Adverse Weather Condition functionality and minimum propulsion power

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Contents

The tightening requirements of the Energy Efficiency Design Index (EEDI) means that the demand for energy efficiency of merchant vessels is continuously increasing. With the EEDI leading to reductions of the power on board, concerns about a possible lack of propulsion power during encounters of adverse weather have been expressed.

This paper gives a detailed description of the challenge of propulsion in harsh weather, and introduces the Adverse Weather Conditions (AWC) functionality. The AWC functionality extends the load diagram of the engine as long as required in an emergency. This increases the heavy running capability of the engine significantly and increases the minimum forward speed of the vessel in harsh weather, without requiring an increase of the engine power installed.

Introduction

In the merchant fleet, a two-stroke engine directly coupled to a fixed-pitch propeller is one of the most applied propulsion solutions due to the superior efficiency.

When a vessel with this propulsion system experiences added resistance in adverse weather, the torque required by the fixed-pitch propeller to maintain the rpm increases. In harsh cases, the torque required can increase beyond the torque limits of the main engine, whereby the power output from the engine is limited to a power that is less than the maximum continuous rating (MCR).

With ever-tightening Energy Efficiency Design Index (EEDI) phases, aiming at reducing the emission of greenhouse gasses, the installed propulsion power for new vessels is decreasing. This means that less power is available for maintaining a safe course in adverse weather.

The Adverse Weather Condition (AWC) functionality introduced and described in this paper makes it possible to increase the engine load limits in such conditions significantly more and for

longer periods than previously possible. Hereby the percentage of accessible MCR power is increased as long as an emergency in harsh weather requires it.

This increases the attainable vessel speed, which helps to ensure the manoeuvring capacity of the vessel. In this paper, the background and the advantages of the AWC functionality will be elaborated.

Additionally, a case study of the expected performance of a 50,000 dwt Handymax bulk carrier sailing in adverse weather with and without AWC function will be presented.

Heavy running propeller

When sailing in adverse weather, the resistance that the vessel experiences increases, which means the propeller becomes "heavy running", i.e. it requires more torque to maintain the same rate of revolution.

A heavy running propeller is equivalent to the experience a cyclist has, when going uphill without changing gear. As

the slope inclines, the cyclist has two options, either to provide a greater torque input to the pedals and hereby maintain the rpm of the wheels, or accept that an unchanged torque will result in lower rpm.

A similar experience of heavy running occurs, when the same cyclist bikes on a flat road at a uniform speed and suddenly encounters headwind. Because of the wind resistance, the cyclist has the same two options: Either to increase the torque input to the pedals and hereby maintain rpm or accept that a unchanged torque input reduces rpm.

The two-stroke engine has the same options, either to increase the engine torque and maintain the rate of revolution or to maintain the torque and accept a reduction in rate of revolution. Increasing the torque of an engine is, however, only possibly to a certain extent, within the limits of the engine load diagram – the AWC functionality extends these limits for the MAN B&W two-stroke engine.

Background for AWC

The EEDI reduces the allowable engine power installed on-board new vessels of otherwise traditional design, if the fuel, by which the vessel is propelled, is not changed from the traditional bunker oil to a less carbon-intensive fuel. The EEDI is presented in Equation 1 in a simplified form:

$$EEDI = \frac{P \times C_F \times SFC}{capacity \times V_{ref}}$$

P is the main engine power and C_F is a carbon factor accounting for the amount of CO_2 emitted per mass of fuel utilised. SFC is the specific fuel consumption at 75% engine load, capacity is the vessel deadweight tonnage and V_{ref} is the vessel speed at 75% engine load in calm water with the hull as in sea trial conditions.

For a specific fuel type and vessel capacity, Equation 1 reduces to Equation 2:

$$EEDI = \frac{P \times SFC}{V_{ref}}$$

From Equation 2 it is clear that one way to reduce the attained EEDI is by reducing the main engine power or the specific fuel oil consumption, while maintaining the highest possible service speed. For more information on the EEDI, see Chapter 4 of the paper "Basic principles of ship propulsion".

For vessels with a low EEDI compared to their vessel sizes, such as bulk carriers and tankers, the AWC function helps to ensure that a safe course-keeping speed can be maintained during adverse weather conditions.

For general information on the propulsion of bulk carriers and tankers in particular, see the papers "Propulsion trends in bulk carriers" and "Propulsion trends in tankers", respectively.

AWC and engine load diagrams

A load diagram of an engine defines the power and speed limits relative to the SMCR point specified within the engine layout diagram, see Figs. 1 & 2.

The load diagram is an important tool for describing an engine. Fig. 1 shows an engine load diagram where different numbered lines mark the limits for the engine. The position of the SMCR point in the *layout* diagram of the engine design does not influence the appearance of the engine *load* diagram,

the *layout* diagram merely shows which combinations of power and rpm for which it is possible to select the SMCR. See Chapter 3 of "Basic principles of ship propulsion" for further notes.

Line 1: The engine layout curve, which passes through the 100% SMCR-rpm and 100% SMCR-power point. The curve coincides with curve 2.

