Basic Principles of Ship Propulsion

DieselFacts presents extracts from a newly updated MAN Diesel & Turbo technical paper

This updated paper has been written by Birger Jacobsen, Senior Two Stroke Research Engineer, based in Copenhagen.

Heavy Waves and Sea and Wind Against

When sailing in heavy seas with much wave resistance, the propeller can be up to 7-8% heavier running than in calm weather, i.e. at the same propeller power, the rate of revolution may be 7-8% lower.

In order to avoid slamming of the ship in bad weather conditions, and thereby damage to the stem and racing of the propeller, the ship speed will normally be reduced by the navigating officer on watch.

A valid example for a smaller ship based on calculations is shown in Fig. 1. This example shows for a given reduced ship speed of 14 knots the influence of increased resistance caused by heavy weather and fouling expressed as increased sea margin.

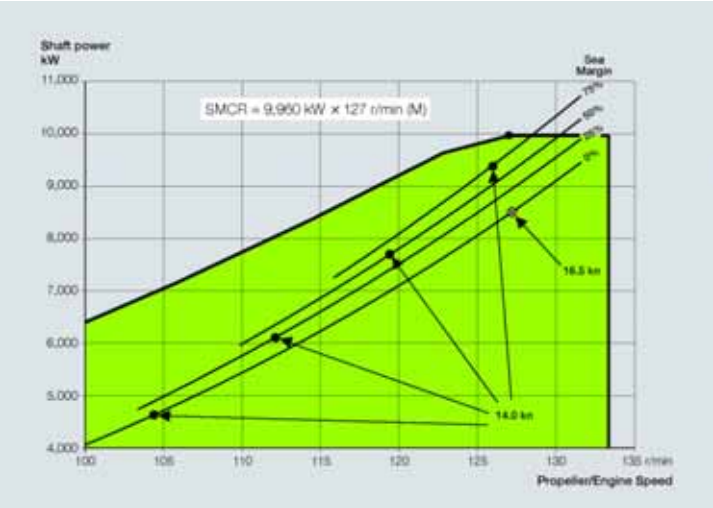

Fig. 1: Influence of sea margin on a small ship sailing at 14 knots

Standard Engine Load Diagram

Definitions

The load diagram (Fig. 2) defines the power and speed limits for the continuous as well as overload operation of an installed engine, which has a specified MCR point M that conforms to the ship's specification.

Normally, point M is equal to the MCR propulsion point MP, but in cases where a shaft generator is installed, point M may incorporate the engine power required for ship propulsion MP and for the shaft generator SG, if installed. During shop test running, the engine will always operate along curve I, with point M as 100% SMCR. If CP-propeller and constant speed operation is required, the delivery test may be finished with a constant speed test.

