TORSIONAL VIBRATIONS & THERMODYNAMICS - HOW DO THEY CONNECT?

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Abstract

As a direct consequence of the EEDI regulation, engines are becoming progressively smaller in relation to the size of ship they shall propel which results in a higher power density (mean effective pressure, mep) of the engine. Additionally, emissions regulations on the one hand and cost considerations on the other make system-wide thinking progressively more important. One example of this is the interaction between the thermodynamics (i.e. firing pressure curves) of the engine and the torsional vibrations in the propulsion system.

A well-known aspect is the LowTV tuning as employed by WinGD since 2005 where the firing pressure curve is modified in the area of the main torsional resonance in the low speed area such that the resulting tangential excitation forces are reduced in order to reduce the countermeasures needed to prevent inadmissible torsional vibrations in the installation components. A more recent example are the low pressure two-stroke gas engines that have become very common in the market. The firing pressure curves in these gas engines are completely different from what is known from the conventional diesel engines - this obviously has its implications for the torsional vibrations.

A third example shall be the variance of the firing pressure characteristics over the rating field, including the resulting implications for torsional vibrations.

INTRODUCTION

The world of large two-stroke diesel engines has been changing rapidly in recent years. Where for many years the changes were limited to engine upgrades with different layouts and the development of different tunings the options today are much more diverse. Brought on by EEDI[1] on the one hand

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[1] The Energy Efficiency Design Index (EEDI) for new ships is the most important technical measure and aims at promoting the use of more energy efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments [1].

and the awareness for green shipping on the other the two-stroke ecosystem now contains amongst others the classical diesel engine, low pressure dual-fuel (DF) engines, high pressure dual-fuel engines as well as engines running all kinds of alternative fuels. Additionally, the EEDI tends to favour smaller engines for the same ships as previously which leads to a generally higher load on the engine and shaft line.

This variability obviously leads to a large variation of possible combustion schemes, each with its associated firing pressure curve and thus also torsional vibration excitations. Three specific cases shall be investigated as illustration of these differences. The tuning for low torsional vibrations (LowTV tuning) has existed for many years and has become the de-facto standard for WinGD engines. Subsequently some characteristics of the WinGD low pressure DF engines shall be illustrated followed by an overview of the variations of conventional diesel engines layout over the rating field.

LOWTV TUNING

It is well known that certain shafting arrangements on ships propelled by direct coupled 2-stroke engines can exhibit high torsional resonance amplitudes at engine loads below 25% of the nominal power (Continuous Maximal Contracted Rating, CMCR), corresponding to the speed range below 60% of the nominal speed. This can be partly mitigated by modifying the shaft line, e.g. by changing the diameter or material of the intermedia shaft or adding heavy tuning wheels and flywheels to the engine. Often enough though, these measures are not sufficient to keep the torsional stresses below acceptable limits – in these cases a torsional vibration damper had been the only feasible solution. These dampers, whilst being very effective, especially in the case of tuned spring dampers, increase the CAPEX of the installation.

An optimised solution can be achieved by changing the tangential excitation forces in order to reduce the torsional resonance amplitudes whilst ensuring safe engine operation. Two main influencing parameters are the exhaust valve closing timing (EVC) which influences the compression pressure and the injection timing (IT) influencing the timing and the amplitude of the maximal cylinder pressure peak (Figure 1). From a vibrations perspective the solution is straightforward: Delay the exhaust valve closing until the excitations are acceptable, IT then plays a minor role (Figure 2).

