Dynamic limiter function

MAN Energy Solutions
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Dynamic limiter function
A new engine control technology for faster ship acceleration

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The dynamic limiter function (DLF) is a new engine control system functionality that has been developed to improve engine and ship acceleration. This paper describes some principles of ship acceleration and why MAN Energy Solutions has chosen to develop DLF and how DLF works.

A vessel must have sufficient acceleration capability, but the acceleration of the shaft line can also be an issue due to barred speed ranges. This paper focuses on shaft line acceleration. If the shaft line acceleration is sufficient then vessel acceleration will in most cases also be sufficient.

If the engine and shaft line have a barred speed range (BSR), it is usually a class requirement to be able to pass the BSR quickly. The quickest way to pass the BSR is the following:

1. Set the rpm setting to a value just below the BSR.
2. Wait while the ship accelerates to a vessel speed corresponding to the rpm setting.
3. Increase the rpm setting to a value above the BSR.

When the BSR is passed as described above, it will almost always be quick. In some cases, for example in certain manoeuvring situations in port or at sea in adverse conditions, it may not be possible to follow the procedure outlined above for passing the BSR. This can be either because there is not time to wait for the vessel speed to build up, or because high vessel resistance makes it impossible to achieve a vessel speed corresponding to the engine rpm setting. In such cases, it can be necessary to pass the BSR at low or zero ship speed.

At zero ship speed, the propeller is operating on the bollard pull propeller curve for the vessel. Based on experience, the bollard pull propeller curve for a vessel with a fixed pitch propeller is 15% to 20% heavy running relative to the light propeller curve for the vessel. This means that in bollard pull condition, the propeller power required in the BSR is significantly higher than when the vessel operates on the light propeller curve (normal sailing) before accelerating through the BSR. Starting the acceleration from zero ship speed may therefore result in longer times for passing of the BSR. Especially if the BSR is placed high in the engine rpm range.

Contents

When studying recent cases where the time for passing the BSR was too long, it became clear that these vessels all had derated 5 or 6-cylinder engines and a BSR quite high in the rpm range. Many of the vessels also had a small propeller light running margin. As a result, the required propeller power was quite high when passing through the BSR. This made the passage of the BSR slower than usual because the power surplus for acceleration of the propeller was low.

These findings led to the definition of two tasks:

1. Establish a simple design rule so that an acceleration issue can be avoided already at the ship design stage.
2. Increase the engine power available during acceleration so that the design rule mentioned in Item 1 puts as few constraints on the ship designer as possible.

As described in this paper, the tasks have been solved by developing:

1. The BSR power margin: a simple design value developed to predict whether the BSR passage will be quick or not.
2. The dynamic limiter function (DLF): a new engine control system functionality to dynamically increase the power available at low engine speed and, thereby, increase propeller acceleration and reduce the BSR passage time.

Background

for quick passage of barred speed range

Due to excessive torsional vibrations at the main critical resonance, many shaft lines have a barred speed range. In order not to damage the shaft line, it must be possible to pass the barred speed range quickly in all relevant conditions. As a general rule, the barred speed range should be passed within seconds, not minutes. The actual maximum acceptable passage time depends on a number of things:

- magnitude of the stress levels shaft material used
- operational profile of the ship: how often is it required to pass the BSR?
- the way the BSR is passed.

If the input to the calculation is appropriately defined, it is possible, in theory, based on fatigue analysis, to calculate the maximum acceptable passage time. The challenge is to appropriately define the input to the calculation, and a detailed evaluation of fatigue lifetime does not usually make sense due to the large uncertainties in the input data. So far, most classification societies have specified that passage of the BSR should simply be quick, but the rules are now being refined (IACS M51, Rev. 4 2015).

The energy efficiency design index

Until recently, passage of the BSR was almost always quick. The reason was that the BSR was placed in the lower end of the rpm range where the propeller power was low. The engine power available was therefore more than sufficient for quick passage of the BSR. Things have changed by the general focus on fuel economy and the introduction of the energy efficiency design index (EEDI). In many newer ship designs, the BSR is placed higher relative to the SMCR (specified maximum continous rating) rpm than it used to be. The following provides an explanation of why this trend is seen.

With respect to the main engine, the EEDI is defined as in Equation 1:

$$EEDI = \frac{P_{ME} \cdot CF_{ME} \cdot SFC_{ME}}{Capacity \cdot V_{ref}}$$

Equation 1

Where P_{ME} is 75% of the main engine power, CF_{ME} is a conversion factor between tonnes of CO_2 emitted and tonnes of fuel consumed, SFC_{ME} is the specific fuel consumption of the main engine. Capacity is the ship capacity proportional to the deadweight tonnage, and V_{ref} is the ship speed at 75% engine load in ideal sea trial conditions.

For a given ship capacity and operation on a given type of fuel, the EEDI is therefore related to the main engine power, specific fuel oil consumption and vessel reference speed as:

$$EEDI = \frac{P_{ME} \cdot SFC_{ME}}{V_{ref}}$$

Equation 2

The EEDI value must be below certain threshold values depending on when the ship is built. It is therefore clear from Equation 2 that the EEDI drives a development to reduce the main engine power and specific fuel oil consumption while maintaining as high a ship speed as possible. This is also the intention with the EEDI. Reducing the main engine power and the SFC can be achieved simultaneously by mean effective pressure (MEP) derating of the main engine. While derating is efficient for improving the EEDI, it has had some consequences for the quick passage of the BSR. Quick passage is affected by two principal effects:

1. The reduction in SMCR engine speed when derating typically moves the BSR up in relation to SMCR.
2. The Miller timing of the engine, forming the basis for the improved SFC, reduces engine torque while the propeller size is usually not reduced.