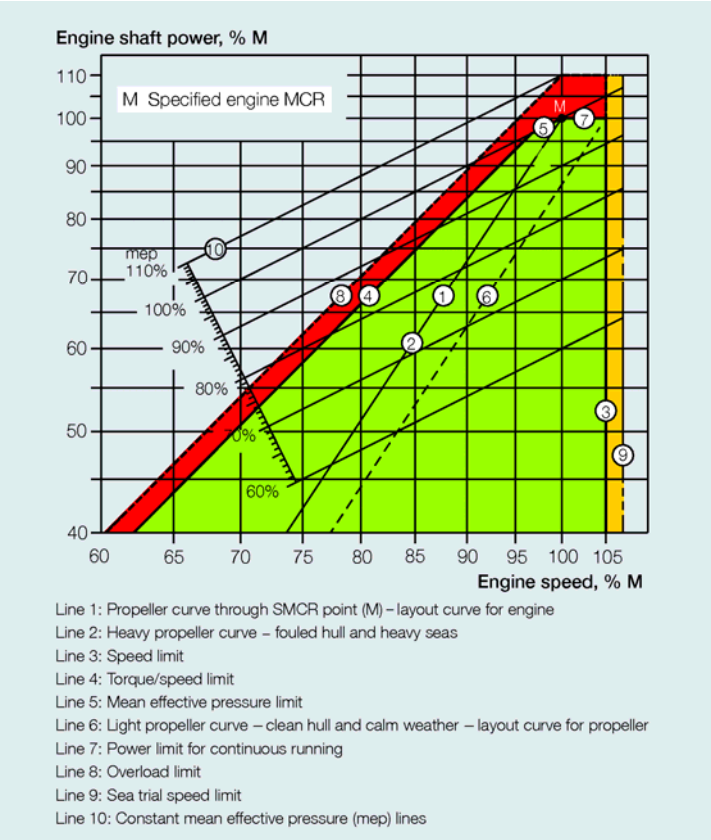

Fig. 2: Standard engine load diagram

Limits to Continuous Operation

The continuous service range is limited by the four lines 4, 5, 7, 3 and, in extraordinary cases, 9. See Fig. 2.

Line 3 and line 9:

Line 3:Represents the maximum acceptable speed for continuous operation, i.e. 105% of M. During sea-trial conditions the maximum speed may be extended to 107% of M, see line 9. The above limits may, in general, be extended to 105% and, during sea-trial conditions, to 107% of the nominal L1 speed of the engine, provided torsional vibration conditions permit.

The overspeed set-point is 109% of the speed in M, however, it may be moved to 109% of the nominal speed in L1, provided that torsional vibration conditions permit.

Running at low load above 100% of the nominal L1 speed of the engine is, however, to be avoided for extended periods of time.

Line 4: Represents the limit at which an ample air supply is available for combustion and imposes a limitation on the maximum combination of torque and speed.

Line 5: Represents the maximum mean effective pressure level (mep) which can be accepted for continuous operation.

Line 7: Represents the maximum power for continuous operation.

Line 10: Represents the mean effective pressure (mep) lines.
Line 5 is equal to the 100% mep-line. The mep-lines are also an expression of the corresponding fuel index of the engine.

Limits for Overload Operation

The overload service range is limited as follows, see Fig. 2. Line 8: Represents the overload operation limitation. The area between lines 4, 5, 7 and the dashed line 8 in Fig. 2 is available for overload running for limited periods only (1 hour per 12 hours).

Recommendation

Continuous operation without a time limitation is allowed only within the area limited by lines 4, 5, 7 and 3 of the load diagram. For fixed pitch propeller operation in calm weather with loaded ship and clean hull, the propeller/engine may run along or close to the propeller design curve 6.

After some time in operation, the ship's hull and propeller will become fouled, resulting in heavier running of the propeller, i.e. the propeller curve will move to the left from line 6 towards line 2, and extra power will be required for propulsion in order to maintain the ship speed. In calm weather conditions the extent of heavy running of the propeller will indicate the need for cleaning the hull and, possibly, polishing the propeller.

The area between lines 4 and I is available for operation in shallow water, heavy weather and during acceleration, i.e. for non-steady operation without any actual time limitation.

The recommended use of a relatively high light running factor for design of the propeller will involve that a relatively higher propeller speed will be used for layout design of the propeller. This, in turn, may involve a minor reduction of the propeller efficiency, and may possibly cause the propeller manufacturer to abstain from using a large light running margin. However, this reduction of the propeller efficiency caused by the large light running factor is actually relatively insignificant compared with the improved engine performance obtained when sailing in heavy weather and/or with fouled hull and propeller.