Line 2: The heavy propeller curve is the light propeller curve (line 6) shifted to

the left by the propeller light running margin. The light running margin is included to account for added resistance from wind, waves and hull fouling.

Line 3: Maximum continuous rpm.

Line 4: This line represents the torque/speed limit for continuous operation of the engine, which is mainly defined by the thermal load of the engine components. This limit can be extended temporarily by the AWC functionality described in this paper.

Line 5: Represents the maximum mean effective pressure (mep) acceptable for continuous operation.

Line 6: The light propeller curve for a clean hull and calm weather. This curve is often used for propeller layout.

Line 7: Maximum power for continuous operation. When increasing the rpm towards lines 3 and 9, the maximum power for continuous operation cannot exceed 100%.

Line 8: Normal overload operating limit of an engine without the AWC functionality.

Line 9: This is the maximum acceptable engine rpm at sea trial condition.

Line 10: PTO layout limit.

Recommended operation

The green area between lines 1, 3 and 7 is for continuous operation with propeller load only.

The yellow area between lines 1, 4 and 5 is for operating in shallow water, heavy weather and during acceleration, i.e. for non-steady operations without any strict time limitation.

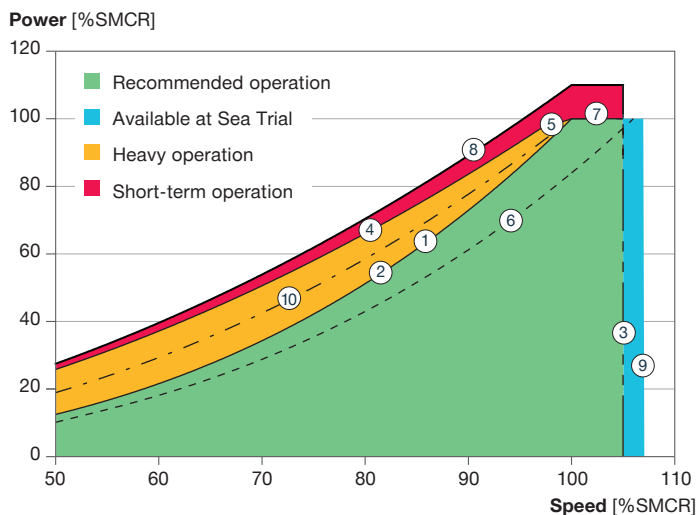The red area between lines 4, 5, 7 and 8 is for overload operation.

Fig. 1: Standard load diagram of MAN B&W engines with line definitions 1 to 10.
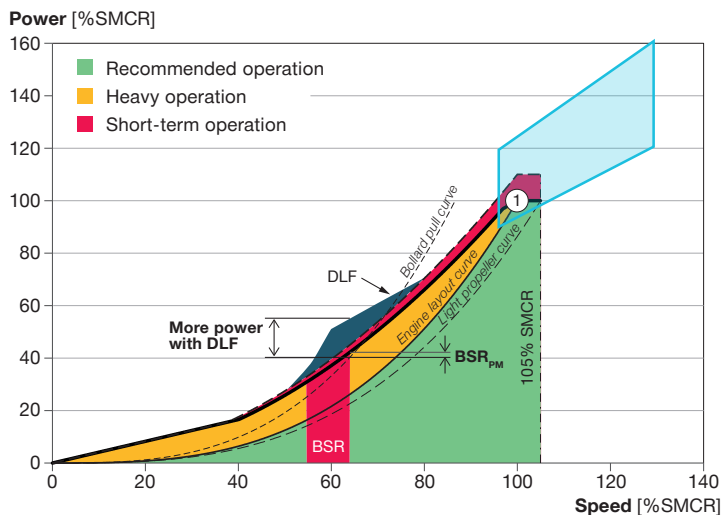

Fig. 2: Illustration of an engine load diagram with addition of the DLF and the bollard pull curve. The load diagram is independent of the SMCR position within the engine layout diagram, shown in blue.

Increased limiter function and dynamic limiter function

As the vessel encounters heavier resistance e.g. in a developing storm, the propeller torque, and hereby the engine torque, increases, shifting the light propeller curve, line 6, upwards, placing it left of the original curve. The operating point hereby approaches the torque limiter, line 4, in the load diagram. In an emergency, the torque limiter can be exceeded by activating the Increased Limiter Function (ILF) on the bridge. This increases the fuel index by 10% as standard on any MAN B&W engine. In its traditional form, the ILF can only be used in 1 hour out of 12 hours.

If the engine is equipped with the Dynamic Limiter Function (DLF), this function is also activated when activating the ILF, and the operating area is extended into the DLF area in the engine load diagram, see Fig. 2.

The DLF itself works by calculating the available air in the engine cylinders before each combustion takes place. When the mass of air is known, the Engine Control System (ECS) calculates the maximum allowable amount of fuel that can be injected into the combustion chamber before reaching the minimum acceptable air excess ratio. After approximately 30 minutes of DLF operation, the engine components need to cool down and the engine gradually reduces the limits back to the normal fuel index limiter. Because the DLF is time-limited, it is not suitable for long time heavy operation, which is required when encountering adverse weather conditions. See the paper "The Dynamic Limiter Function" for further information.