The first effect is explained in more detail in this chapter, and the second effect, and how the dynamic engine torque has been increased, is described in the chapter “Engine Design for Quick Passage of the Barred Speed Range”.

Relative position of the barred speed range

When the engine of a given ship type is derated, the engine layout point (SMCR) is typically moved down in power along a propeller curve. This means that derating moves the layout point from L1 towards L4 in the layout area for the engine. At the same time, the basic engine, shaft and propeller design is not significantly changed with respect to torsional vibrations. This means that the vibrational characteristics of the system are approximately the same, unless action is taken to change those characteristics. The result is that the main critical frequency of the shaft system, and thereby the BSR, remains at about the same rpm. When the layout point is reduced in rpm, the BSR therefore moves up relative to the SMCR. This is illustrated in Fig. 1, 2 and 3.

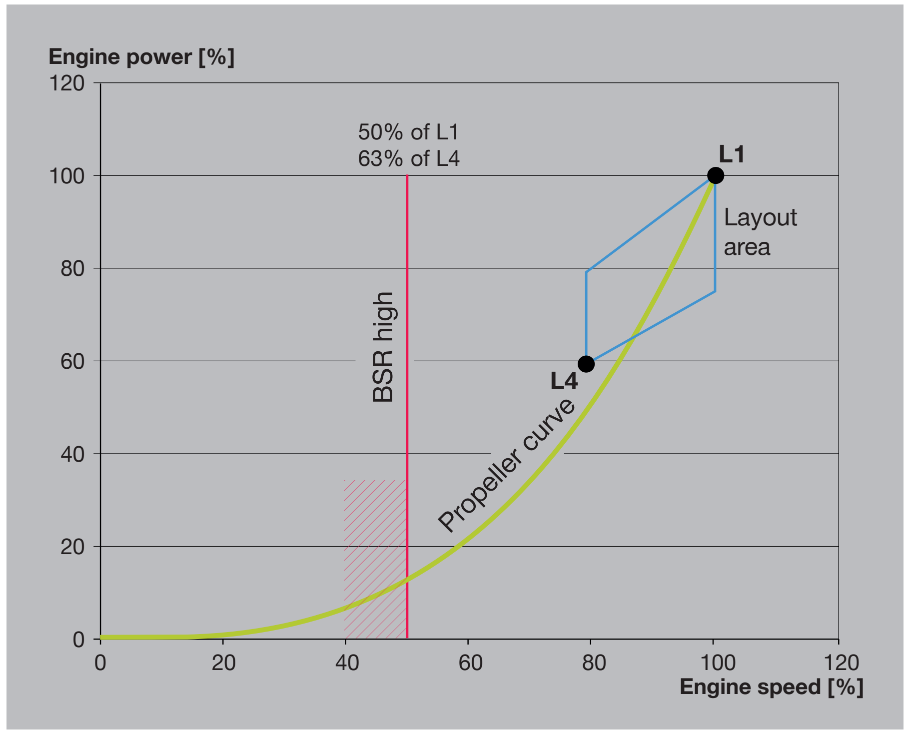

Fig. 1: General focus on fuel economy and the introduction of the EEDI have led to reductions in engine power. Engine SMCR is increasingly selected near the L4 rating instead of the L1 rating. Because the rated speed is then lower, this often results in the BSR being placed higher in relation to the layout point: 50% of L1 rpm is 63% of L4 rpm.

Fig. 2 and 3 illustrate why passage of the BSR becomes slower if derating is done without ensuring that the BSR is kept sufficiently low in the rpm range. In both figures, the BSR is placed at the same absolute engine rotation speed (rpm).

Bollard pull

In Fig. 2 and 3, it is assumed that the bollard pull (zero ship speed) propeller heavy running relative to the light propeller curve is 17.5%. This is based on previous experience, which has shown that this value is typically 15% to 20%.

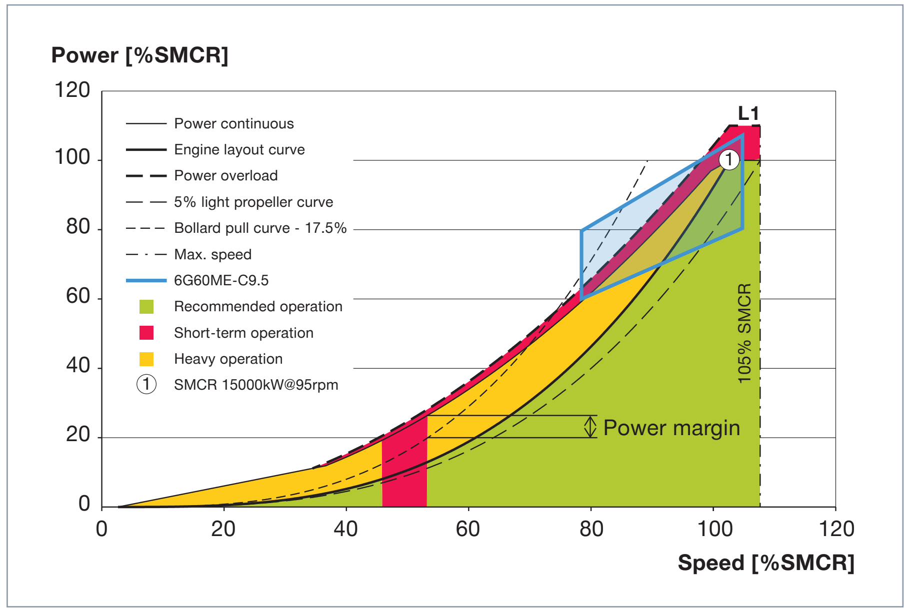

Fig. 2: Near L1 rated engine with indication of the margin between the engine load diagram and the bollard pull propeller curve. The margin is large, resulting in quick passage of the barred speed range (BSR) even at zero ship speed.