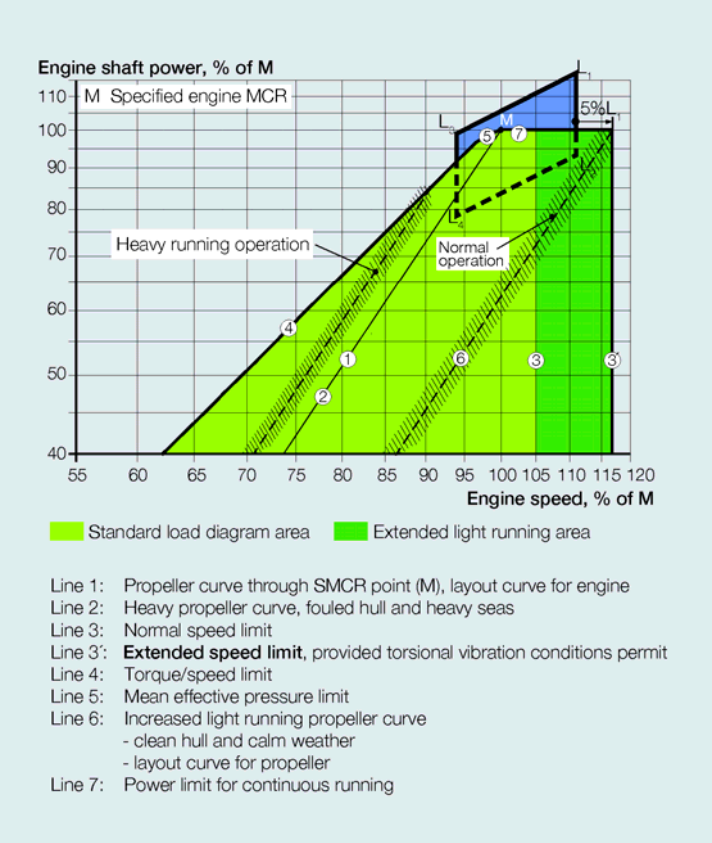

Fig. 3: Extended load diagram for speed derated engine with increased light running

Extended Engine Load Diagram

When a ship with fixed pitch propeller is operating in normal sea service, it will in general be operating around the design propeller curve 6, as shown on the standard load diagram in Fig. 2. Sometimes, when operating in heavy weather, the fixed pitch propeller performance will be more heavy running, i.e. for equal power absorption of the propeller, the propeller speed will be lower and the propeller curve will move to the left.

As the two-stroke main engines are directly coupled to the propeller, the engine has to follow the propeller performance, i.e. also in heavy running propeller situations. For this type of operation, there is normally enough margin in the load area between line 6 and the normal torque/speed limitation line 4, see Fig. 2. To the left of line 4 in torque-rich operation, the engine will lack air from the turbocharger to the combustion process, i.e. the heat load limits may be exceeded and bearing loads might also become too high.

For some special ships and operating conditions, it would be an advantage - when occasionally needed - to be able to operate the propeller/main engine as much as possible to the left of line 6, but inside the torque/speed limit, line 4.

Such cases could be for:

- ships sailing in areas with very heavy weather
- ships operating in ice
- ships with two fixed pitch propellers/two main engines, where one propeller/one engine is declutched for one or the other reason. Thus, measurements show an approximate 8-10% heavy running of the remaining propeller in operation for a twin-skeg ship.

The increase of the operating speed range between line 6 and line 4 of the standard load diagram may be carried out as shown in Fig. 3 for the extended load diagram for speed derated engine with increased light running. The maximum speed limit (line 3) of the engines is 105% of the SMCR speed, as shown in Fig. 2.

However, for speed and, thereby, power derated engines it is possible to extend the maximum speed limit to 105% of the engine's nominal L1 speed, line 3', but only provided that the torsional vibration conditions permit this. Thus, the shafting, with regard to torsional vibrations, has to be approved by the classification society in question, based on the extended maximum speed limit.

When choosing an increased light running to be used for the design of the propeller, the load diagram area may be extended from line 3 to line 3', as shown in Fig. 3, and the propeller/main engine operating curve 6 may have a correspondingly increased heavy running margin before exceeding the torque/speed limit, line 4. A corresponding slight reduction of the propeller efficiency may be the result, due to the higher propeller design speed used.

Constant ship speed line for increased propeller diameter

The larger the propeller diameter, the higher the propeller efficiency and the lower the optimum propeller speed. A more technically advanced development drive, therefore, is to optimise the aftbody and hull lines of the ship - including bulbous bow, also considering operation in ballast condition - making it possible to install propellers with a larger propeller diameter.