AWC functionality

The AWC functionality, is placed in continuation of the DLF and works according to the same principles by increasing the accessible torque, when the ILF is activated. By installing the AWC functionality, it is possible to
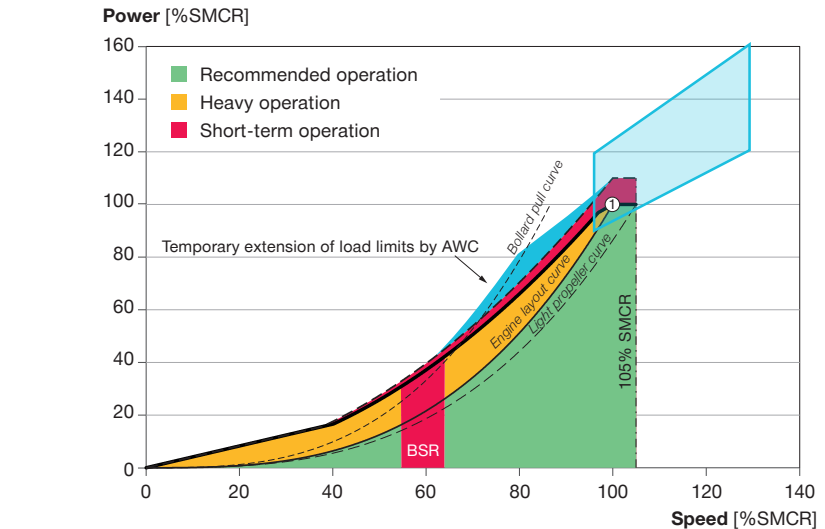

Fig. 3: Illustration of an engine load diagram with the AWC limiter applied. From the right, the light propeller curve, engine layout curve and the bollard pull curve.

access an even higher percentage of the MCR at lower rpm, as illustrated in Fig. 3.

Fig. 3 shows an illustration of an engine load diagram with the AWC functionality inserted. As seen in the load diagram, the AWC function extends the operating area in the range from 60% to 97% engine speed. The bollard pull curve in Fig. 3 represents the maximum propeller load when running ahead at zero advance speed, which based on experience typically lies 15% to 20% heavier than the light propeller curve, and set to 17.5% on the figure.

The AWC functionality enables the engine to follow the bollard pull curve up to 80% power and 80% rpm, working at 100% mean effective pressure in this point. This ensures that 80% of the SMCR power is available during encounters of adverse weather conditions, depending on the nature of the bollard pull curve and the propeller light running margin of the design.

Moreover, the operation of the AWC functionality is not under any strict time limits, which means it can be used as long as required in an emergency. Initiatives have been taken to reduce the thermal load on engine components during utilisation of the AWC

functionality as described in the following.

Working principles of AWC

In principle, the AWC functionality increases the amount of fuel injected into the combustion chamber, which increases the torque output of the engine. The AWC function delays the fuel injection, which limits the peak pressure and temperature in the combustion chamber. Thermal loads of piston crown, exhaust valve, cylinder liner and cylinder cover are hereby reduced and kept below the temperatures attained at the SMCR.

Over the years, possible pressure ratios of turbochargers have increased significantly. This enables a greater scavenge air pressure and increases the excess air ratio which reduces the thermal load of the engine components.

The delayed fuel injection improves conditions in the combustion chamber but increases the SFOC by 3% to 4%, compared to when the engine operates on the traditional torque limit curve.

The AWC functionality must be considered available for emergencies only. Frequent exposure to adverse

weather conditions with utilisation of the AWC will reduce guiding overhaul intervals like other special engine configurations. The avoidance of adverse weather encounters is still to be sought by good seamanship, weather routing, etc.

The AWC functionality is available for all ME-C10.5 and ME-C9.7 engines or newer. The function is integrated in the ECS and activated by the "Increased limiter function" button on the bridge. Consequently, it is neither necessary to change any hardware on the engine nor to implement additional buttons in the bridge control system.

The AWC functionality is not replacing the requirements for designing a propulsion system with sufficient propeller light running margin. MAN Energy Solutions recommends a light running margin of 4% to 7%, and up to 10% in special cases. Vessels with larger-than-usual PTOs, vessels operating in areas with very heavy weather and vessels operating in ice are examples of special cases. Similarly, vessels with two fixed pitch propellers/main engines, where one propeller/one main engine for some reason is blocked/declutched from time to time are considered special cases, which will benefit from an increased light running margin.

The AWC functionality should not be applied to increase the power taken out through a shaft generator/power take out (PTO), as such operation is not considered an emergency. Installation of the AWC functionality does not alter the PTO layout limit as it is described in Chapter 3 of "Basic principles of ship propulsion".

