Improved efficiency propulsion plants

MAN Energy Solutions
Future in the making

Optimisations for EEDI phase III

Future in the making

Contents

The matching of hull, engine, and propeller has been challenged since the introduction of the EEDI phases, which calls for a propulsion power reduction. This paper explains how improved efficiency and reduced emissions can be achieved with three-bladed propellers, so that propulsion plants may comply with upcoming EEDI phases. The results of an investigation of torsional vibrations and surface hull pressure pulses are presented to provide a better overview of the interaction between hull and propeller. Two case studies, which include propeller optimisation studies, and analyses of torsional vibration and hull surface pressure pulses, are discussed to illustrate the benefits and challenges that may arise.

Introduction

As international regulations to reduce greenhouse gas (GHG) emissions tighten, higher requirements are placed on the propulsion system design of merchant ships. IMO's Energy Efficiency Design Index (EEDI) is a key measure in the reduction of greenhouse gas emissions by 2030 and 2050. In fact, it sets the minimum energy efficiency design requirements for different ship types and sizes. EEDI phases have been launched since 2013, and they have gradually become stricter, reducing CO_2 emission from 10% to 20%, depending on ship type and size, see Fig. 1. The EEDI Phase III requirements call for a further reduction to the range of 30-50%, depending on vessel type and size. To comfortably meet this target, further optimisations and innovative solutions should be studied and tested. Since propulsion power is related to the majority of CO_2 emissions from the entire ship, a reduction of propulsion power will often be unavoidable if the fuel type is not changed. A power reduction will lead to challenges and, potentially, also changes in the choice of propulsion plant for a newbuilding of an existing well-proven ship design [1].

The choice of propulsion plant is a crucial and multi-objective stage of a ship design. The matching of ship, engine, and propeller has a major impact on the performance of the ship, and it affects operational costs and the environmental footprint of the ship, see Fig. 2. Hence, the imposed propulsion power reduction due to the EEDI Phase III will result in changes and challenges when matching ship, engine, and propeller. Therefore, a range of optimisation measures that can reduce the propulsion power required should be implemented during matching of the ship and the propulsion plant to compensate for the reduced propulsion power. To that end, the selection of the

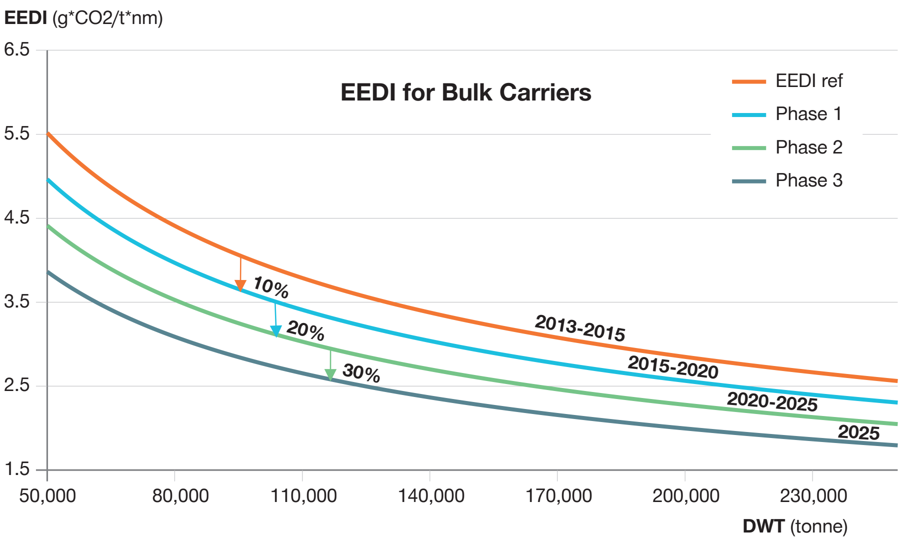

Fig. 1: Overview of EEDI phases

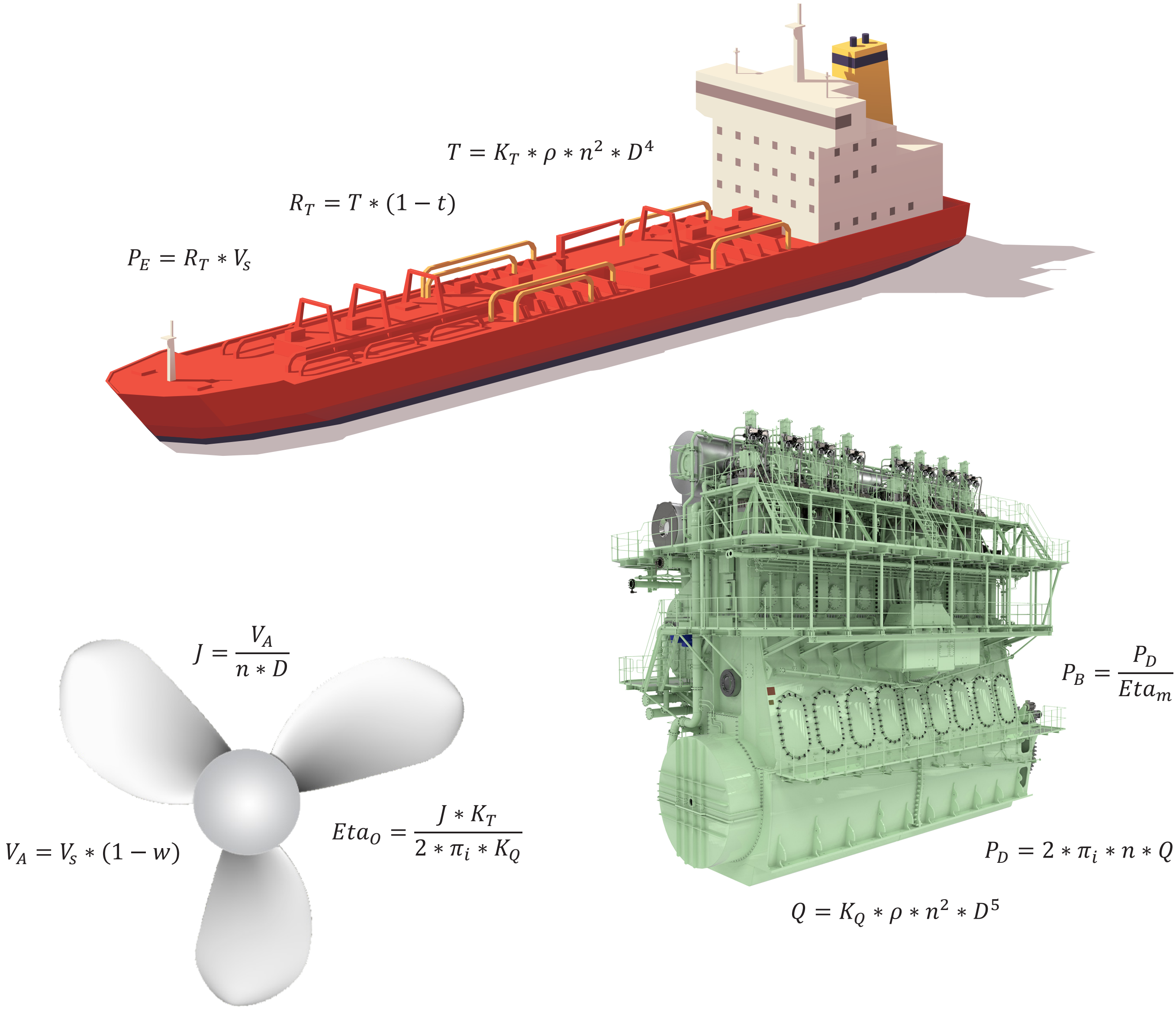

Fig. 2: Hull-engine-propeller matching (source: www.friendship-systems.com)

propulsion plant should be revised according to potential optimisation measures. PTO solutions, energy saving devices (propeller cap with fins, Mewis Duct, rudder fins, etc.), hull line optimisation, and high-efficiency Kappel 2.0 propellers are a few of these measures.

Optimisation of the propeller is among the potential measures. Propeller optimisation is a complex subject with multiple criteria that have to be considered. One of these criteria is the number of propeller blades.

Typically, the lower limit of the propeller blade number is dictated by: installed power, quality of the wake field of the vessel, cavitation limits, and vibrations. Since the installed propulsion power for EEDI Phase III has been reduced, the number of propeller blades can also be reduced thanks to the smaller area ratio required. The reduced number of blades for a propeller means higher propeller efficiency due to less drag. Another characteristic property of a propeller with fewer blades is that the optimum propeller speed and diameter increase. This gives room for adjustments to match propeller and engine, and partially compensate for the propulsion power reduction imposed.

This paper gives an insight into the possibilities and challenges when exchanging a four-bladed propeller with a three-bladed propeller to comply with EEDI Phase III. The results of two different case studies will be discussed.

Case study overview

Based on the experience of MAN Energy Solutions, some of the ship types that will face potential challenges complying with EEDI Phase III have been selected for the investigation of three-bladed propellers. Table 1 gives an overview of the investigated cases.

Table 1: Case studies

	Ship type	Dwt
Case study 1	Kamsarmax bulk carrier	≈85,000
Case study 2	Suezmax tanker	≈160,000

Calculation description and methodology

An analysis has been made to ensure the most realistic comparison of propulsion plants with four- and three-bladed propellers from a shipowner or a shipyard point of view. The analysis investigates how the number of blades affects the hydrodynamic performance of the propeller and on the matching with the engine and ship.