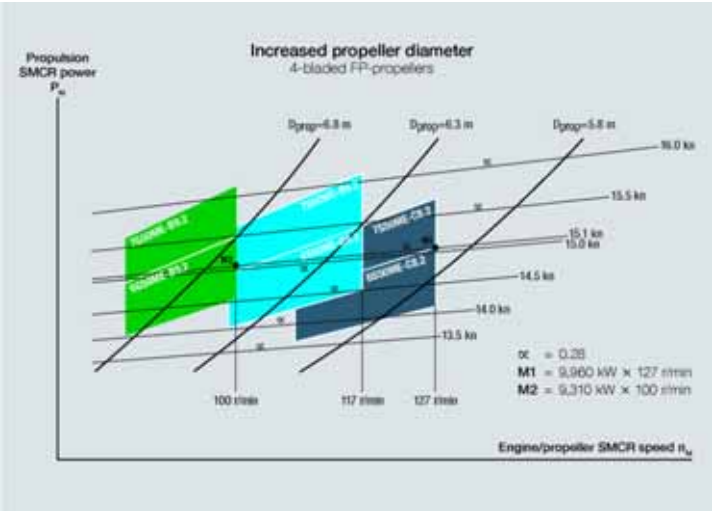

Fig. 4: Layout diagram and constant ship speed lines. Example for a Handymax tanker with different propeller diameters

The constant ship speed line a shown in Fig. 4 indicate the power required at various propeller speeds to keep the same ship speed provided that the optimum propeller diameter with an optimum pitch diameter ratio is used at any given speed, taking into consideration the total propulsion efficiency.

Normally, for a given ship with the same number of propeller blades, but different propeller diameter, the following relation between necessary power and propeller speed can be assumed:

$$P_2 = P_1 \times (n_2 / n_1)^{\alpha}$$

where:

P = Propulsion power

n = Propeller speed, and

α= the constant ship speed coefficient.

For any combination of power and speed, each point on the constant ship speed line gives the same ship speed.

When such a constant ship speed line is drawn into the layout diagram through a specified propulsion MCR point 'Ml', selected in the layout area, another specified propulsion MCR point 'M2' upon this line can be chosen to give the ship the same speed for the new combination of engine power and speed.

Provided the optimum pitch/diameter ratio is used for a given propeller diameter the following data applies when changing the propeller diameter:

For general cargo, bulk carriers and tankers α = 0.25 - 0.30, and for reefers and container vessels a = 0.15 - 0.25.

Fig. 4 shows an example of the required power and speed point Ml, through which a constant ship speed curve α = 0.28 is drawn, obtaining point M2 with a lower engine power and a lower engine speed but achieving the same ship speed.

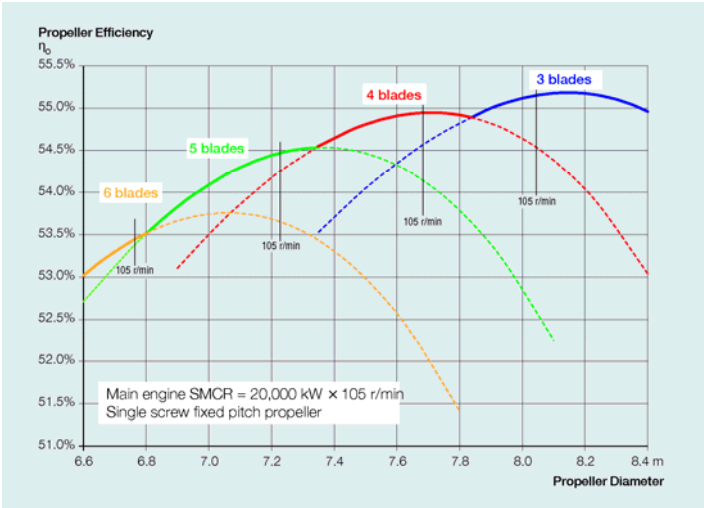

Fig. 5: Selection of number of propeller blades for a ship with main engine with SMCR = 20,000 kW x 105 rpm

Thus, when for a handymax tanker increasing the propeller diameter, and going for example from the SMCR propeller speed of n_{M1} = 127 r/min to n_{M2} = 100 r/min, the propulsion power needed will be $p_{M2} = p_{M1} \times (100/127)_{0.28} = 0.935 \times P_{M1'}$ i.e. involving a power reduction of about 6.5%. In this example, another main engine has been applied, verifying the fuel savings potential of this ultra low speed type engine. When changing the propeller speed by changing the pitch diameter ratio, the constant will be different.

$$n_M = C \times \sqrt[3]{\frac{P_M}{(D_{prop})^5}}$$

n_M *in r/min*
D_{prop} *in m*
P_M *in kW*
C is a constant depending on the number of propeller blades, see below.

