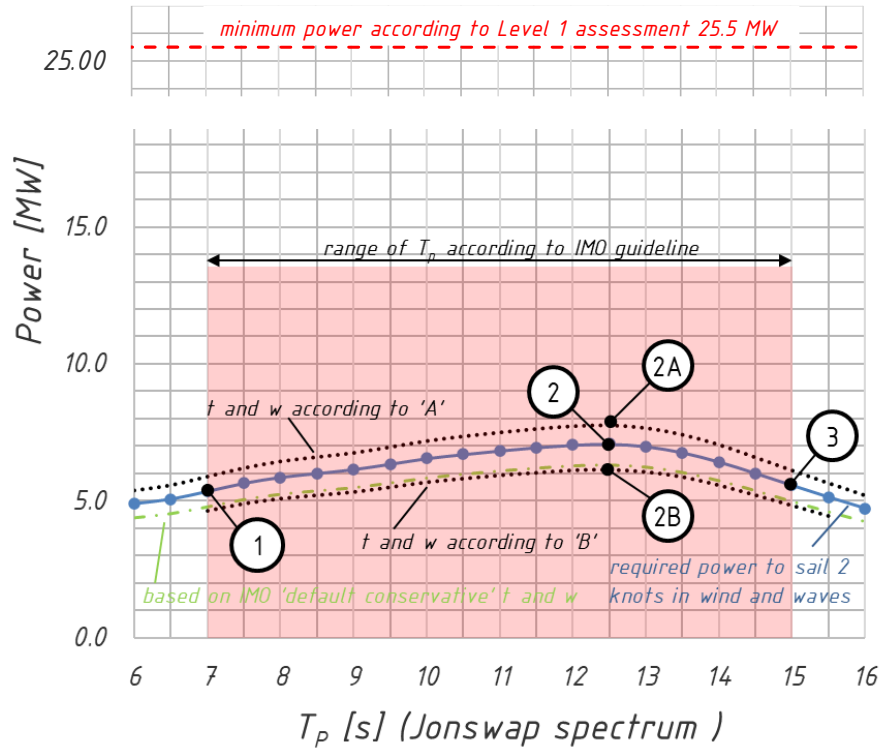


Figure 10: Required power to maintain a speed of 2 knots in wind and waves as function of modal period T_p

It must be kept in mind, that the above value of $P_{Ds} = 7.1$ MW is only the *required shaft power* to propel the ship at 2 knots. For Diesel engines the minimum *installed power* P_{Dmin} i.e. the Maximum Continuous Rating (MCR) might have to be much higher. This because of the torque limitations at low *rpm* and is explained in the next section.

5.7 Torque limitations

Finally, it remains to be determined the Maximum Continuous Rating (MCR) of an engine that can provide the value of $P_{Ds} = 7.1$ MW at a revolution rate of 45.2 rpm.

5.7.1 The IMO-guideline

As described in section 5 of the IMO-guideline the required minimum MCR for Diesel engines is calculated considering the torque limitation line and all other relevant engine limits.

5.7.2 Case study KVLCC2

Figure 11 plots the operational points 1-3 (i.e. power/*rpm* combinations corresponding to wave spectra 1-3) into load diagrams for two Diesel engines.

Engine 1, with an MCR of 24 MW at a rate of revolution of 75 1/min, is a typical VLCC-engine (green solid line). It can bring the KVLCC2 up to a design speed of 15.5 knots in calm water with a sea margin of 15%.

Engine 2 (red dash-dotted line) is much smaller (12 MW @ 69 rpm) and can be considered a “slow steaming” option. It will propel the ship at about 12.2 knots in calm water with the same sea margin as the larger engine.