The studied propellers belong to the Wageningen B-screw series, which is one of the most common and popular series in the maritime industry. In terms of blade number and area ratio configurations, the Wageningen B-screw series includes around 20 configurations. These cover two-bladed propellers with low area ratios and up to seven-bladed propellers with high area ratios. Furthermore, the propeller geometry is kept consistent in the different configurations, which enables studies with trustworthy results. However, it should be noted that testing of the B-series was conducted over a long period (more than 30 years) using different basins with different equipment. This has resulted in large variations of the propeller speed for the tested propellers, which impacts the results. This must be considered when comparing the B-series propellers, especially for three-bladed propellers.

For each case study, hull characteristics and propulsive coefficients are calculated by a combination of well-known methods and internal tools. The resistance of the hull is calculated by the Holtrop-Mennen method. The propulsive coefficients are estimated according to internal tools combined with actual measurements for corresponding ship sizes.

The first step in each case study is to calculate the resistance and the propulsive coefficients, i.e. thrust deduction factor (t), wake fraction (w), and rotative efficiency (η_r). Next, a Wageningen B-screw series analysis is performed for the existing propulsion plant complying with EEDI Phase II. These two steps comprise the basis of the optimisation study.

The next step is calculating the propulsion power for compliance with EEDI Phase III. Here, the propeller curve of the existing (reference) propulsion plant is used to find the corresponding engine speed for the calculated Phase III propulsion power. Hence, the new SMCR (power and rpm) of the EEDI Phase III is the starting point and the initial condition of the Wageningen B-screw series optimisation analysis for the propellers with three blades. Therefore, the Wageningen B-screw series optimisation analysis will use this initial condition in the calculation of optimum and extended propeller speed.

Each case study considers combinations of propeller blade number and shaft speed for comparison and evaluation purposes. More specifically, the optimum shaft speed is calculated for propellers with three and four blades. Moreover, different shaft speeds are considered to allow the best matching of propeller, engine, and ship.

The propeller diameter has been kept constant in each case study, even though the optimum diameter for the propeller with three blades is larger. The propeller diameter was kept constant due to the influence from induced pressure impulses, torsional vibrations, operating profiles of the specific ships (often sailing in ballast draught), and for direct comparison and evaluation of the propeller with four blades.

Calculations have been performed to ensure that the new characteristics of the propellers (due to different power, different engine speed, and reduced number of blades) are matched with the engine and hull without negatively impacting the propulsion plant performance. Surface hull pressure impulse calculations have been made to evaluate the interaction of the propeller and the hull. Furthermore, a torsional vibration analysis has been carried out to check the interaction of the propeller and the engine, and, therefore, the ship.

The following sections give a short description of the surface hull impulse calculation and the torsional vibration analysis method.

Surface-hull pressure impulses

Propeller-induced noise and vibrations are among the main causes of mechanical failures in the propulsion plant, and may also affect the on-board comfortability. The induced noise and vibrations strongly depend on the propeller tip clearance, shaft immersion, propeller speed, and propeller geometry characteristics, such as the number of blades, area ratio, skew, rake, and pitch at the blade tip, see Fig. 3.

The prediction of propeller induced pressure pulses is performed empirically, numerically, and experimentally. The empirical method employs regression-based formulas for estimating surface hull impulses. This method is widely used for the initial estimation of the pressure impulses, since it gives an adequate level of accuracy and reliability. An alternative to empirical predictions is numerical

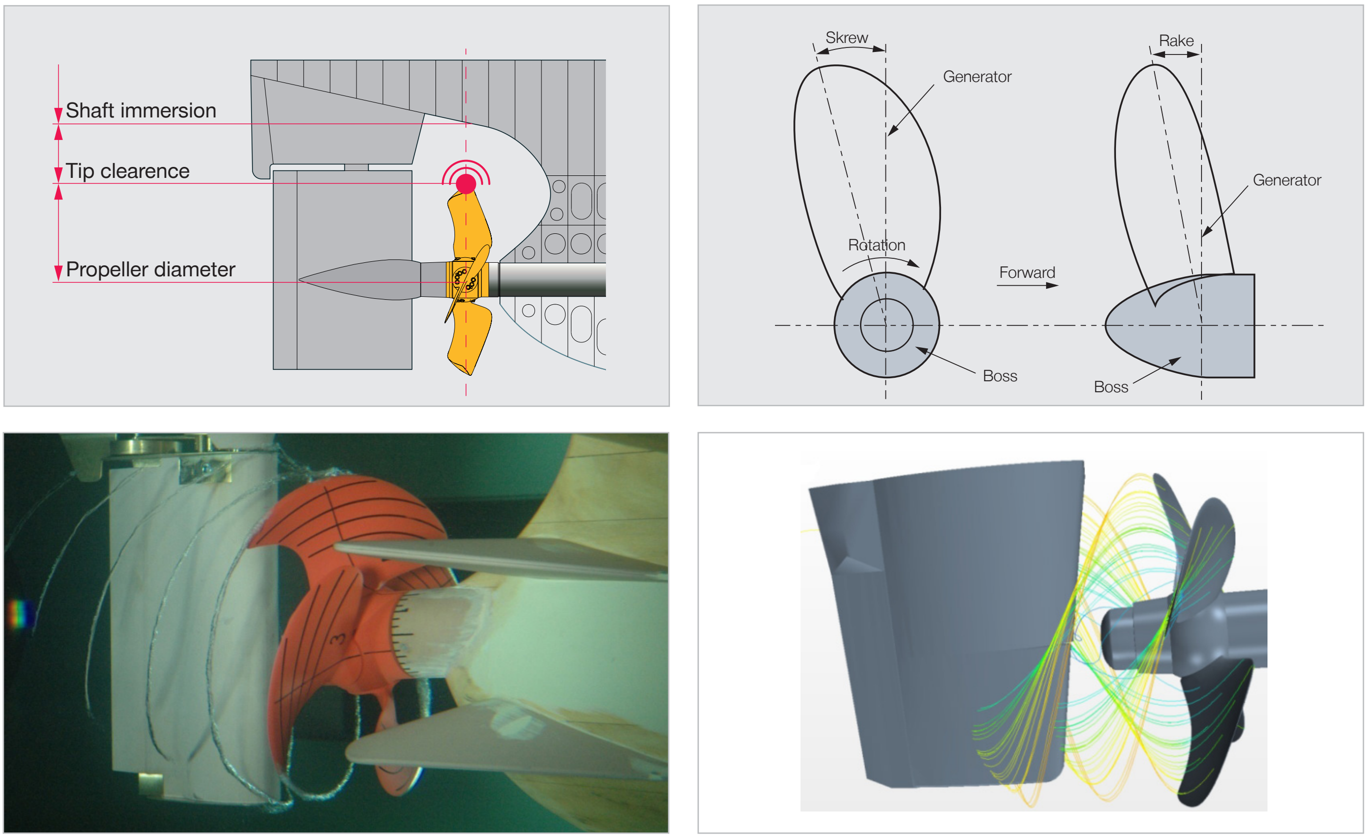

Fig. 3: Pressure impulse description

predictions based on compressible Naiver-Stokes equations, or other computational fluid dynamic (CFD) methods. The level of accuracy for the numerical predictions has improved significantly in the last years with small deviations compared to experimental predictions. Numerical predictions are widely used for propellers where the outcome of the pressure impulse prediction is not so critical.

The last and most accurate method is experimental prediction of pressure impulses performed on a scale model in cavitation tunnels at tank test institutes. Multiple pressure transducers are mounted on the hull surface above the propeller. Since a scale model of the actual hull and propeller is used for the predictions, this method is the most accurate. Experimental measurements are common practice for newbuildings, and especially for propellers where low-level pressure impulses are a design objective [2].

Torsional vibrations

The excitation of torsional vibrations in a shaft system is caused by torque alterations. The torque alterations originate from gas pressure differences in the engine cylinders and the crankshaft connecting rod mechanism during the working cycle of the engine. Another source of torsional vibration excitation is the interaction of the propeller and the hull through the wake field. In fact, the whole shaft system, including propeller, propeller shaft, intermediate shaft, crankshaft, and flywheel, is involved in torsional vibrations. Since these torque alterations are cyclical, a harmonic analysis can be employed to calculate the torque alteration as the total number of torques acting with other frequencies than the engine-rotational frequency [3].

Managing torsional vibrations is paramount to avoid serious issues with the crankshaft and the other components of the propulsion plant. Table 2 shows the propulsion plant parameters that play a key role for the torsional vibration analysis.

There is an interdependence between the parameters, which necessitates careful and thorough consideration of each parameter.

Table 2: Key parameters for the torsional vibration analysis

Engine	Shaft line	Propeller	Hull
Number of cylinders	Length of shaft line	Propeller inertia	Wake field
Engine speed	Shaft line diameters	Number of blades	

Case study 1: Kamsarmax bulk carrier

The Kamsarmax bulk carrier is the biggest variant of the Panamax category. It is designed to fit the Panama Canal and to be accommodated at the port of Kamsar in Guinea. This ship type is favoured for its fuel efficiency, versatility, and cargo capacity. Typically, it is for EEDI phase II equipped with a 6S60ME engine coupled to a fixed pitch propeller (FPP) with four blades. This associated range of engines offers a combination of low SFOC, convenient dimensions for the hull form, and low operational and initial costs [4].