Number of Propeller Blades	3	4	5	6
Contant (C)	125	115	104	93

Source: MAN Diesel & Turbo

Estimations of engine/propeller speed at SMCR for different single screw FP-propeller diameters and number of propeller blades

Based on theory and experience, the connections between main engine SMCR power P_M, SMCR speed n_M and propeller diameter d = D_{prop} can as guidance be estimated as follows:

In the constant C, a light running propeller factor of 4-5% is included. The above formula is valid for standard single screw FP-propeller types.

The constant C is an average value found for existing ships (before 2011) and reflects the design ship speed applied in the past.

For lower design ship speed which seems to be the coming tendency due to EEDI (Energy Efficiency Design Index) and fuel costs, the constant C will be higher. For an NPT propeller (New Propeller Technology), the estimated, claimed engine/propeller speed n_M might be approx. I 0% lower.

Number of propeller blades

Propellers can be manufactured with 2, 3, 4, 5 or 6 blades. The fewer the number of blades, the higher the propeller efficiency will be. However, for reasons of strength, propellers which are to be subjected to heavy loads cannot be manufactured with only two or three blades.

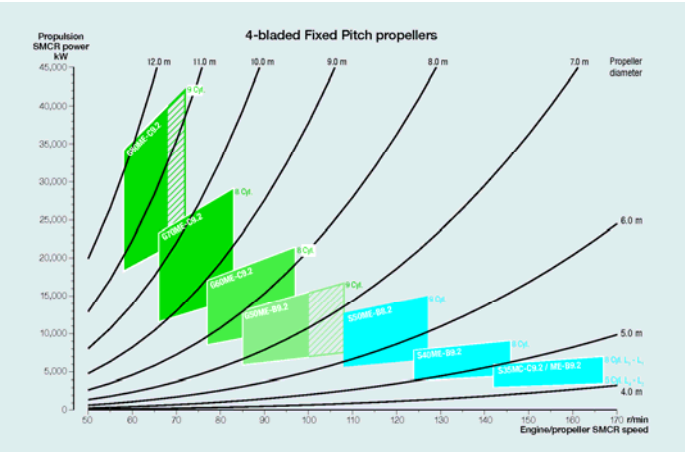

Fig. 6: Example of selection of 4-bladed Fixed Pitch propeller diameter (All figures source MAN Diesel & Turbo)

Normally 4-, 5- and 6-bladed propellers are used on merchant ships. In the future maybe 3-bladed propellers may be used due to reduced design ship speed. Ships using the MAN B&W two-stroke engines are normally large-type vessels which, so far, use at least 4-bladed propellers. Ships with a relatively large power requirement and heavily loaded propellers, e.g. container ships, may need 5 or 6-bladed propellers.

The optimum propeller speed depends on the number of propeller blades. Thus, for the same propeller diameter, a 6-bladed propeller has an about 10% lower optimum propeller speed than a 5-bladed. For vibrational reasons, propellers with certain numbers of blades may be avoided in individual cases in order not to give rise to the excitation of natural frequencies in either the ship's hull or its superstructure.

The influence of a selected number of propeller blades is shown as an example in Fig. 5 for a ship installed with a main engine with SMCR = 20,000 kW x 105 r/ min. For each number of propeller blades, the corresponding applied propeller diameter according to the previous formulae is shown too.

A more comprehensive propeller diameter example, based on the mentioned formulae, is shown in Fig. 6 and is valid for 4-bladed FP-propeller types. By means of a given propulsion SMCR (power and speed) point, it is possible to estimate the corresponding FP-propeller diameter.

However, in the upper power and propeller diameter range, it is, for technical reasons, probably necessary to select a 5-bladed or 6-bladed propeller type with a reduced propeller diameter and lower pressure pulses (vibrations). Some examples of main engine types (layout diagrams) to be selected are shown too.

The text for this article is based on extracts from the newly updated MAN Diesel & Turbo paper "Basic Principles of Ship Propulsion", written by Birger Jacobsen, Senior Two-Stroke Research Engineer in Copenhagen. An M.Sc. graduate of the Technical University of Denmark, Jacobsen joined the company back in 1969 and since 1979 has worked in the Marine Installation Department. He has since become the prolific author of varied technical papers on engine applications and propulsion trends in different vessel segments. The original paper is freely available in its entirety upon request from MAN Diesel & Turbo.•

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