The AWC functionality should only be considered a retrofit solution for vessels with an acceptable light running margin at the time of vessel delivery, which also experience a need for extra torque when operating in adverse weather. The functionality should not be used as a measure to remedy the challenges of a poorly designed propulsion system with inadequate light running margin.

AWC and influence on evaluation of minimum propulsion power

Lowering a vessel's installed power has been acknowledged as a method to obtain a lower EEDI value, but at the same time, it has also raised the concern that it could result in underpowered vessels with reduced manoeuvrability in heavy weather. As a result of this, IMO has published an interim assessment method for determining the minimum propulsion power required to maintain a safe manoeuvrability of vessels in adverse conditions, Ref. [1].

The evaluation of minimum propulsion power can be performed by assessment level 1 or assessment level 2. Assessment level 1 allows calculation of the minimum power line value based on the vessel type and the deadweight, with coefficients a and b according to Ref. [1], see illustration in Fig. 4.

However, if the propulsion power installed is below the given minimum power line value of assessment level 1, then an evaluation on the vessel's design must be performed according to assessment level 2.

It should be noted that this guideline originally was valid for phase 0 and phase 1 of EEDI only. The final

guidelines are still under discussion at the time of writing, however, the present paper assumes that the interim guidelines apply to EEDI phase 2 as well. The reader is advised to stay updated and observe the latest guidelines from the IMO.

Assessment level 2 takes actual capabilities of the propulsion plant into consideration, i.e. level 2 accounts for the load diagram of the engine along with the light running margin of the propeller, etc. As the AWC functionality extends the engine load limits as long as required in an emergency, the application of AWC has a significant positive effect on the minimum speed a vessel can maintain in this evaluation. This is illustrated in the subsequent case study of the Handymax bulk carrier.

If the vessel – despite the application of the AWC functionality – cannot fulfil the criteria to any of the assessment levels, various options can be considered: The light running margin of the propeller, i.e. margin between the engine load limits and the calm water propeller curve, can be increased.

Alternative fuels, that lower the EEDI, will allow for a more powerful engine. Hull lines, and especially the bow, can be refined to minimise resistance in general, and from interaction with waves specifically, etc.

Power [kW]

Minimum Power Line Value = a × dwt + b
a = 0.0652 and b = 5,960.2 for tanker
a = 0.0763 and b = 3,374.3 for dwt < 145,000 dwt
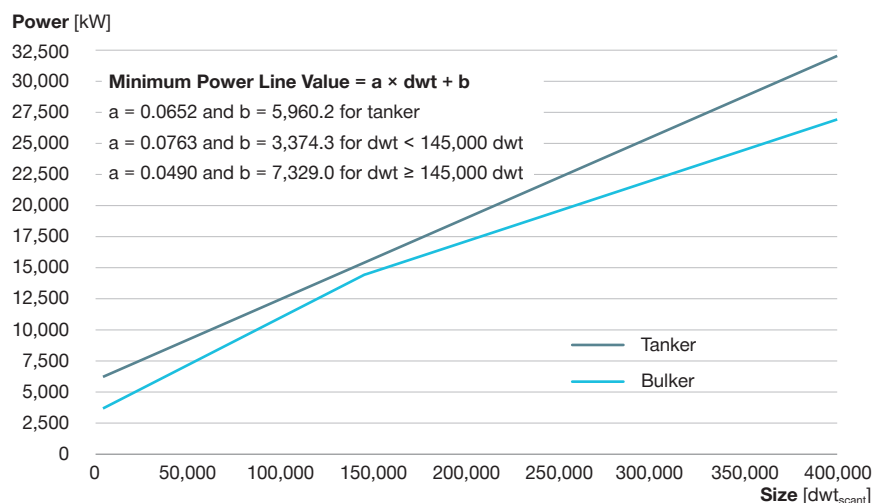a = 0.0490 and b = 7,329.0 for dwt ≥ 145,000 dwt

Fig. 4: Assessment level 1 of [1] for fulfilling minimum propulsion power requirements for tankers and bulk carriers as function of the scantling deadweight.

Case study on Handymax bulk carrier

The application and benefits of AWC, both with respect to rule compliance and actual performance, are exemplified through a case study on a 50,000 dwt Handymax bulk carrier. The case study includes a theoretical evaluation of the propulsion plant's capabilities with respect to minimum propulsion power. Furthermore, a practical evaluation of the Handymax bulk carrier operating fully laden with and without the AWC functionality in a developing seaway has been performed to illustrate the effects of applying AWC.

Main particulars of the bulk carrier considered are given in Table 1. With the very low SMCR applied, the vessel is according to calculations capable of fulfilling EEDI phase 3 by using traditional bunker. Considering this SMCR, specific attention must be given to the vessel with respect to minimum propulsion power.

Examples of minimum propulsion power evaluation with and without AWC

Following the simple equation 3, minimum propulsion power level 1, 7,189 kW is required for a bulk carrier of 50,000 dwt capacity, as it may be identified on Fig. 4 as well. As the SMCR is lower than this, a requirement for an evaluation according to assessment level 2 is set.