The SMCR power for this compliant EEDI phase II ship type is approximately 9000 kW depending on the hull form. Table 3 shows ship particulars and propulsion plant characteristics for this specific case study. Considering that an FPP is coupled to the 6S60ME engine, a light running margin (LRM) of 5% has been applied. This means that the propeller has been designed for 9000 kW (SMCR power) and 88.2 rpm (SMCR speed with 5% LRM).

In accordance with the ship particulars, the Holtrop-Mennen method and internal tools have been applied to calculate the ship resistance and the propulsive coefficients of wake fraction (w), thrust deduction factor (t), and rotative efficiency (η_r) for a range of ship speeds. Table 4 shows the resistance and propulsive coefficients for a ship design speed of 14.5 knots.

According to the calculated resistance and propulsive coefficients, a Wageningen B-screw series propulsion study was performed for the EEDI Phase II propulsion plant. Fig. 4 depicts the nominal propeller curve, the light propeller curve, and the engines available for Phase II. To comply with Phase III it has been estimated that the power of 9000 kW for Phase II has to be reduced to approximately 7800 kW (Table 5). However, as the necessary power reduction is an estimate, an increase or decrease of this power for similar ship types can be expected.

From the propeller curve of the EEDI Phase II in Fig. 4, the corresponding engine speed of the EEDI Phase III propulsion power of 7800 kW has been estimated to 80.1 rpm. As a result, the 6S60ME engine, which is typically chosen for this ship type, is not available for EEDI Phase III.

Compliance with EEDI Phase III could be achieved with either a 6 or 7G50ME engine or by increasing the propeller

Table 3: Propulsion plant characteristics and vessel particulars

Ship particulars			Propulsion plant characteristics for EEDI Phase II		
Dwt	[t]	82,000	**Engine type**	[-]	6,S60
L_{WL}	[m]	229.0	**SMCR power**	[kW]	9,000
L_{PP}	[m]	225.0	**SMCR speed**	[rpm]	84
B_{WL}	[m]	32.3	**Propeller type**	[-]	FPP
T_{Design}	[m]	12.2	**Propeller diameter**	[mm]	7,400
$T_{Scantling}$	[m]	14.5	**No. of blades**	[-]	4
C_B	[-]	0.875	**A_e/A_0**	[-]	0.403
D	[-]	20.2	**P/D**	[-]	0.75

EEDI		
EEDI Phase II	≈ 3.49	$gCO_2/(nm^*t)$
Propulsion power for EEDI Phase II	9,000	kW
Attained EEDI II	≈ 3.49	$gCO_2/(nm^*t)$

Table 4: Resistance and propulsive coefficients for the Kamsarmax bulk carrier at 14.5 knots

V_s Ship speed	R_t Resistance	w Wake fraction	t Thrust deduction	η_r Rotative efficiency
[knots]	**[kN]**	**[-]**	**[-]**	**[-]**
14.5	**714.3**	**0.36**	**0.23**	**1.00**

Table 5: Required power for EEDI Phase III

EEDI Phase III	≈ 3.05	$gCO_2/(nm^*t)$
Predicted propulsion power for EEDI Phase III	7800	kW

speed to match the 5S60ME engine. However, an increase of the propeller speed will lead to a lower pitch and, therefore, to a decrease in propeller efficiency for the existing propeller with four blades.

As the next step, a Wageningen B-screw series study is performed to find the optimum shaft speeds for propellers with four and three blades, respectively, for the EEDI Phase III propulsion power. In this optimisation study, a reduced design speed of 13.5 knots has been selected since the propulsion power has been reduced. Table 6 shows the resistance and the propulsive coefficients of the ship design speed of 13.5 knots for the EEDI Phase III.

This optimisation study comprises an iterative calculation where the goal is to obtain the minimum resistance at a design speed of 13.5 knots. This is achieved by changing the shaft speed until minimum resistance is obtained for the design speed. Fig. 5 illustrates the results of this optimisation study, where the optimum shaft speed for the four-bladed propeller is 72 rpm, and 79 rpm for the three-bladed propeller. As it was expected, the optimum shaft speed for the three-bladed propeller is higher than for the propeller with four blades. This is due to the difference in number of propeller blades. See chapter 2 of "Basic Principles of Ship Propulsion" [1].

Therefore, combinations of shaft speed and number of propeller blades have been investigated to evaluate the compliance with EEDI Phase III. These propellers are referred to by a letter-figure combination: R-9000-84-4 and R-7800-80-4. The letter R indicates reference propellers (only for R, otherwise just random letters), the first number is the power ($P_{B\ SMCR}$), the second number is the propeller speed ($N_{S\ SMCR}$), and the last number is the number of propeller blades (Z).

Table 6: Resistance and propulsive coefficients for the Kamsarmax bulk carrier at 13.5 knots

V_s	R_t	w	t	η_r	Sea margin	Engine margin
[knots]	[kN]	[-]	[-]	[-]	[-]	[-]
13.5	580.7	0.36	0.24	0.99	15%	10%

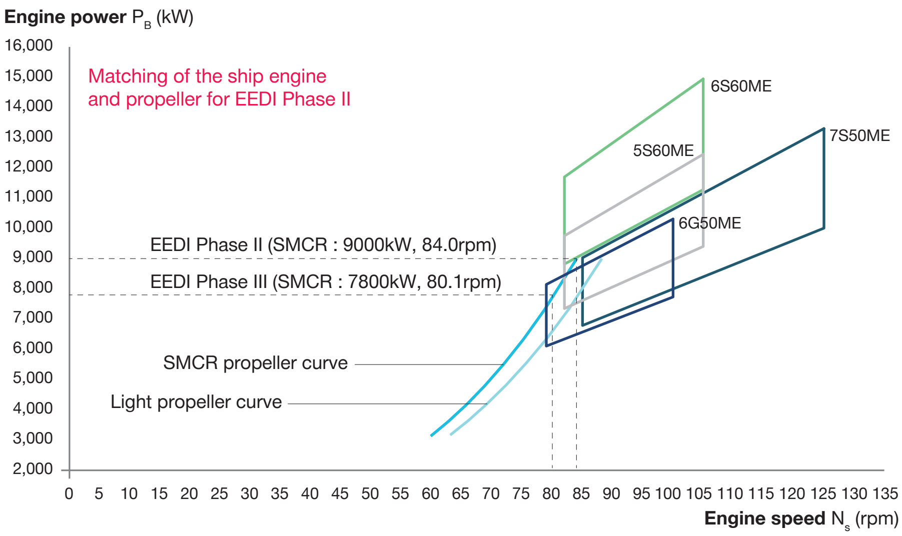

Fig. 4: EEDI Phase II propeller curves and engines available

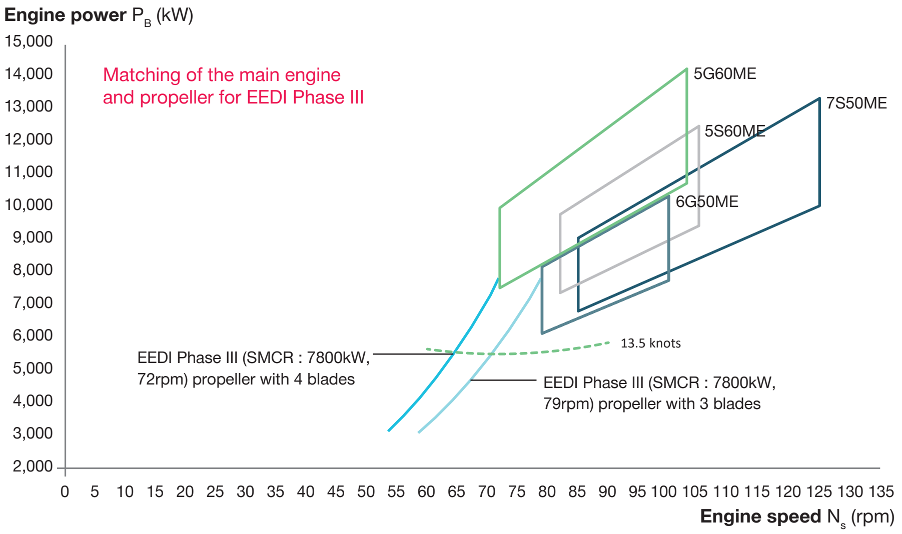

Fig. 5: EEDI Phase III with optimum propeller speeds

Table 7 shows characteristics for the two propellers, which correspond to the propellers of the existing propulsion plant complying with EEDI Phases II and III, respectively. Furthermore, the propellers are used as reference in the comparison and evaluation of propellers with different speed and number of blades.

Table 8 shows an overview of the investigated propellers. The same letter-figure configuration has been applied. For variants: A-7800-72-4 and A-78000-79-3, the propeller speeds are different since these correspond to the optimum propeller speeds.

For the other variants, the propeller speed was increased to correspond with the minimum engine speed necessary to enable selection of the specific engine type. Hence, variants B-7800-82-4 and B-7800-82-3 have identical propeller speeds that match the 5S60ME-C10 engine. For variants C-7800-85-4 and C-7800-85-3, the propeller speed matches the 7S50ME-C10 engine.