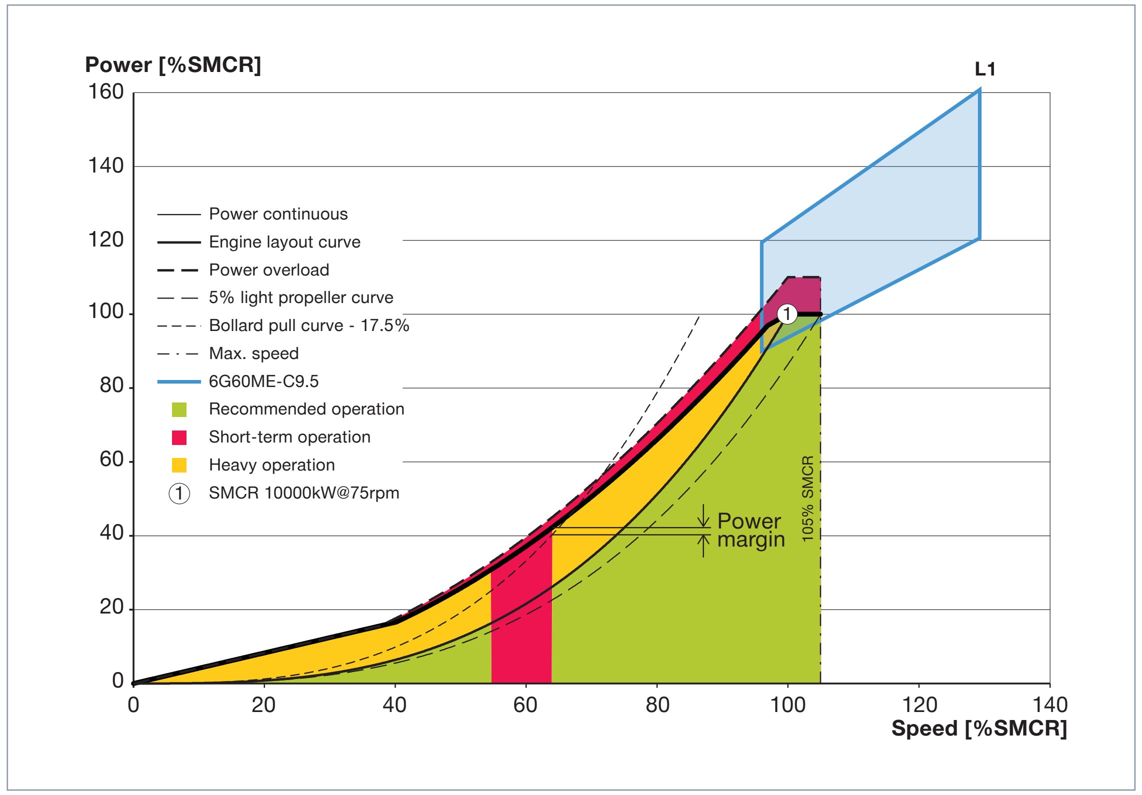

Fig. 3: Near L4 rated engine with indication of the margin between the engine load diagram and the bollard pull propeller curve. The margin is small resulting in slower passage of the barred speed range (BSR) at zero ship speed. If the BSR was moved down in rpm or more light running was applied to the propeller, the power margin would become bigger and the passage of the BSR would be quicker.

Propulsion system design

for quick passage of barred speed range

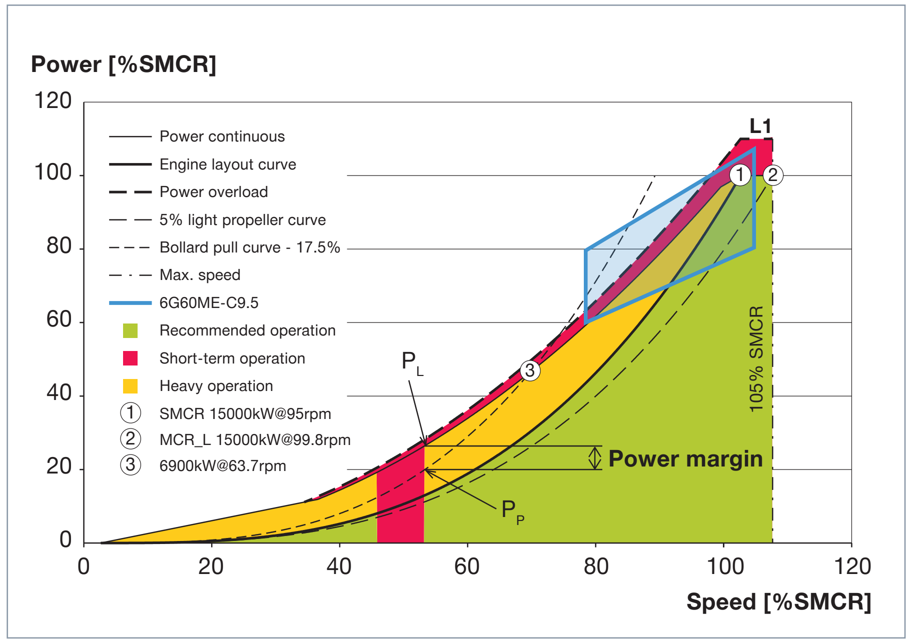

Fig. 4: MAN B&W engine load diagram with indication of a barred speed range (red), the required propeller power at the upper end of the BSR in the bollard pull condition (Pp) and the available power surplus for propeller acceleration (P_L-Pp). The diagram has power on the Y-axis, but at a given rpm power is proportional to torque. The BSR power margin is 33% in this case.