An assessment according to level 2 at the time of writing requires model tank tests to determine the transfer function for added wave resistance in head seas. Such tests are not available for the generic hull considered here and instead the added wave resistance in head seas is calculated by a method developed in the SHOPERA project and JASNAOE, see Ref. [2] and Ref. [3].

– L_{PP} is the length between perpendiculars in m.
– V_{vessel} is the speed in m/s.
– B is the breadth of the vessel in m.
– d is the draught in m.
– H_S the significant wave height in m.

Propeller characteristics, which relates resistance to engine power, are obtained via the Wageningen B-series, while propulsion coefficients such as the wake fraction and thrust deduction fraction are estimated by internal tools.

As the length between perpendiculars of the vessel is below 200 meters, $L_{PP} <$ 200 m, the minimum propulsion power guideline requires the performance of the vessel to be evaluated in a significant wave height of H_S = 4 m and a wind speed of V_{wind} = 15.7 m/s corresponding approximately to Beaufort 7.

Table 1: Vessel particulars for a typical 50,000 dwt Handymax bulk carrier, EEDI phase 3 compliant

Scantling draught	m	13.1
Design draught	m	12.0
Length overall	m	183.0
Length between perpen.	m	174.0
Block coefficient, L_{PP}	m	0.82
Breadth	m	32.2
Engine		6S50ME-C9
SMCR	kW	5870
SMCR	rpm	85
Sea margin	%	15
Engine margin	%	10
Light running margin	%	5
Type of propeller		FPP
Propeller diameter	m	6.8

$$R_{add\ wave} = 1336 \left(5.3 + V_{vessel}\right) \left(\frac{B \times d}{L_{pp}}\right)^{0.75} \times H_s^2$$

Fig. 5 shows an illustration of main engine loading while propelling the fully laden vessel in calm waters. The EEDI reference speed at 75% engine load with the hull as in sea trial condition, as considered here, is calculated to 13.3 knots.
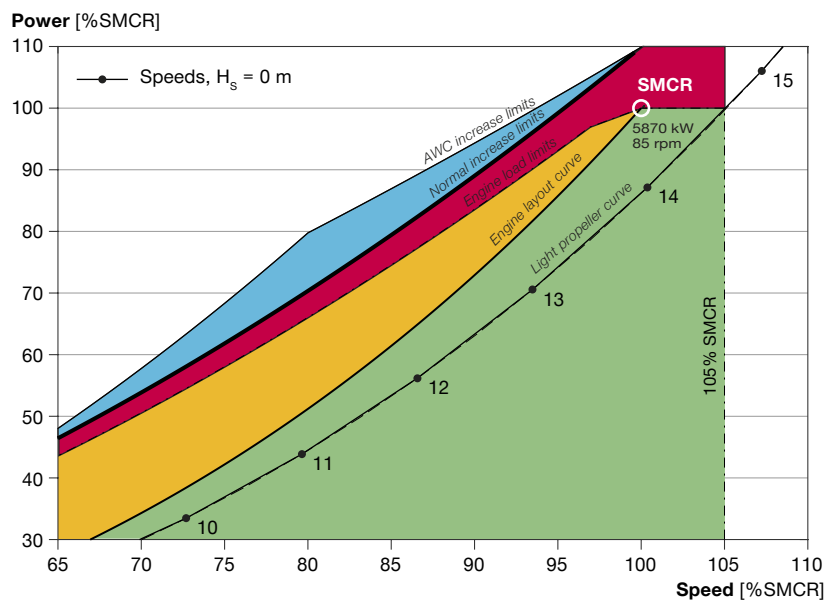

Fig. 5: Performance of the Handymax bulk carrier in calm water. Numbers along the black curve represent attainable vessel speeds in knots.

In this sea state, the propeller curve is heavy running and moves to the left compared to the calm water propeller curve illustrated in Fig 6. Here, it is seen that the vessel as such is compliant with minimum propulsion power guidelines without the AWC functionality, as the vessel can maintain the minimum navigational speed[1] of four knots within the normal load diagram. In fact, the vessel is capable of maintaining almost 7 knots before crossing the torque limiter of the two-stroke main engine. This is well above the required minimum navigational speed.

However, MAN Energy Solutions is obliged to keep vessels as safe as possible, and for this purpose the AWC functionality has been developed. The functionality can be activated if the vessel finds itself in an emergency in a more severe sea state than that specified by assessment level 2 of the IMO guidelines [1] as the example in Fig. 7 illustrates.