Fig. 6 shows the investigated propellers with three blades that can be matched with available engine types due to the increased propeller speed. The dashed lines are the light propeller curves with 5% light running margin for the investigated propellers (continuous lines). The light propeller curves correspond to the actual engine power and speed that the propellers will be designed and manufactured for. Therefore, the light propeller curves are used for the optimisation studies to find the optimum engine power and speed for the ship design speed of 13.5 knots.

Note that the increased shaft speeds of 82 rpm and 85 rpm do not deviate too much from the optimum shaft speed of 79 rpm, hence the propeller efficiency will not drop significantly.

Furthermore, the light propeller curve of variant A-78000-79-3 intersects the curve of 13.5 knots (green line on Fig. 6) at its lowest point (lowest propulsion power), which verifies that this is the optimum point. Note that the constant

Table 7: Reference propellers for EEDI Phases II and III

R-9000-84-4			R-7800-80-4		
$P_{B\ SMCR}$	kW	9000.0	$P_{B\ SMCR}$	kW	7800.0
$N_{S\ SMCR}$	rpm	84.0	$N_{S\ SMCR}$	rpm	80.0
Z	-	4.0	Z	-	4.0

Table 8: Overview of investigated propellers

A-7800-72-4			A-7800-79-3		
$P_{B\ SMCR}$	kW	7800.0	$P_{B\ SMCR}$	kW	7800.0
$N_{S\ SMCR}$	rpm	72.0	$N_{S\ SMCR}$	rpm	79.0
Z	-	4.0	Z	-	3.0

B-7800-82-4			B-7800-82-3		
$P_{B\ SMCR}$	kW	7800.0	$P_{B\ SMCR}$	kW	7800.0
$N_{S\ SMCR}$	rpm	82.0	$N_{S\ SMCR}$	rpm	82.0
Z	-	4.0	Z	-	3.0

C-7800-85-4			C-7800-85-3		
$P_{B\ SMCR}$	kW	7800.0	$P_{B\ SMCR}$	kW	7800.0
$N_{S\ SMCR}$	rpm	85.0	$N_{S\ SMCR}$	rpm	85.0
Z	-	4.0	Z	-	3.0

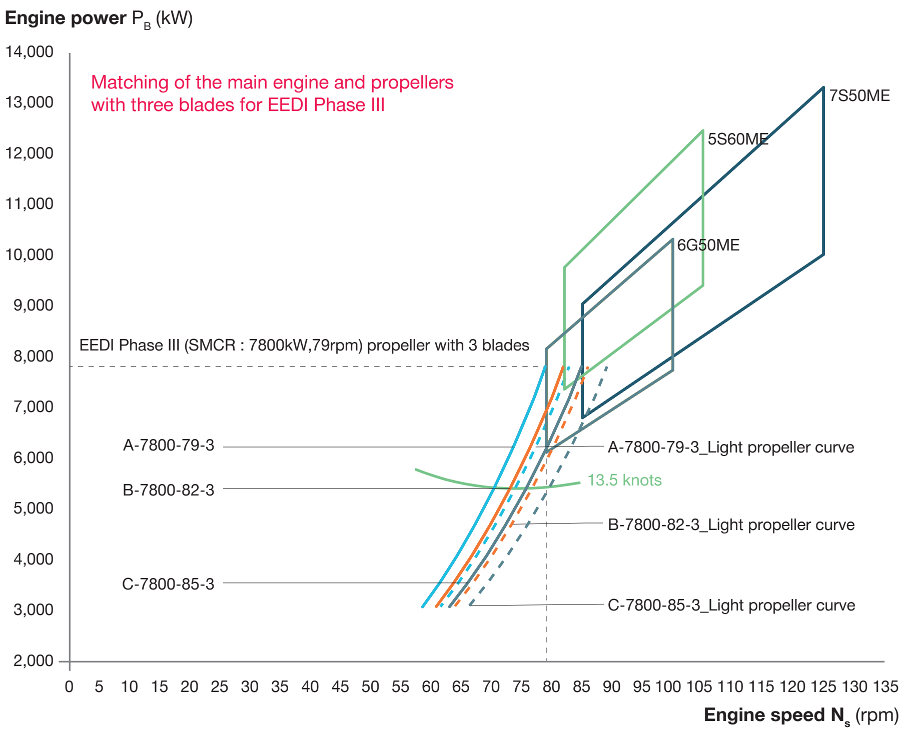

Fig. 6: Variants with three propeller blades

speed curve at 13.5 knots has increased slightly for the light propeller curves of the other two variants.

Fig. 7 shows the investigated propellers with four blades and their corresponding engine types. As seen, the propeller speed of propellers B-7800-82-4 and C-7800-85-4 is not close to the optimum propeller speed of 72 rpm. It will result in a decrease of the propeller efficiency compared to the optimum A-7800-72-4. Therefore, the light propeller curves (dashed lines) of variants B-7800-82-4 and C-7800-85-4 intersect the 13.5 knots curve at points where the propulsion power is increased.

However, the efficiency drop for propellers B-7800-82-4 and C-7800-85-4 is not significant compared to the reference propeller R-7800-80-4. Moreover, if these propellers are coupled to a suitable engine, the efficiency drop could be compensated for.

Last step in the calculation is to evaluate the effect of propeller speed and number of propeller blades.

Table 9 shows comparisons between the reference propeller R-7800-80-4 and the propellers investigated. The reference propeller R-7800-80-4 is used for this comparison to have an identical power for the propellers compared and, consequently, a similar area ratio. The comparison will give an insight into the combined effect of propeller speed and number of propeller blades.

The conclusion is that all propellers with three blades (A-7800-79-3, B-7800-82-3 and C-7800-85-3) will give a reduction of propulsion power consumption compared to the propeller with four blades (R-7800-80-4) regardless of the propeller speed.

Regarding the propellers with four blades (A-7800-72-4, B-7800-82-4 and C-7800-85-4), the result for A-7800-72-4 (optimum propeller speed) is a propulsion power reduction around 1.54%, the other two (B-7800-82-4, C-7800-85-4) give an increase in power consumption.

Another comparison performed, is a direct comparison between propellers with the same propeller speed, but with different number of propeller blades, see Table 10. For all comparisons, the propellers with three blades result in a reduction in propulsion power consumption. The largest reduction is observed when comparing variants C-7800-85-4 and C-7800-85-3.

Based on Wageningen B-screw, series limitations, and the experience of MAN Energy Solutions, it has been concluded that the efficiency of the B-series propeller with three blades is overestimated, mainly due to the propeller speed variation from B-series testing. Taking this into account, a smaller difference in power consumption should be expected. However, it is clear that when changing to a propeller with three blades, a lower power consumption could be achieved.

Table 9: Comparison of propulsion power for the propeller variants and the reference

Propulsion power, relative difference to the reference R-7800-80-4			
A-7800-72-4	≈ -1.54%	A-7800-79-3	≈ -3.23%
B-7800-82-4	≈ +0.75%	B-7800-82-3	≈ -2.94%
C-7800-85-4	≈ +1.40%	C-7800-85-3	≈ -2.54%

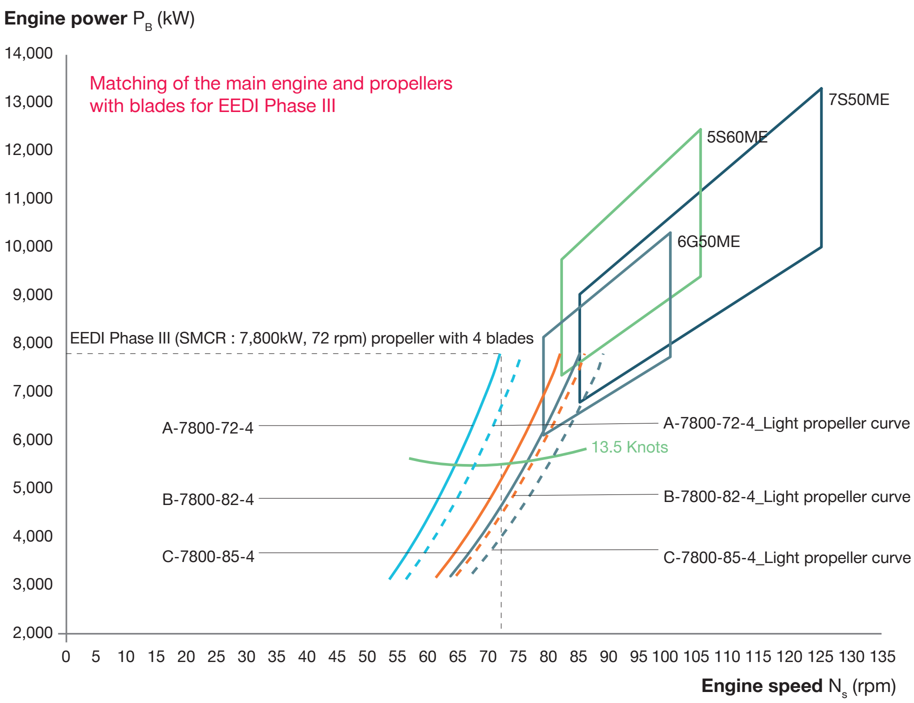

Fig. 7 Variants with four propeller blades

Table 10: Direct comparison of studied propellers

Relative propulsion power difference for the investigated propellers	
A-7800-72-4	A-7800-79-3
≈ -1.7%	
B-7800-82-4	B-7800-82-3
≈ -3.7%	
C-7800-85-4	C-7800-85-3
≈ -4.5%	

The comparison in Fig. 8 shows the advantage of the lower power consumption that the propeller with three blades will give compared to propellers with four blades. Not only at the design speed of 13.5 knots, but in the complete ship speed range. The propulsion power reduction is 2.5%–3.5% for B-7800-82-3, and 3.5%–5% for C-7800-82-3.