Based on the cases with slow passage of the BSR that have been examined, a design value has been established that makes it possible to estimate, during the vessel design phase, whether it will be possible to pass the BSR sufficiently quick at low and zero ship speed. This design value is called the BSR power margin.

The barred speed range power margin

The BSR power margin is illustrated on the engine load diagram in Fig. 4. The BSR power margin is defined as shown in equation 3:

$$BSR_{PM} = \frac{P_L - P_P}{P_P} \cdot 100\%$$

Equation 3

In Fig. 4, the power margin is 33%. Fig. 5 shows that the time for BSR passage is short for high values of the BSR power margin, but below about 10% BSR power margin, it increases quickly.

This means that if the BSR power margin calculated/estimated in the ship design phase is only slightly above 10%, then even a small error in the calculation/estimation can result in a too long passing time of the BSR during sea trial of the vessel. Such an error could result from, for example:

- The propeller light running turns out to be lower than predicted.
- The propeller/hull combination turns out to have a higher degree of bollard pull heavy running than expected.
- Results of torsional vibration measurements require that the BSR has to be moved up in rpm.

It is therefore recommendable to apply a conservatively large calculated/estimated BSR power margin in the ship design phase if the acceleration performance of the vessel type is not already known to be sufficient based on for example sea trials of sister vessels.

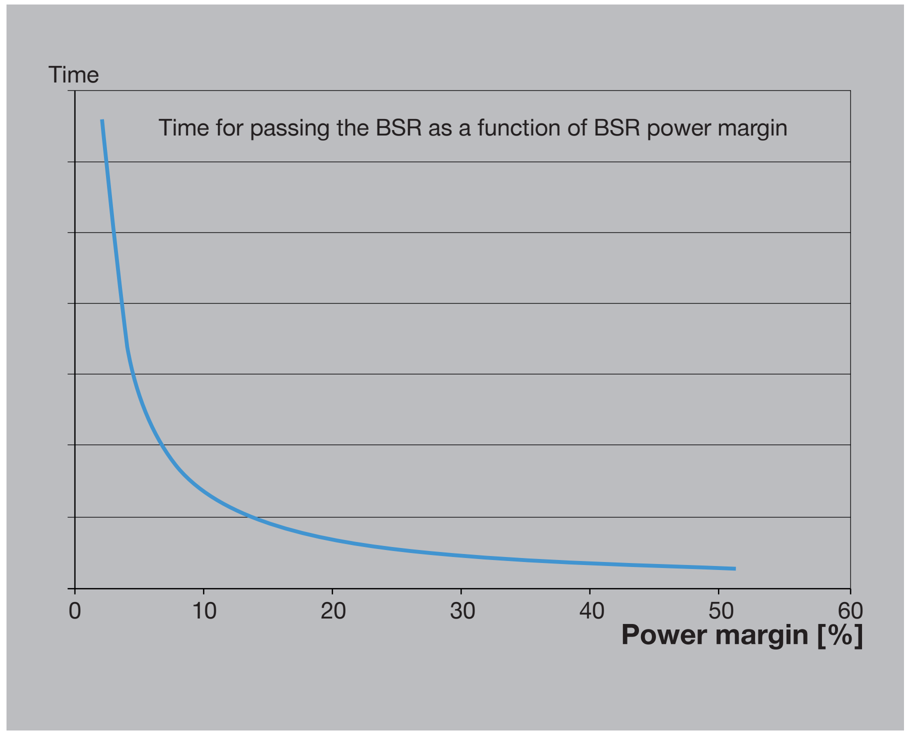

Fig. 5: Time for passing the BSR is dependent on the BSR power margin. Below about 10% the passage time quickly increases.

Engine design

for quick passage of barred speed range

In the search for reductions in fuel oil consumption, much development work has been centred around derating. When derating an engine, a significant SFOC (specific fuel oil consumption) reduction can be obtained by applying the so-called Miller cycle. The essence of the Miller cycle is to use a smaller top dead centre (TDC) volume while maintaining compression and firing pressures at their usual values by closing the exhaust valve later than usual. The end result is an engine with a lower maximum power output, but with a higher efficiency. The small TDC volume is achieved by adjusting the shims under the piston. This is a physical change that the engine control system cannot modify, such an engine is therefore refered to with the term derated. As described above, this has a positive effect on the vessel's fuel consumption and on the EEDI, but it may also have been a contributing factor in the cases where vessels have experienced slow passing of the barred speed range.

The delayed exhaust valve closing means that the air amount trapped in the cylinder is lower than for an engine without Miller timing. With a reduced air amount, the fuel injection must also be reduced, which results in a reduction in torque. Because propellers are normally not reduced in size when derating, this reduces the acceleration capability of the vessel.

However, as the exhaust valve of the ME-C engine is fully electronically controlled, it is not necessary to maintain Miller timing in all situations. For example, the exhaust valve can be closed earlier for improved torque during acceleration. It is also possible to open the exhaust valve earlier to increase the flow of energy to the turbocharger and, in this way, build up the scavenge air pressure faster, also with the purpose of improving acceleration. These are some of the elements that make up the engine control functionality that have recently been developed. Altogether, this new engine control functionality is called DLF, or dynamic limiter function.

The dynamic limiter function

The intention of DLF is to maximize the short duration power output without jeopardising long-term engine reliability. In order to understand the functionality of DLF, it is worthwhile to consider the functionality of the normal fuel index limiters. The principle behind the normal fuel index limiters is that mechanical and thermal overload should be avoided as well as emission of excessive black smoke from the engine. The parameters for the normal fuel index limiters are set so that the engine can run continuously on these limits without risking a breakdown.