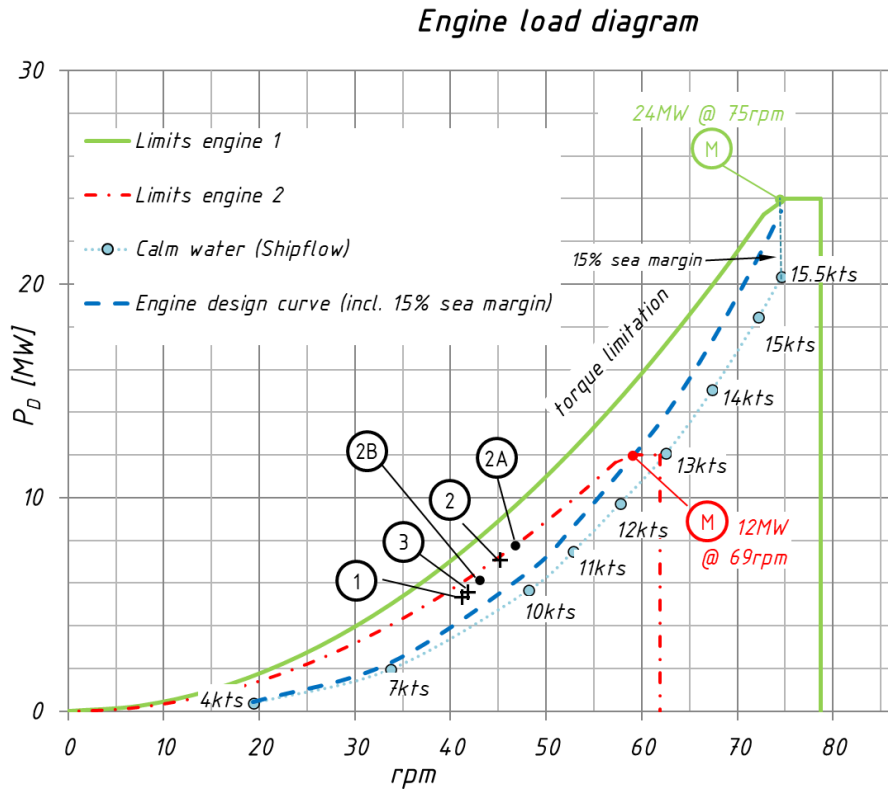


Figure 11: Load diagram for two Diesel engines

It can be seen from the figure, that the larger engine will deal effortlessly with all the situations the KVLCC2 might encounter under the “IMO adverse conditions”. This is because all the operational points (1,2,3, 2A and 2B) end up below the torque limit line (solid, green curved line). Here the latter two points correspond to variations of point 2 with a conservative (2A) and an optimistic (2B) choice of t and w .

Engine 2 on the other hand will just be able to provide the required power for $V_s = 2$ knots. As illustrated in the figure at Point 2 the available engine power equals the required power:

$$P_{DS,available} = P_{DS,required} = 7.1 \text{ MW ; (@ 45.2 rpm)}$$

It can therefore be concluded that a KVLCC2 equipped with Engine 2 would precisely comply with the IMO guideline, and that $P_{Dmin} = 12$ MW is the minimum MCR value.

It is interesting to note that for an optimistic choice of t and w (2B) the ship complies with some margin with the IMO regulation whereas a conservative choice of t and w (Point 2A) would require a somewhat larger engine.

6 Results and discussion

Using the KVLCC2 tanker as a case study the “IMO guidelines for Determining the Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions”, [3], was studied in some detail. Results of model tests and CFD-simulations show:

- The simple Level 1 assessment from the IMO-guideline yields, that the minimum installed power in wind and waves is 25.5 MW.
- According to the more advanced Level 2 assessment this power reduces to 12 MW.
- Interestingly, the same result (12 Mw) was obtained by applying the previous revision of the IMO guideline which required a higher ship speed (4 knots) but assumed lower waves and wind speed.
- It is of the utmost importance to consider the torque limitations of Diesel engines because the propeller is highly loaded and operates far away from the design point.
- An analysis of the individual resistance components shows, that, under the wind and wave conditions from the IMO-guideline, the total resistance consists of about 3% calm water resistance, 34% wind resistance and 63% added resistance.
- The fact that added resistance dominates the power prediction leads to the conclusion, that it is particularly important to predict this force component correctly. Because of the low tests speed (2 knots) and the issue of tank wall reflection it is important to carry out added resistance tests in a wide basin, not a narrow tank.
- The IMO guideline appears to be contradictory on what range of peak wave periods TP should be used in the assessment (step 16 of the IMO assessment contradicts the TP values listed under the spectrum definitions).
- During the Level 2 assessment of the KVLCC2 it became obvious, that the IMO “default conservative” value of $t=0.1$ appears to be very optimistic.

7 References

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