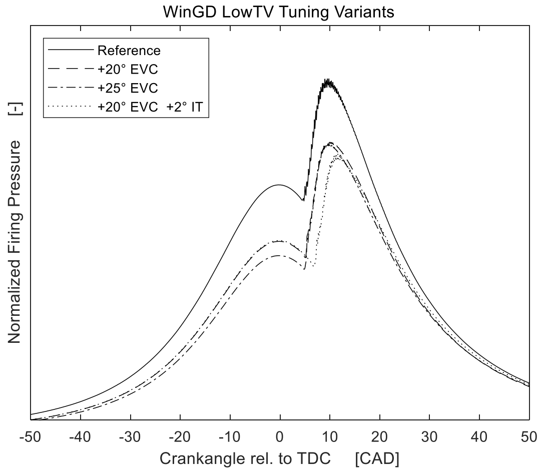

Figure 1 - Firing Pressure Curves with and without LowTV Tuning

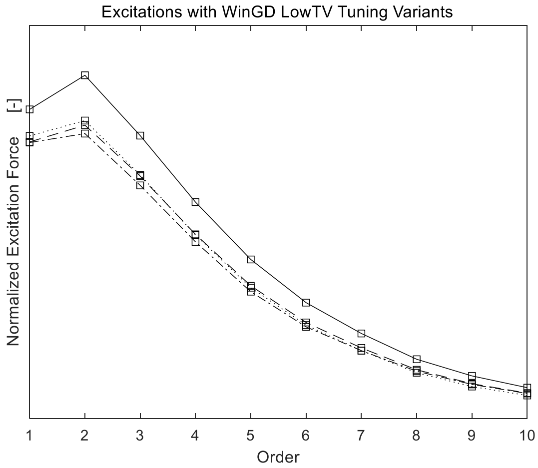

Figure 2 - Excitations with and without LowTV Tuning.

The thermodynamic perspective however is not quite as obvious. Large two-stroke diesel engines conventionally run on Heavy Fuel Oil (HFO) which is a residual fuel with conventionally high sulphur content, high viscosity and low ignitability compared to Marine Diesel Oil (MDO, Figure 3, Figure 4, [2]). The diesel process relies on the self-ignition of the injected fuel – appropriate in-cylinder conditions need to be guaranteed under all combinations of fuel quality (differences in Heat Release Rate HRR between different fuels can be seen in Figure 4) and ambient conditions. A reliable self-ignition of HFO requires temperatures of the compressed air of around 540 °C at the time of injection (IT). For reliable engine operation the EVC delay therefore needs to be limited in order to ensure this minimal temperature under all ambient conditions. Additionally, a sufficiently high in-cylinder air-to-fuel ratio λ needs to be maintained in order to ensure that the emissions of HC and smoke remain at acceptable limits – delaying the EVC generally leads to a lower λ.

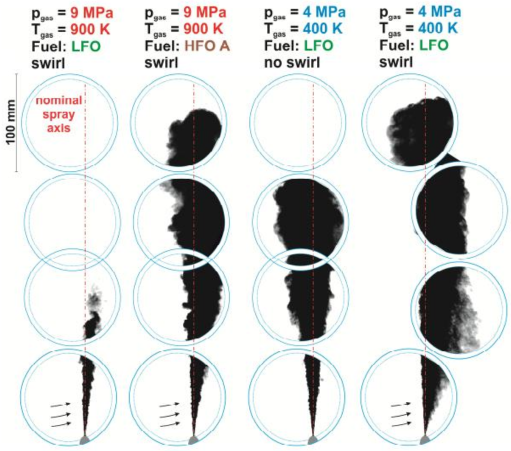

Figure 3 - Illustration of Spray Morphology in Comparison of Evaporation, Swirl and Fuel Quality [2]. Note the much slower evaporation for HFO compared to LFO.

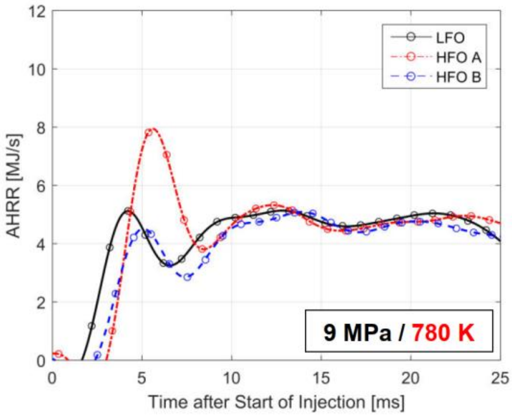

Figure 4 - Apparent heat release rates for three different fuel qualities (LFO vs. HFO A vs. HFO B) at 780 K gas temperature and a constant gas pressure of 9 MPa [2]. Note the longer ignition delay for HFO as well as the large variability in HRR.

The benefits though are immediately apparent in the reduction of the torsional stresses on the shaft line of a ship installation – the application of the LowTV tuning alone reduces the stresses below the relevant limits without having to install a torsional vibration damper (Figure 5).