Here, H_S = 5.5 m and V_{wind} = 19 m/s is considered, corresponding approximately to Beaufort 8. In this case the performance is very different as the vessel will not be able to maintain 2 knots of forward speed within the traditional load diagram of the main engine. However, it has been calculated that the vessel can maintain a forward speed of 3 knots by activation of the AWC functionality.
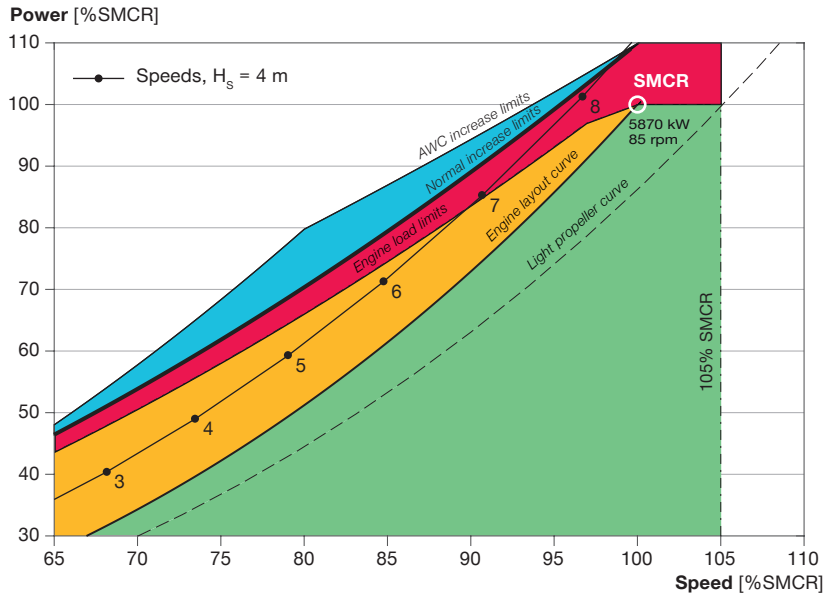
Fig. 6: Expected performance of the Handymax bulk carrier in Beaufort 7. Numbers along the black speed curve represent the attainable vessel speeds in knots.
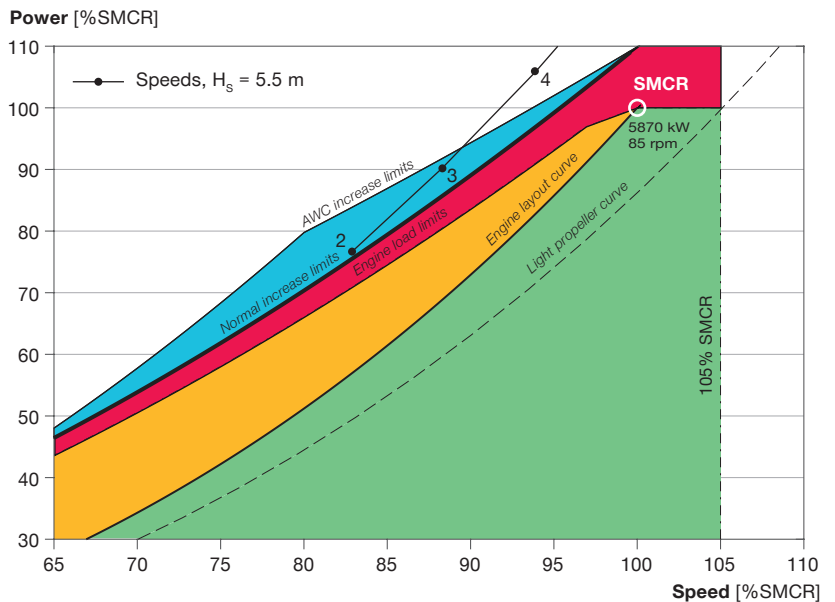
Fig. 7: Expected performance of the Handymax bulk carrier in Beaufort 8. Numbers along the black speed curve represent the attainable vessel speeds in knots.

1. Depending on the area of the rudder, the requirement for minimum course keeping speed also set by the guideline in [1] may be stricter than the requirements for the minimum navigational speed.

Influence of the propeller light running margin

Fig. 8 illustrates the importance of a sufficient light running margin. In this calculation, all parameters are as listed in Table 1, except the light running margin which is reduced to a value of 2%. A small light running margin of this order is not recommended for a new design, but a reduction of light running margin can occur over time as the hull and propeller foul.

The reduced light running margin means that only 5 knots can be maintained within the normal load diagram of the engine in Beaufort 7. Compared to the performance of a propulsion plant with 5% light running margin, as illustrated in Fig. 6, this is a reduction of 2 knots.

In the situation, where a vessel is delivered with 2% light running margin, a negative light running margin can be experienced as fouling grows on the hull. The negative light running margin will reduce the vessel's speed capabilities in adverse weather conditions even further - even if AWC is activated.

Performance in a developing sea of Beaufort 7-8 with and without AWC

An evaluation of the bulk carrier described in Table 1 operating fully laden with and without the AWC functionality in a developing sea has been performed.

Fig. 9 illustrates the engine performance *without* AWC, whereas Fig. 10 illustrates the performance *with* AWC, when sailing in head seas. The development of the sea state, represented by the development of significant wave height, Hs, is included in the bottom part of both figures along with the rpm of the engine.