The idea behind DLF is that accelerations are short duration events that occur at less than maximum power and rpm. It is therefore possible to exceed the normal fuel index limiters and generate a higher torque, and thereby power, during accelerations without jeopardising engine reliability. It is also possible to utilise the flexibility of the ME-C and ME-B engines to produce a higher power/torque without generating excessive black smoke, because the engine can be dynamically tuned to have increased amounts of air available for combustion while accelerating.

The DLF system adjusts the engine operating parameters for maximum torque when required and for maximum 30 minutes. When the DLF has been active for 30 minutes it will gradually roll back to the normal fuel index limiters. DLF will then not be available until the engine components have had sufficient time to cool. This may take several hours.

The DLF calculates the air available in the engine cylinder before each combustion event. The ability of the engine control system to calculate the air available in the cylinder is based on the results of extensive CFD analysis and experimental validation. An example of the CFD results is shown in Fig. 6.

When the mass of available air is calculated, the engine control system can proceed to calculate how much fuel can be injected until either the minimum acceptable air excess ratio is reached (the new DLF lambda limiter) or the maximum intermittent torque allowable at the actual rpm is reached (the new DLF torque limiter). These calculations are performed by the engine control system between each combustion event, and the method results in significantly increased torque and power output from the engine during accelerations.

All of the above is achieved by electronic control only, via the ME-C engine's electronic control of the fuel injection and exhaust valve timing. It is not necessary to change any hardware on the engine. The effect of the DLF is indicated graphically in Fig. 7.

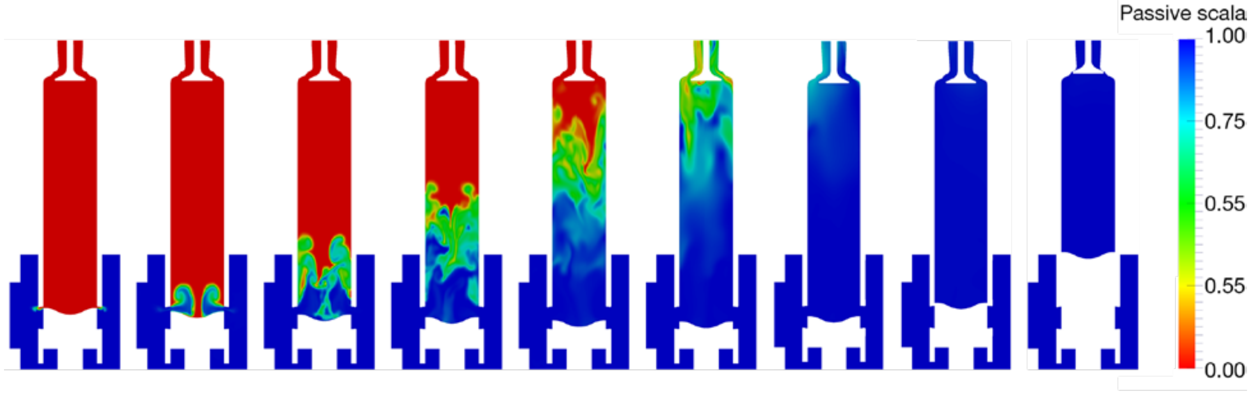

Fig. 6: CFD simulations showing the degree of scavenging of the cylinder. Red colour is exhaust gas. Blue is scavenge air.

Test results

The DLF development was completed with testing on board a number of vessels that had experienced acceleration issues. Some of the main results including the effect on torsional vibrations are presented in the following.

Barred speed range passing time

DLF was applied with success on a Kamsarmax bulk carrier in the final phase of DLF development (test vessel 4). Fig. 8 shows how the BSR passing time was significantly reduced on this vessel.

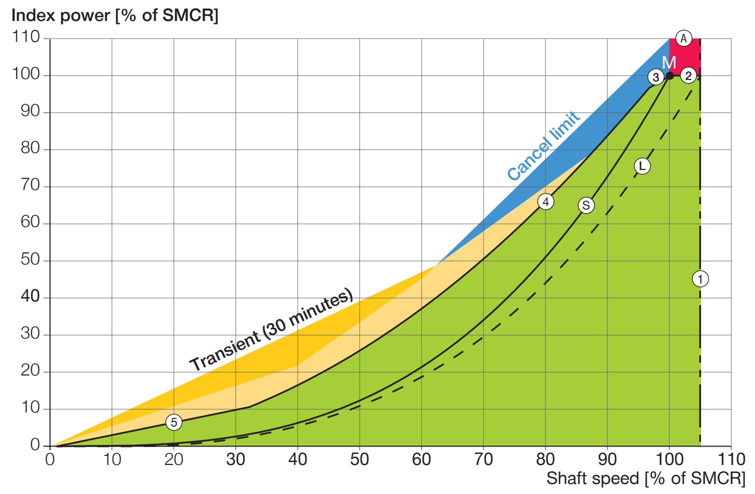

Fig. 7: Traditional and DLF limiters. The area indicated with "Transient (30 minutes)" shows the change in fuel index, shown as power, that becomes available due to DLF. The area indicated with "cancel limit" shows the power that becomes available when using the traditional cancel limit button, which is still available and which is working independently of DLF.