Hull-surface pressure pulses

Calculations have been carried out using an internal tool to evaluate the impact of reducing the number of blades and increasing the propeller speed on the induced pressure pulses from the propeller. The internal tool is based on empirical formulas derived from multiple numerical and experimental predictions for different ship types and propellers. Tables 11 and 12 contain the results of the induced pressure pulses for the investigated propellers compared to the reference propellers R-9000-84-4 and R-7800-80.

These two comparisons will give an indication of the pressure pulse tendency when going from EEDI Phase II to Phase III (Table 11) and for the investigated propellers for EEDI Phase III (Table 12). Based on the results, the conclusion is that both the number of propeller blades and the propeller speed have an impact on the induced pressure pulses.

Starting with the comparison of the existing propeller for EEDI Phase II (R-9000-84-4) with the investigated propellers, the result is that the pressure pulses have increased for all propellers with three blades. For the propellers with four blades, this applies only for the propeller with the increased propeller speed (C-7800-85-4).

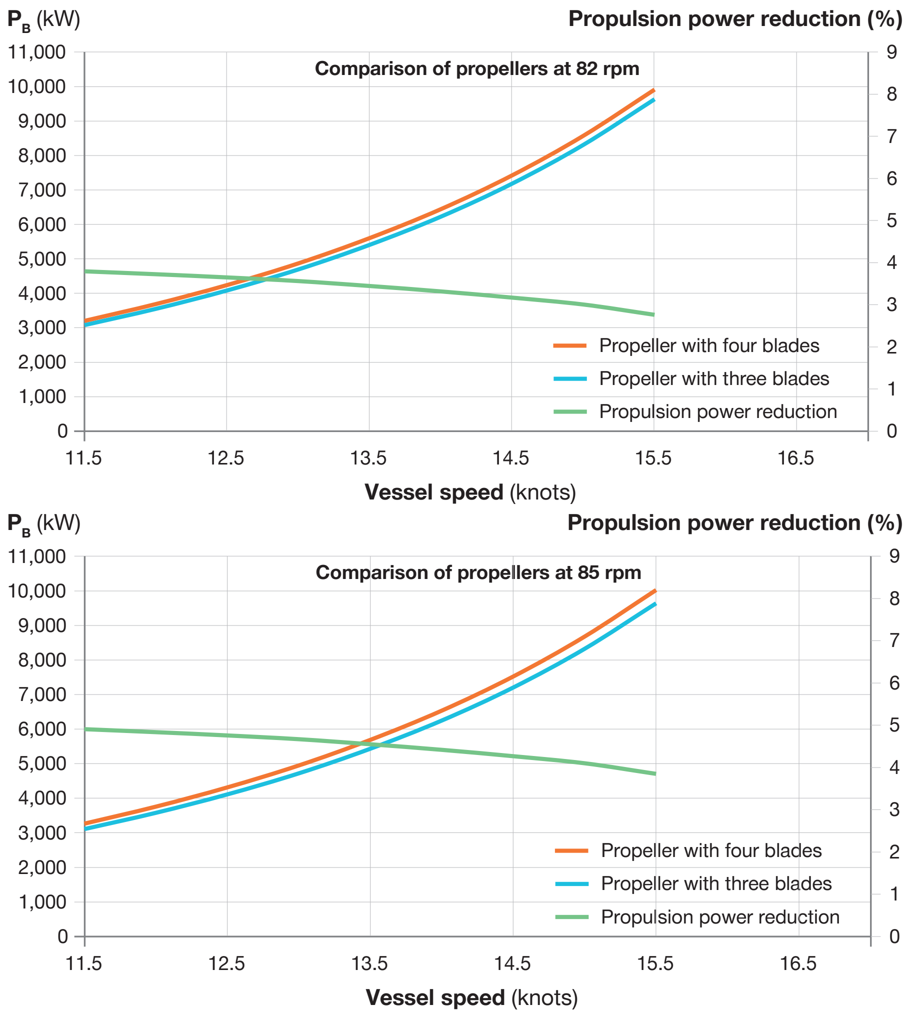

Fig. 8 : Propulsion power difference in the ship speed range

Table 11: Induced pressure pulses, comparison with R-9000-84-4

Pressure pulses, relative difference to R-9000-84-4

A-7800-72-4	≈ -8.2%	A-7800-79-3	≈ +11.4%
B-7800-82-4	≈ -1.6%	B-7800-82-3	≈ +15.5%
C-7800-85-4	≈ +2.4%	C-7800-85-3	≈ +18.0%

Table 12: Induced pressure pulses, comparison with R-7800-80-4

Pressure pulses, relative difference to R-7800-80-4

A-7800-72-4	≈ -5.9%	A-7800-79-3	≈ +14.2%
B-7800-82-4	≈ +0.8%	B-7800-82-3	≈ +18.4%
C-7800-85-4	≈ +5%	C-7800-85-3	≈ +20.9%

The largest increase is observed for C-7800-85-3, and C-7800-85-4. However, for the four-bladed propeller, the increase is much lower than for the propeller with three blades. In fact, there is an increase of around 2.4% for C-7800-85-4, and 18% for C-7800-85-3. This leads to the conclusion that reducing the number of propeller blades could cause an increase in pressure pulses. Moreover, the increased propeller speed could also increase pressure pulses, but on a lower level.

Table 11 shows the same tendencies as in Table 12. However, since in this comparison the reference propeller R-7800-80-4 has the same power as the investigated propellers, the pressure pulse tendencies for the propellers complying with EEDI Phase

III can be observed. Propellers with three blades cause higher level of pressure pulses compared to the propellers with four blades.

Table 13 shows another comparison of the investigated propellers. This comparison enables us to compare propellers with the same propeller speed and power, but with different number of propeller blades. It allows us to focus on the number of propeller blades to establish the impact on the pressure pulses.

Table 13 shows that the number of propeller blades has a clear impact on pressure pulses. From both of the comparisons, an increase in pressure pulses of around 15%-17% is observed for propellers with three blades. This increase is caused only by the reduced number of propeller blades. As expected, the fewer blades, the higher the load on each blade, which leads to a higher cavitation level at the blade surface and tip and to incresed pressure pulses.

Note that the level of pressure pulses must be within the guidance set by classification societies for these types of vessels [6].

The increase of induced pressure pulses could be suppressed by adjusting a range of propeller geometry parameters and characteristics.

The first parameter that could contribute to a reduction of pressure pulses is an increase in the area ratio of the propeller. This will limit the cavitation level to a smaller area of the propeller blade.

The second parameter is an increase in the propeller rake, which can increase the distance between the hull and the propeller tip and lead to a decrease in the induced pressure pulses.

Finally, yet importantly, an increase in the pitch unloading of the propeller blade tip will minimise the interaction between the tip vortex and the hull. This can also contribute to the reduction of the induced pressure pulses.

The adjustment of the propeller geometry parameters requires extra caution during the propeller design process, since any misapplication of these parameters can lead to a drop in the propeller efficiency.

Table 13: Induced pressure pulses, comparison of the variants

Pressure pulses, relative difference of investigated propellers

B-7800-82-4	B-7800-82-3
≈ +17%	
C-7800-85-4	C-7800-85-3
≈ +15%	

Torsional vibration analysis and engine property analysis

As mentioned, the consideration of torsional vibrations is of utmost importance for the selection and the safe operation of propulsion plants. According to the number of propeller blades and propeller speed combinations that have been studied, the range of engines that is available should be evaluated. Table 14 gives an overview of the available engines and the corresponding variants. To get an indication of the most suitable engine, the following two aspects are considered:

1. Properties and particulars for each engine
2. Requirement for torsional vibration damper

The upper part of Table 14 includes properties and particulars of each engine, that is mass, length, width, height, and SFOC.

The lower part of Table 14 contains the values of the investigated propellers regarding the torsional vibration analysis. These values include the propeller-polar inertia in water, propeller mass in air, and propeller area ratio. Based on these values and the shafting in Fig. 9, a preliminary torsional vibration analysis has been performed regarding the need for mounting a torsional vibration damper for each plant. However, as each propulsion plant has different properties, i.e. shafting length and diameter, shaft material, etc., only a detailed torsional vibration analysis could with certainty show if a torsional vibration damper is required.