The colour bar relates the sea state and engine rpm to the location of the operating point of the propeller/main engine in the engine load diagram illustrated in the upper part of the
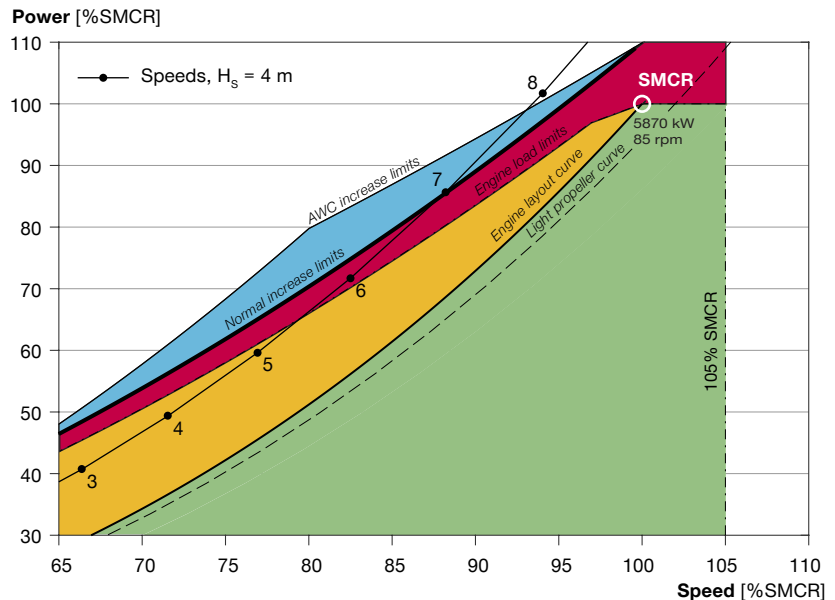

Fig. 8: Expected performance of the Handymax bulk carrier in Beaufort 7 with reduced light running margin. Numbers along the black speed curve represent the attainable vessel speeds in knots.

figures. In both situations the telegraph is set at 82% of maximum engine rpm, when the vessel sets to sea.

In both cases, it is clearly identified that the propeller becomes increasingly heavy as the sea state develops, increasing the power required to maintain the same rpm. After three days of sailing, the significant wave height develops from approx. 3 m to 5 m.

In the case without AWC, it is no longer possible for this low-EEDI vessel to maintain the rpm of the engine as the torque-limiter is activated. At this point, the vessel maintains a speed through the water of 3.7 knots. As the engine operates at the maximum torque permitted, the rpm will drop (light blue) until an equilibrium is established between the delivered thrust and the resistance, or the wave height reduces. In the case without AWC, the speed through the water drops to 2 knots as the wave height peaks. After the peak in wave height (dark blue), the engine accelerates the vessel along the torque limiter curve. At a certain point, the set

point of the telegraph is reached and the torque, and hereby power, reduces as the sea state eases, while the rpm is kept constant at the setting.

In the case with AWC, the propeller is just as heavy running as without AWC during the third day of sailing. The difference occurs as the significant wave height peaks (light blue). As the AWC is activated, the normal torque-limiter does not limit the torque delivered. Therefore, the engine is capable of delivering the increased torque required by the increasingly heavy running propeller as the sea state develops. Thereby the rpm can be maintained at the set point. In this case, the extended limits of AWC is not met.