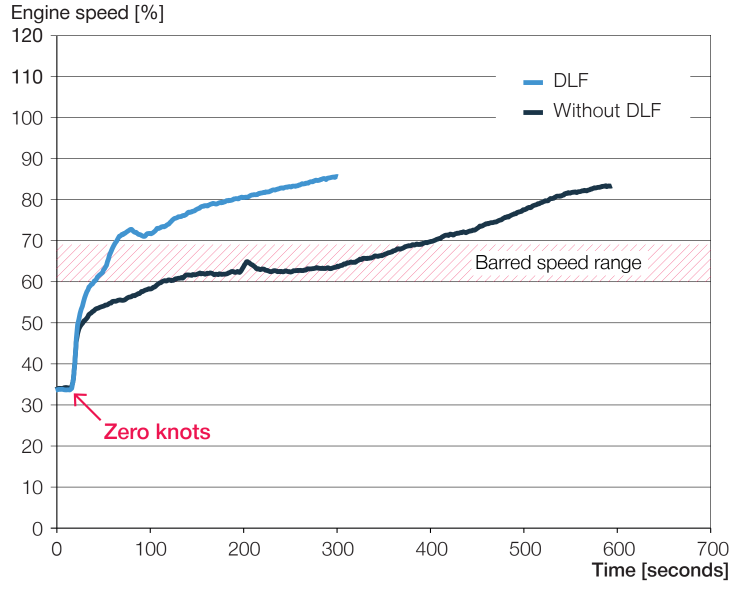

Fig. 8: Test vessel 4 (82,000 dwt bulk carrier). Acceleration with a highly placed barred speed range ending at 69% of SMCR speed. Results are shown with and without DLF Standard. Vessel is going astern with the engine in dead slow ahead until zero knots is reached, then the test is started by putting the handle to navigational full.

Torsional vibrations

Introduction

The design requirements for torsional vibrations and stress levels in the intermediate shaft and propeller shafts are normally based on the IACS M68 rule. Torsional vibrations are calculated and validated through measurement in steady-state condition and a BSR is required when the stress amplitude exceeds the continuous stress limit. Within the BSR, the maximum stress in steady-state condition may not exceed the transient stress limit. In service condition, the number of stress cycles and their amplitude under transient BSR passages determine the fatigue lifetime. The lifetime of the shafts is therefore not a direct result of the shaft stresses in steady-state condition.

Acceleration measurements

In the test vessels that were used for development of DLF, the torsional vibration (TV) stress levels in the shaft line were reduced during acceleration when DLF was active, see Fig. 9. This may seem surprising since DLF increases the torque from the engine. There are some possible reasons for this:

- The time for passing the BSR is significantly reduced when applying DLF. The time spent with a shaft speed near the resonance frequency is therefore also reduced, and the resonance is not able to develop to the same extent.
- The propeller is loaded more heavily during the faster accelerations with DLF, which we expect will increase the propeller damping.
- The cylinder pressure excitation is different with DLF

Sweep test measurements

Although all testing of DLF so far has shown reduced TV stress levels during acceleration, the classification societies requires the TV stress levels to be verified on sea trial in a steady-state condition, by a so-called sweep test.

During the sweep test the engine rpm setting is very slowly increased, and the TV stress levels are measured. In such a test, DLF will not be activated because the acceleration is intentionally very slow. This means that the influence of DLF on TV stress levels is not seen in a normal TV verification test. For this reason the DLF software includes a parameter setting called DLF "always on". In this mode the applied DLF tuning changes are constantly active. This means that they will be active also during the sweep test when the TV stresses are measured.

The stress levels during sweep test are influenced by the DLF parameters. This has led to the definition of two different levels of DLF: DLF Standard and DLF Full, which are described in the following:

DLF Standard

DLF Standard applies only the measures that are known not to increase the torsional vibration stress level, including during a sweep test where DLF is "always on". When retrofitting DLF Standard, it is therefore not required to renew the TV measurements.

DLF Full

In cases where sufficient acceleration is not achieved with DLF Standard, it is possible to adjust the DLF parameters to achieve a further increase in torque during acceleration. Earlier exhaust valve closure is an example of a method that is applied. This is called DLF Full. When applying DLF Full, the TV stress levels have also been reduced during acceleration tests. But if a sweep test is performed with DLF Full "always on", TV stress levels may, or may not, increase. When retrofitting DLF Full, it is therefore required to renew the TV measurements in order to verify that stress amplitudes are still below the transient stress limit in the sweep test.

Example: Test vessel 1 with DLF Full

Fig. 10 shows the sweep test results from a very large ore carrier (VLOC), test vessel 1, where shaft stress levels with DLF Full "always on" and without DLF can be compared. The maximum TV stress measured in the intermediate shaft in the barred speed range (26~35 rpm) was 94 MPa on the critical rpm with DLF "always on" (A). For reference, the sweep test was repeated without DLF. The maximum TV stress amplitude was then 85 MPa (B). So in this particular case, DLF Full increased the TV stress levels when it was forced to "always on" during the sweep test (both conditions are well below the IACS-M68 transient limit which is 107 MPa for this vessel).