Firstly, an increased polar moment of inertia in water for the propellers with three blades can be observed (Table 14). This is caused by the increased chord length of the propeller blade for three-bladed propellers compared to four-bladed propellers, which may be counterintuitive (Fig. 10). As a consequence, the amount of water entrained during the rotation of the propeller will be bigger for the propellers with longer blade chord

Table 14: Engine overview for the propeller variants

		EEDI Phase II propulsion plant	**Potential propulsion plants for compliance with EEDI Phase III**						
	Units	6G70ME-C10.5	6G50ME-C9	5S60ME-C10		7S50ME-C10		5G60ME-C10	6G50ME-C9
Propeller	-	**R-9000-84-4**	**R-7800-80-4**	**B-7800-82-4 & B-7800-82-3**		**C-7800-85-4 & C-7800-85-3**		**A-7800-72-4**	**A-7800-79-3**
SMCR power	kW	9000	7800	7800		7800		7800	7800
SMCR speed	rpm	84	80	82		85		72	79
Mass	t	332	246	-		262		395	246
Height	mm	10,500	10,775	10,500		9875		12,175	10,775
Length of engine	mm	7442	6620	6502		7497		7390	6620
Width of bedplate at top flange	mm	3550	3652	3550		3290		4220	3652
SFOC at 75% load	g/kWh	156.0	160.9	152.4		154.5		154.6	161.3
Propeller	-	**R-9000-84-4**	**R-7800-80-4**	**B-7800-82-4**	**B-7800-82-3**	**C-7800-85-4**	**C-7800-85-3**	**A-7800-72-4**	**A-7800-79-3**
Polar inertia in water	kg/m²	67,500	60,300	61,000	67,000	57,500	64,500	71,300	68,000
Mass in air	kg	22,200	20,500	23,500	23,000	20,400	22,000	25,000	22,000
Torsional vibration damper	-	Not expected	Expected	Expected	Expected	Not expected	Expected	Expected	Expected

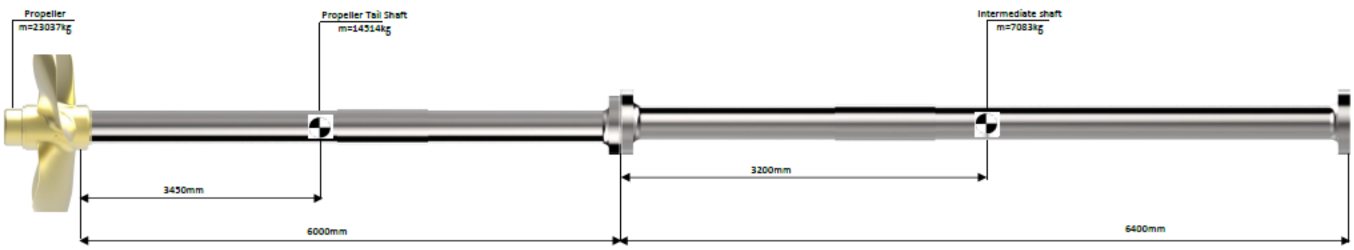

Fig. 9: Shaft line of the propulsion plants

length. Therefore, the entrained moment of inertia increases for propellers with three blades. When adding this to the mass moment of inertia, the polar moment of inertia for the three-bladed propellers increases. This increase means that a torsional vibration damper may be needed for plants coupled to propellers with three blades.

The EEDI Phase II propulsion plant, where the 6S60ME-C10 engine is coupled to the propeller R-9000-84-4, is used as the reference propulsion plant regarding the dimensions of engine room and hull. Moreover, it is used as a reference regarding the mounting of a torsional vibration damper which is typically not required for this propulsion plant.

Starting the evaluation with the 6G50ME-C9 engine coupled to the three-bladed propeller R-7800-80-4, the main disadvantage is the higher SFOC. Furthermore, the length, width, and height of the engine are slightly larger, which may result in engine room and hull modifications. For this engine-propeller configuration, the propeller inertia is also high, which may require a torsional vibration damper mounted to the propulsion plant.

In terms of dimensions, the 5S60ME-C10 is a suitable engine since adjustments to engine room and hull are not required. Furthermore, the SFOC is lower than the reference SFOC. This engine can be matched with either variant B-7800-82-4 or B-7800-82-3. The propeller variant with three blades (B-7800-82-3) will result in a lower propulsion power than the four-bladed variant (B-7800-82-4). However, both variants most likely need installation of a torsional vibration damper.

Similar to the 5S60ME-C10 engine, the 7S50ME-C10 engine is an appropriate engine when it comes to dimensions and SFOC. This engine can be coupled to either variant C-7800-85-4 or C-7800-85-3. It will result in a lower propulsion power and may require a torsional vibration damper for the C-7800-85-3 propeller. On the other hand, for the C-7800-85-4 propeller, a higher propulsion power is expected, whereas a torsional vibration damper is not expected.

The conclusion for the last two propulsion plants with propellers A-7800-72-4 and A-7800-79-3 and optimum propeller speeds is that the 5G60ME-C10 engine is a challenge for this ship type as regards dimension. The reason is that the engine height and width are much larger than for the engine on the reference propulsion plant.

Furthermore, a torsional vibration damper is required because the propeller inertia is increased significantly, which will result in increased initial cost of the propulsion plant.

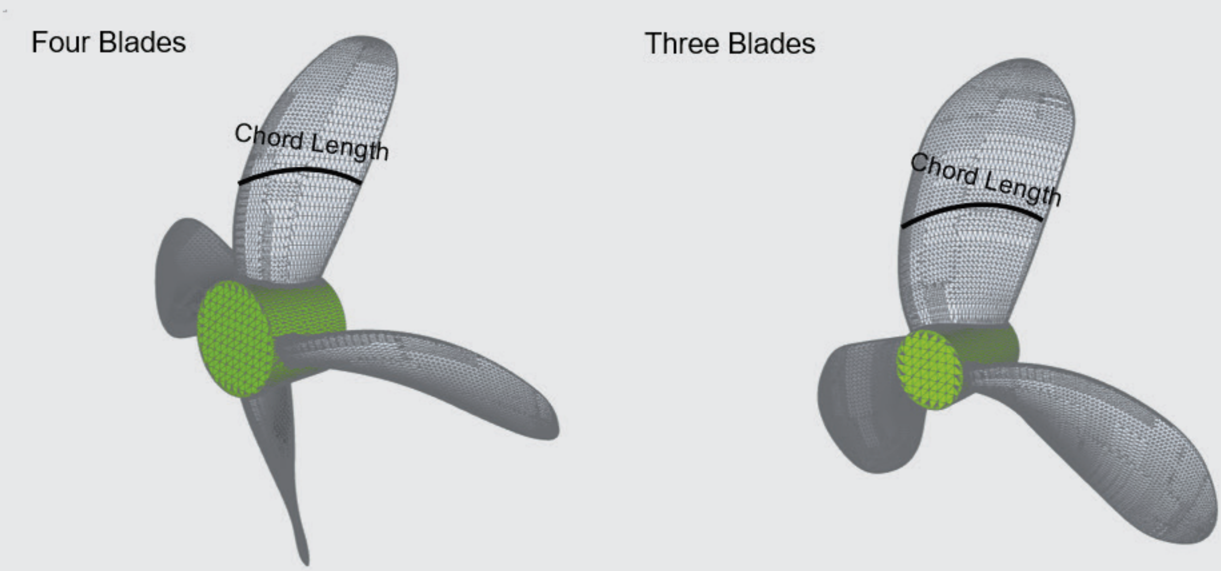

Fig. 10: Blade chord length for the propellers with four and three blades (source: www.friendship-systems.com) [5]

Case study 2: Suezmax tanker

The second case study considers a Suezmax tanker. This type of vessel is approximately 160,000 dwt and the term Suezmax reflects that this ship type is allowed to pass through the Suez canal. Typically, Suezmax tankers are equipped with a 6G70ME-C10.5 engine coupled to a fixed pitch propeller with four blades. Table 15 shows the ship particulars and the propulsion plant characteristics.

Since the series of calculations performed are identical to those in case study 1, the results will not contain detailed descriptions of the calculations. According to the predicted propulsion power of EEDI Phase III given in Table 16, a Wageningen B-screw series propulsion study has been performed and the results are given in the following.

The propeller variants considered for this case study are given in Table 17. The propeller variant R-12500-67-4 corresponds to the existing propulsion plant for power and propeller speed complying with EEDI Phase III. This propeller variant will be used as a reference when comparing with the other variants. The other three propeller variants, A-12500-67-3, B-12500-73-3, and C-12500-73-4, correspond to the different propeller speeds ($N_{S\ SMCR}$) and number of propeller blades (Z), which have been investigated to obtain compliance with EEDI Phase III.