Not hitting the limits makes a significant difference, and up to 80% of the SMCR power is delivered with AWC, whereas without only 58% of the SMCR power is available during the peak of wave height. This is also reflected in a significant difference in the speed through the water of the vessel – with AWC 4.2 knots can be maintained.
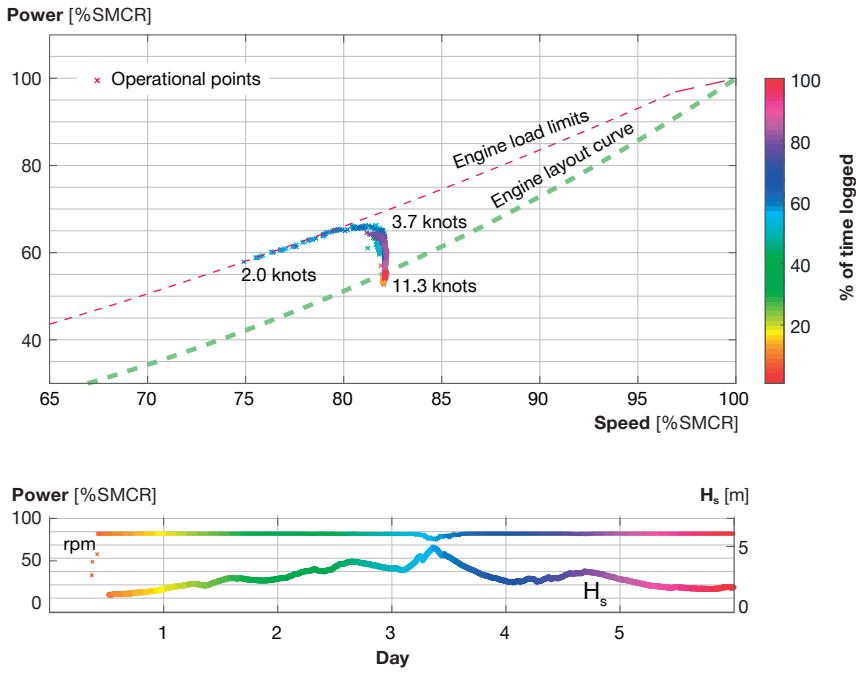
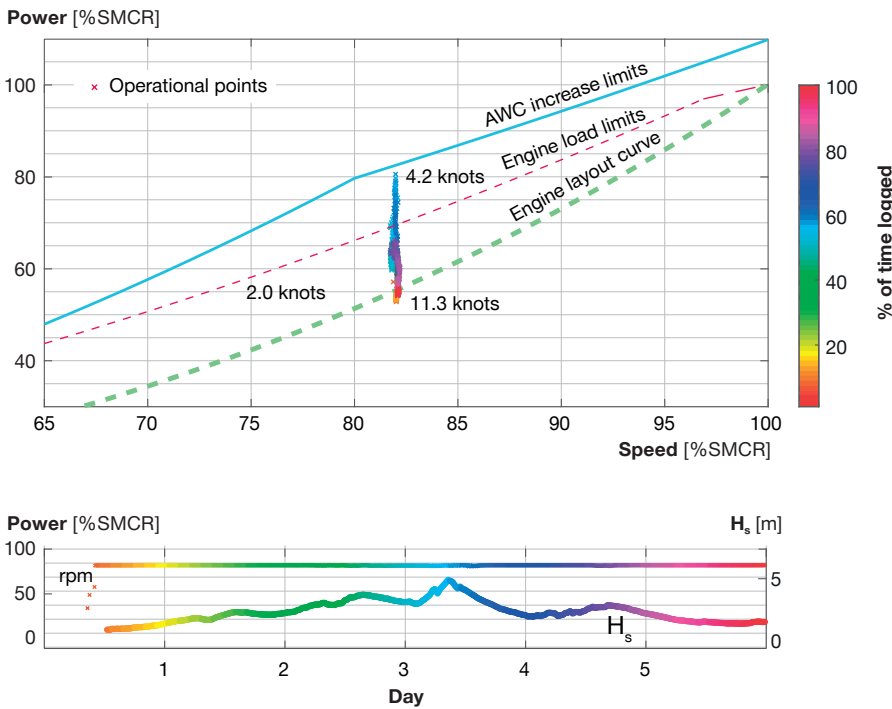Fig. 9: Expected performance of 50,000 dwt bulk carrier in heads seas *without* AWC.

Fig. 10: Expected performance of 50,000 dwt bulk carrier in heads seas *with* AWC.

Conclusion

When encountering adverse weather the propeller becomes increasingly heavy running and requires an increased torque in order for the vessel to maintain a safe manoeuvring speed.

The increased torque required can prevent an engine directly coupled to a fixed pitch propeller from delivering its full power, as the propeller is so heavy that full rpm cannot be reached.

The AWC functionality extends the load limits of the engine in the range from 60% to 100% engine speed. Hereby, it is possible to access a higher percentage of the MCR at lower rpm and maintain a higher speed as long as required in an emergency. The AWC functionality is available for all ME-C10.5 and ME-C9.7 engines or newer.

Reducing the power installed onboard is one of the ways to meet the increasingly stricter EEDI-requirements. The AWC functionality enables shipyards to install engines with less maximum power, while still fulfilling assessment level 2 of the minimum propulsion power guidelines set by IMO.

In a theoretical case study of a 50,000 dwt Handymax bulk carrier situated in a developing sea with and without the AWC functionality, it is shown that the attainable speed in heavy weather of Beaufort 8 is approximately doubled by AWC. Tests show a similar performance depending on vessel type, size, light running margin, etc.

The AWC functionality should not be seen as a remedy for a too small light running margin. The recommendation of 4-7% light running margin, up to 10% in special cases, is unchanged.

Frequent exposure to adverse weather conditions will reduce guiding overhaul intervals like other special engine configurations, why it is not recommended to utilise the AWC functionality for other purposes.

AWC can be considered for retrofit onboard vessels equipped with a modern ME-C engine of mark 10.5 or 9.7 with an acceptable light running margin at the time of delivery, which experiences a need for extra torque when operating in adverse weather.

For questions to and application of the AWC functionality, including feasibility of a retrofit, please contact MarineProjectEngineering2S@man-es.com.

References

[1] "2013 Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions, as amended (Resolution MEPC.232(65), as amended by resolutions MEPC.255(67) and MEPC.262(68)).", IMO, 2015

[2] "Draft revised guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions." IMO, MEPC 71-INF.28, 2017.

[3] "Supplementary information on the draft revised guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions." IMO, MEPC 71-INF.29, 2017

Abbreviations

DLF   Dynamic limiter function
EEDI   Energy efficiency design index
ECS   Engine control system
ILF   Increased limiter function
IMO   International Maritime Organiza-
        tion
MCR   Maximum continuous rating
MPP   Minimum propulsion power