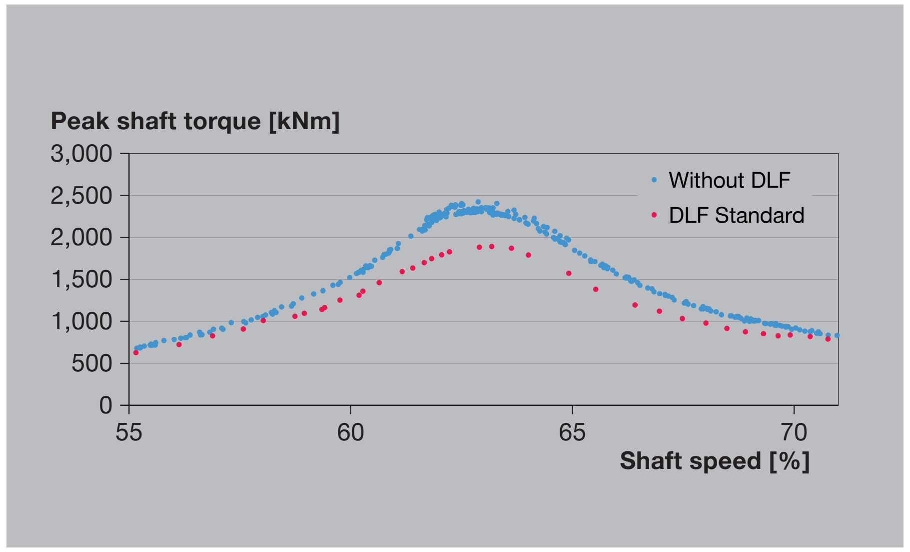

Fig. 9: Test vessel 4 (82,000 dwt bulk carrier). Torsional vibration torque amplitude levels during acceleration from zero ship speed with and without DLF Standard. The stress levels are lower with DLF. The measurements are from the same test as in Fig. 8.

On the same vessel during acceleration with DLF Full, the stress level was lower at approximately 73 MPa. This value is lower than for the sweep test without DLF (B). Similar results were seen for all of the tested vessels, this means that even though the stress levels may increase with DLF Full in sweep condition (DLF "always on"), the stress levels and the number of stress cycles during service will be reduced. Which will result in an increased fatigue lifetime of the propulsion shafting.

Example: Test vessel 4 with DLF Full

Table 1 shows the results from test vessel 4 (82,000 dwt bulk carrier) where TV shaft stress levels did not increase although DLF Full "always on" was applied during the sweep test. As seen on all DLF test ships, the TV stress levels during acceleration through the BSR were lower with DLF than without DLF.

General torsional vibration experience with DLF

The general experience from DLF testing on four different vessels is summarised in Table 2.

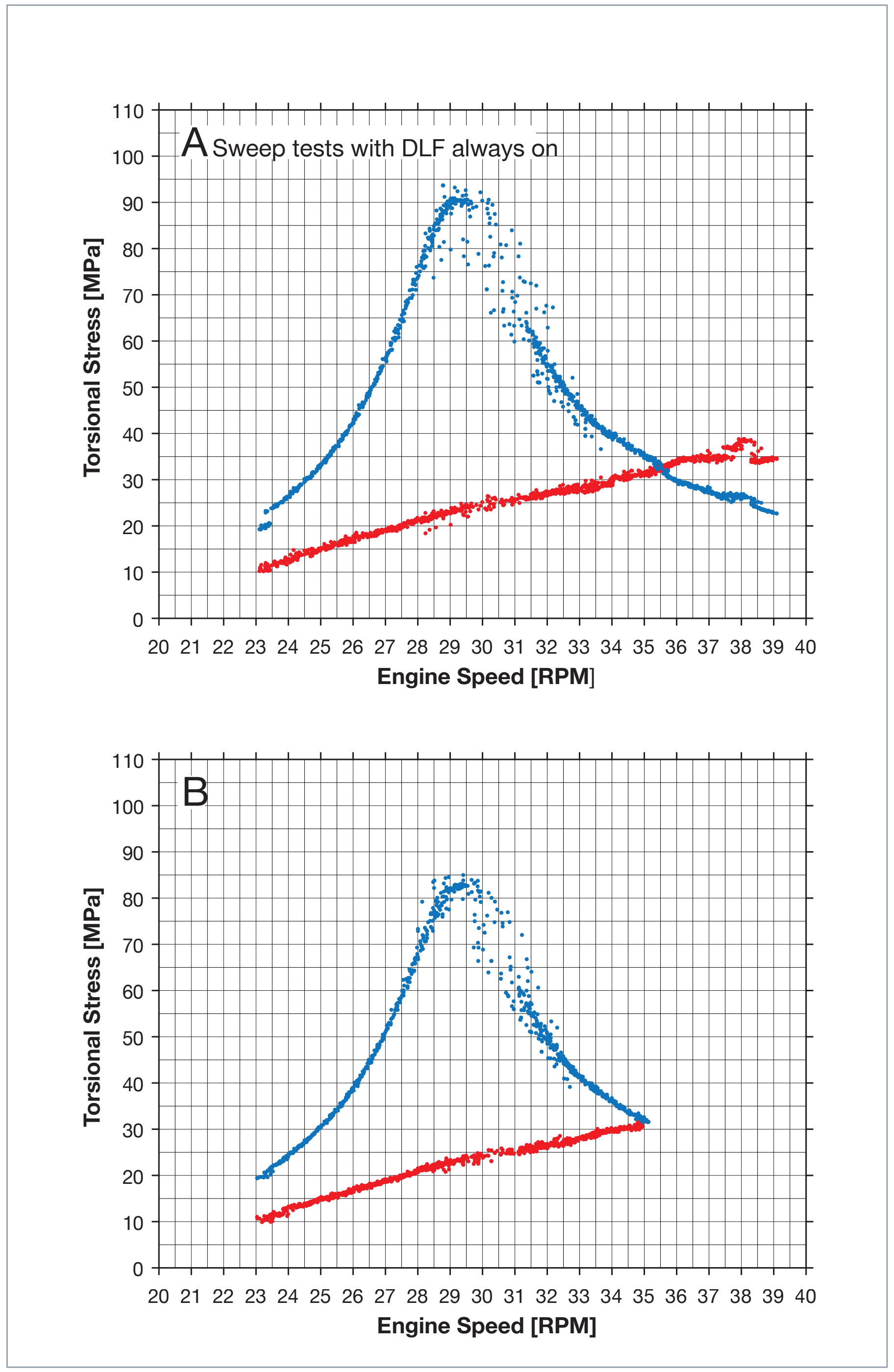

Fig. 10: Test vessel 1 (260,000 dwt bulk carrier). Torsional vibration stress levels during sweep test with DLF Full "always on" (A) and without DLF (B). In this particular case, DLF Full "always on" shows higher stress levels. A peak value of 94 MPa for DLF Full "always on" compared to 85 MPa for the reference (no DLF).