Table 15: Ship particulars and propulsion plant characteristics for the Suezmax tanker

Ship particulars			Propulsion plant characteristics for EEDI Phase II		
Dwt	[t]	158,000	**Engine type**	[-]	6G70ME-C10.5
L_{WL}	[m]	274.0	**SMCR power**	[kW]	15,160
L_{PP}	[m]	269.0	**SMCR speed**	[rpm]	72
B_{WL}	[m]	48.0	**Propeller type**	[-]	FPP
T_{Design}	[m]	16.0	**Propeller diameter**	[mm]	9200
$T_{Scantling}$	[m]	16.0	**No of blades**	[-]	4
C_B	[-]	0.795	**A_e/A_0**	[-]	0.39
D	[-]		**P/D**	[-]	0.73

EEDI		
EEDI Phase II	≈ 2.69	$gCO_2/(nm*t)$
Propulsion power for EEDI Phase II	15,160	kW
Attained EEDI II	≈ 2.69	$gCO_2/(nm*t)$

Table 16: Required power for EEDI Phase III

EEDI Phase III	≈ 2.36	$gCO_2/(nm*t)$
Predicted propulsion power for EEDI Phase III	≈ 12,500	kW

Table 17: Propeller variants overview

R-12500-67-4			A-12500-67-3			B-12500-73-3			C-12500-73-4		
$P_{B\ SMCR}$	**kW**	**12.500**	**$P_{B\ SMCR}$**	**kW**	**12.500**	**$P_{B\ SMCR}$**	**kW**	**12.500**	**$P_{B\ SMCR}$**	**kW**	**12.500**
$N_{S\ SMCR}$	**rpm**	**67**	**$N_{S\ SMCR}$**	**rpm**	**67**	**$N_{S\ SMCR}$**	**rpm**	**73**	**$N_{S\ SMCR}$**	**rpm**	**73**
Z	**-**	**4**	**Z**	**-**	**3**	**Z**	**-**	**3**	**Z**	**-**	**4**

Fig. 11 illustrates the engines available that can be matched with the investigated propeller variants. For the propeller variants R-12500-67-4 and A-12500-67-3, the 5G70ME-C10.5 engine is available. However, it can be observed that by increasing the propeller speed to 73 rpm, the engines 6S70ME-C10.5 and 5S70ME-C10.5 become available for selection. With a reduced number of the propeller blades, a propulsion power reduction could be achieved.

According to the performed comparison of Table 18, the same tendencies can be observed also for this case study. The propeller variants with three propeller blades (A-12500-67-3, B-12500-73-3) offer a propulsion power reduction of around 2-4% while the variant with four blades (C-12500-73-4) increases the propulsion power consumption by around 4%. The comparisons have been performed for both 13.5 knots and 14.5 knots, which correspond to ship design speeds that are typical for this ship type.

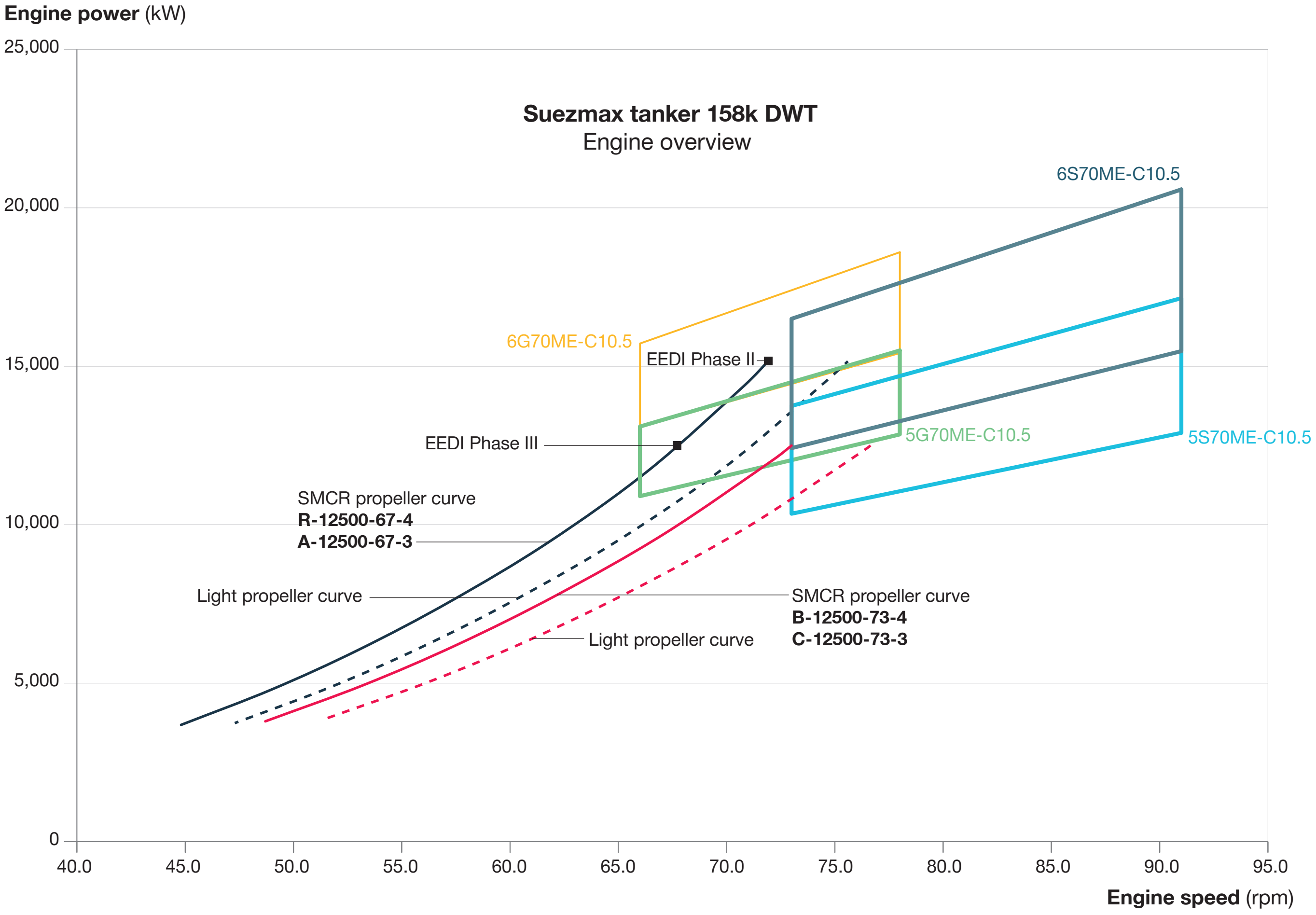

Fig. 11: Matching of available engine and propeller variant for EEDI Phase III

Table 18: Comparison of propulsion power for the propeller variants and the reference

Propulsion power, relative difference to R-12500-67-4

Propeller	Vs (kn) 13.5	Vs (kn) 14.5	Propeller	Vs (kn) 13.5	Vs (kn) 14.5
C-12500-73-4	**≈ 3.8%**	**≈ 3.8%**	A-12500-67-3	**≈ -4.0%**	**≈ -4.0%**
			B-12500-73-3	**≈ -2.0%**	**≈ -2.0%**

Hull-surface pressure pulses

Regarding the induced pressure pulses, similar tendencies can be observed for this case study as for case study 1. Table 19 gives an indication of the pressure pulse levels for the propeller variants compared to propeller R-15160-72-4. The R-15160-72-4 propeller is the initial propeller complying with EEDI Phase II. The conclusion is that both the higher propeller speed and the lower number of propeller blades will lead to an increase in pressure pulses. However, it should be noted that the level of pressure pulses is within the guidance set from classification societies for these types of vessels [6].

Torsional vibration analysis and engine property analysis

Similar to case study 1, Table 17 gives an overview of the combinations of engine and propeller variants investigated in this case study. The requirement of a torsional vibration damper is evaluated together with engine properties and particulars to find the best combination for the specific ship type, and to obtain compliance with EEDI Phase III.

According to the results of the preliminary torsional vibration analysis in Table 20, a torsional vibration damper is expected for all combinations of propeller variants and available engines. This tendency has been observed already for case study 1. Therefore, it can be assumed that for propellers with three blades, a torsional vibration damper will most likely be needed. Similar to case study 1, only a detailed torsional vibration analysis can firmly determine if a torsional vibration damper is required, since shafting arrangements and properties are different for each individual propulsion plant.

Table 19: Induced pressure pulses, comparison to R-15160-72-4

Pressure pulses, relative difference to R- 15160-72-4			
R-12500-67-4	**≈ -4.65%**	B-12500-73-3	**≈ +14.6%**
A-12500-67-3	**≈ +9.64%**	C-12500-73-4	**≈ +0.03%**

Table 20: Engine overview for the propeller variants

		EEDI Phase II propulsion plant	Potential propulsion plants for compliance with EEDI Phase III					
	Units	6G70ME-C10.5	5S70ME-C10.5		6S70ME-C10.5		5G70ME-C10.5	
Propeller	-	**R-15160-72-4**	**B-12500-73-3**	**C-12500-73-4**	B-12500-73-3	C-12500-73-4	R-12500-67-4	A-12500-67-3
SMCR power	kW	15,160	12,500		12,500		12,500	
SMCR speed	rpm	72	73		73		67	
Mass	t	586	424		502		521	
Height	mm	13,625	12,675		12,675		14,225	
Length of engine	mm	8443	7581		8679		8486	
Width of bedplate at top flange	mm	4628	4150		4150		4628	
SFOC at 75%	g/kWh	153.9	156.8		154.5		155.4	
Propeller	-	**R-15160-72-4**	**B-12500-73-3**	**C-12500-73-4**	B-12500-73-3	C-12500-73-4	R-12500-67-4	A-12500-67-3
Polar inertia in water	kg/m2	194,000	185,000	170,000	185,000	170,000	183,000	198,000
Mass of air	kg	43,000	42,000	40,000	42,000	40,000	46,000	45,000
Torsional vibration damper	-	Not expected	Expected	Expected	Expected	Expected	Expected	Expected

Acceleration capabilities and heavy running for lower rating engines

For propulsion plants complying with EEDI Phase III by a power reduction, while keeping the same propeller, it is relevant to consider the reduced absolute margin between the light propeller curve and the torque limit.

In Fig. 12, a power reduction of 14% is applied from the EEDI phase II compliant rating. This corresponds to the approximate power reduction needed for EEDI phase III compliance, but it will be project specific.