DLF roll-out

In general, DLF Standard is applied. If sea trials show that a higher dynamic torque is needed, DLF Full can be applied to the extent that the engine and torsional vibrations permit.

ME-C

DLF is now the standard on new 5 and 6-cylinder engines. 5 and 6-cylinder engines have been chosen because they have the highest placed BSR relative to SMCR rpm, and this is where we have seen cases with slow passage of the BSR. DLF can be applied on engines with more than six cylinders if it is considered necessary. This is evaluated on a case-by-case basis.

ME-B

DLF Standard is also available for the ME-B engine type and has been tested with great success. Significant acceleration improvements were achieved, and DLF is standard for new 5 and 6 cylinder ME-B engines.

Since our ME-B engine design does not have the fully flexible exhaust valve timing known from ME-C engines, applying DLF Full is not possible without hardware changes, by which even further acceleration improvements can be achieved.

Vessels in service

Depending on the engine control computer hardware installed, it is possible to apply DLF to engines already delivered.

A DLF upgrade requires a pre-inspection by the crew, based on which MAN Energy Solutions performs the necessary engineering, and that a service engineer attends the vessel to perform the upgrade, and a cost is therefore associated with such an upgrade.

Please do not hesitate to contact PrimeServ Diesel Copenhagen (dr-cph@man-es.com) or your local PrimeServ hub for inquires about DLF upgrade.

Configuration	Test	Time in BSR [s]	Peak amplitude stress [MPa]	Tau2 limit [MPa]
No DLF	Sweep	480	120	121
DLF Full “always on”	Sweep	480	119	121
No DLF (but increased limiters)	Acceleration	50	105	121
DLF Full	Acceleration	20	94	121

Table 1: Test results for DLF Full on test vessel 4 (82,000 dwt bulk carrier). Intermediate shaft stress amplitude and barred speed range passage time from zero ship speed

Engine mode	Acceleration stress levels	Sweep test stress levels
No DLF	Reference	Reference
DLF Standard	Lower	Unchanged
DLF Standard, “always on”	Lower	Unchanged
DLF Full	Lower	Unchanged
DLF Full, “always on”	Lower	Unchanged or higher

Table 2: Effect of different DLF settings on torsional vibration stress levels in the intermediate shaft relative to the situation with no DLF. The effect on acceleration and sweep tests shown represents the results from the four vessels that have formed the basis for DLF testing.

Conclusion

Developments in ship and engine design driven by the general desire for lower fuel consumption and the introduction of the energy efficiency design index (EEDI) have resulted in some ships being too slow to pass the barred speed range (BSR). Too slow passage of the BSR may have negative consequences for the shaft lifetime and for ship manoeuvring.

R&D work was started as a result of the reports of too slow passage of the BSR. It has led to significant progress in terms of understanding and assuring sufficient engine and propeller acceleration, particularly with respect to quick passage of the BSR. It has been found that the following parameters influence the ability to pass the BSR quickly:

- the position of the barred speed range in relation to the SMCR rpm
- the propeller light running margin
- the degree of heavy running of the propeller in the bollard pull condition
- the dynamic torque capability of the engine.

A design value has been developed to evaluate the combined effect of the first three points mentioned above. It has been named the BSR power margin. By using the BSR power margin in the vessel design phase, it is possible to design a vessel for quick passage of the BSR.

With respect to point 4 above (the dynamic torque capability of the engine), a new dynamic limiter function (DLF) has been developed for the ME-C engine. DLF is an engine control system upgrade, which increases the torque that the engine can develop for up to 30 minutes, and it therefore reduces the time for passing the BSR. It is available in two versions:

1. “DLF Standard” which significantly reduces the time for passing BSR and which can be retrofitted without renewing torsional vibration measurements, an upgrade of the engine control system to a newer version may also be required.
2. “DLF Full” which can further reduce the time for passing the BSR. DLF Full may, or may not, increase the steady state torsional vibration stress levels, with DLF “always on”. The use of DLF Full is therefore, so far, subject to confirmation of acceptable stress levels (below the IACS-M68 transient limit). For new vessels such confirmation is performed during sea trials. For existing vessels, retrofit of DLF Full requires renewal of the torsional vibration measurements.

For ME-B engines hardware changes to allow modification of the exhaust valve timing will be required in order to apply DLF Full.

DLF increases the torque available from the engine for up to 30 minutes, but it does not increase the torque that the engine can continuously deliver. A sufficient propeller light running margin is still needed to achieve sufficient engine power and vessel speed in long lasting heavy conditions such as:

- heavy weather
- shallow or otherwise restricted waters
- ice.

Through the use of the BSR power margin in the vessel design phase and, by applying DLF on the MAN B&W ME-C engine, it is now possible to make sure that a vessel will exhibit quick passage of the BSR.

MAN PrimeServ world-class service

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The MAN Energy Solutions group offers worldwide, round-the-clock service, 365 days a year. In addition to MAN Energy Solutions' service headquarters in Augsburg, Copenhagen, Frederikshavn, Saint-Nazaire, Hamburg and Stockport, service centers on all continents provide comprehensive and continuous support.

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Our Copenhagen MAN PrimeServ Academy offers professionally trained instructors with extensive knowledge of and experience with MAN B&W two-stroke engine technology and products.

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MAN PrimeServ Academy in Copenhagen

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