As seen from Fig. 12, when reducing the power along the nominal propeller curve, the relative light running margin will be maintained. However, the absolute margin from the light propeller curve to the torque limit of the EEDI phase III SMCR will be reduced compared to the absolute margin to the torque limit for the EEDI phase II compliant SMCR.

Consequently, as the vessel is the same, this may result in relatively reduced acceleration capabilities and a higher degree of heavy running for the EEDI phase III compliant rating. To counterbalance this characteristic of reduced power for EEDI Phase III propulsion plants, it is recommended to increase the relative light running margin. Thus, the same absolute margin from the new light propeller curve to the torque limit will be maintained. Hereby, the risk of heavy running and the acceleration capabilities will be kept similar to EEDI phase II compliant propulsion plants.

In the example here, the light running margin has to be increased from 5% for the EEDI phase II compliant rating to 7% for the phase III compliant rating, if the same absolute margin from the light propeller curve to the torque limit is to be maintained (Fig. 13).

This increase of the light running margin can be attained by reducing the SMCR speed of the engine, while the light propeller curve is maintained (Fig. 13). By decreasing the SMCR speed,

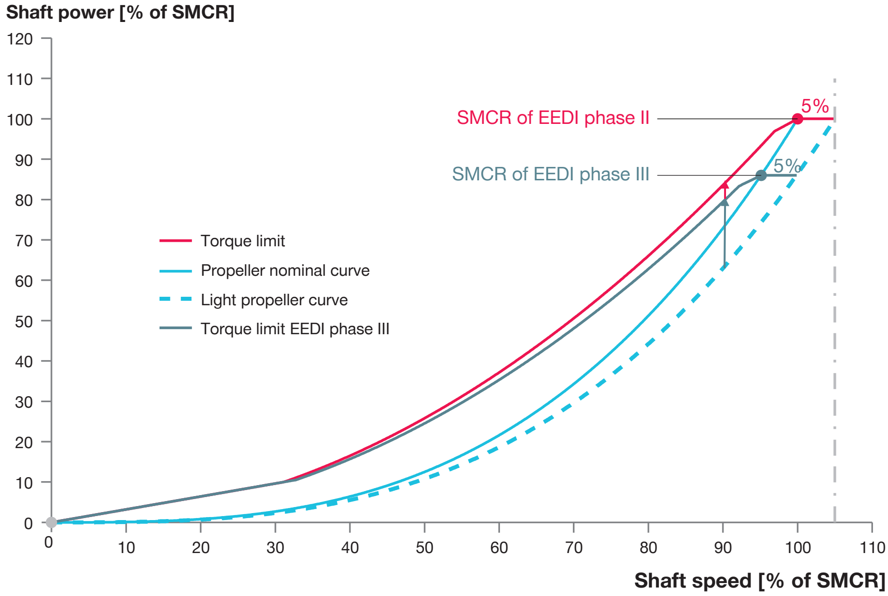

Fig. 12: Absolute margin between the light propeller curve and the torque limit

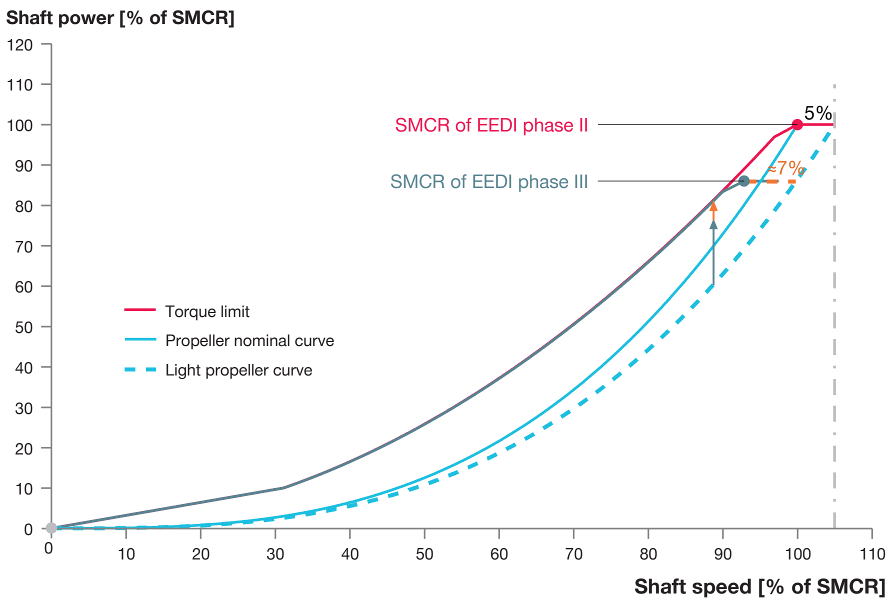

Fig. 13: Increased LRM by SMCR speed reduction

the engine will be slightly less mep-derated with an insignificant/negligible increase of SFOC as the result.

Alternatively, the propeller pitch can be decreased to increase the light running margin (Fig. 14). A project specific evaluation will uncover the best solution.

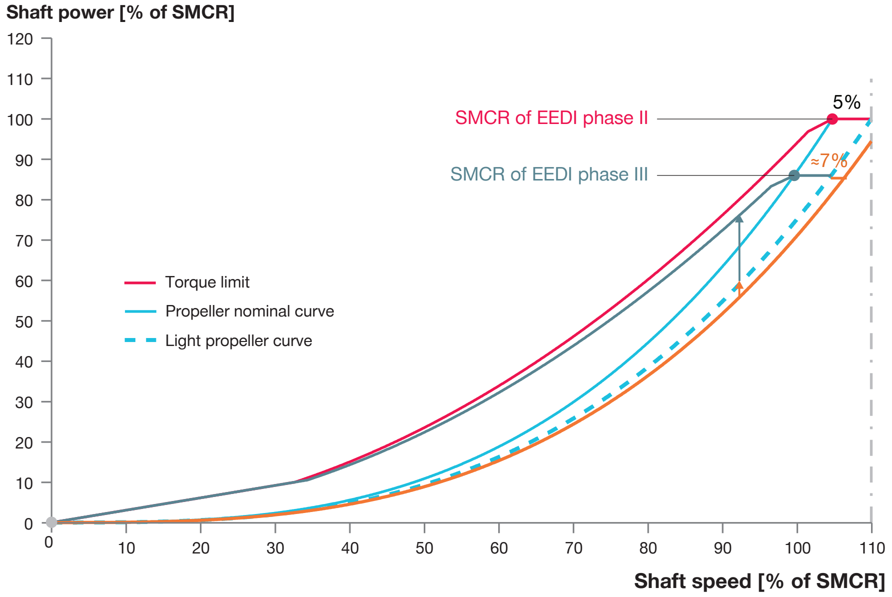

Fig. 14: Increased LRM by propeller pitch reduction

Conclusion

Going from EEDI Phase II to Phase III can create some challenges regarding matching of ship, engine, and propeller, in addition to selecting the most suitable propulsion plant. In this paper, propellers with three blades have been investigated as a tool for obtaining compliance with EEDI Phase III. Compared to propellers with four blades, the main characteristics of the three-bladed propellers are higher efficiency and higher optimum propeller speed. These characteristics have been utilised to meet the EEDI Phase III requirements and overcome the challenges.

One of the most important benefits of three-bladed propellers is the higher optimum propeller speed compared to the propeller with four blades. Thanks to this characteristic, the range of engines available becomes much wider. This means that more viable engines for the specific ships are available for EEDI Phase IIII propulsion plants. It gives both shipyards and shipowners the opportunity to select the most suitable MAN B&W engine according to their priorities.

Another benefit expected for propellers with three blades is the higher efficiency compared to propellers with four blades. This means that a reduction of propulsion power consumption should be expected for EEDI phase III propulsion plants coupled to propellers with three blades.

Although three-bladed propellers add important benefits to EEDI Phase III propulsion plants, the torsional vibrations, and induced pressure pulses must be considered.

The higher propeller speed and the lower number of propeller blades impact the induced pressure pulses. The calculations show increased levels of pressure pulses for both four- and three-bladed propellers combined with a higher propeller speed. However, the increase in pressure pulses is within acceptable guidance limits.

Furthermore, a series of mitigation measures could be employed to the propeller design to minimise the pressure pulses when selecting a three-bladed propeller.

The high inertia of the three-bladed propellers is likely to add torsional vibration dampers as an expected extra component for the potential propulsion plants coupled to propellers with three blades. Even though additional costs could be anticipated due to the torsional vibration damper, this could be compensated for by the reduced costs of the extended range of available MAN B&W engines, which are lighter (fewer cylinders or reduced stroke) and hence cheaper. However, this is subject to plant-specific torsional vibration analysis for each propulsion plant.

The above can be summarised by concluding that the propeller with three blades can be utilised as a component towards compliance with EEDI Phase III. This gives the benefit of an extended range of available MAN B&W engines thanks to the higher optimum propeller speed and lower propulsion power consumption resulting from the higher propeller efficiency.

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Abbreviations

EEDI:	Energy efficiency design index
IMO:	International Maritime Organization
GHG:	Greenhouse gas
PTO:	Power take off
CFD:	Computational fluid dynamics
FPP:	Fixed pitch propeller
SMCR:	Specified maximum continuous rating
LRM:	Light running margin
SFOC:	Specific fuel oil consumption

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