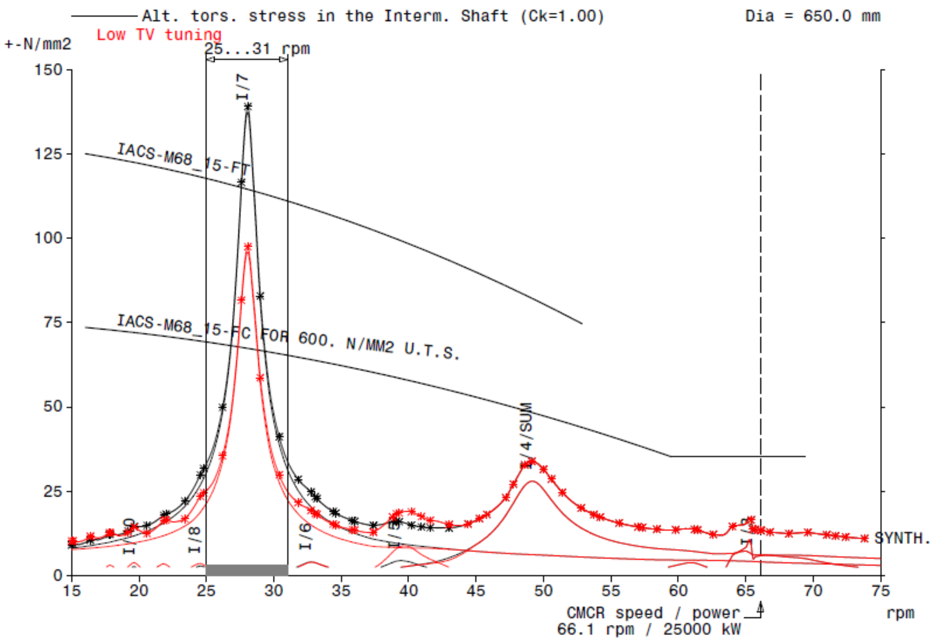

Figure 5 - Example of the effect of LowTV Tuning on a 7X82-B diesel engine.

Overall, this is a very efficient method for reducing the torsional vibrations without changing any hardware. The price to pay comes in the form of a lower engine efficiency which results in a somewhat higher brake specific fuel consumption (BSFC). For this reason, this method is mainly applied in the speed range below 15% load, i.e. in the speed range where the absolute BSFC and the time of operation is low.

DUAL FUEL ENGINES

WinGD dual fuel engines can operate either on gas (LNG) or conventional crude oil derivates. In gas mode the fuel is injected with low pressure mid-stroke through the liner wall – this results in a premixed gas-air mixture (Figure 6) which then either is ignited by the pilot (diesel) injection or self-ignites, especially at higher loads. The resulting Otto-cycle combustion proceeds much faster than the conventional diffusion-driven diesel combustion – this is visible in the steeper pressure rise and much higher firing ratio for the same power output (Figure 7) when compared to diesel mode (Figure 8).

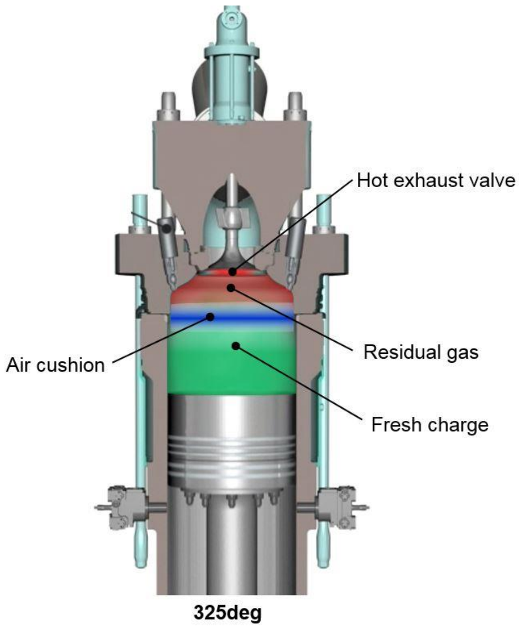

Figure 6 - Stratification of the fresh charge in gas mode.

Similar to the LowTV tuning described above, the start of gas combustion is, amongst other parameters, defined by the compression end temperature and is thus governed by the compression ratio. Whilst the engine has a high efficiency in gas mode, the low compression ratio in diesel mode directly results in a low firing pressure and thus a relatively high BSFC. Another effect of the premixed combustion are the very low NOx emissions – in gas mode the WinGD DF engine can easily achieve IMO Tier III limits without any kind of exhaust gas aftertreatment. So, in gas mode the engine is not, unlike the diesel mode, primarily NOx limited.

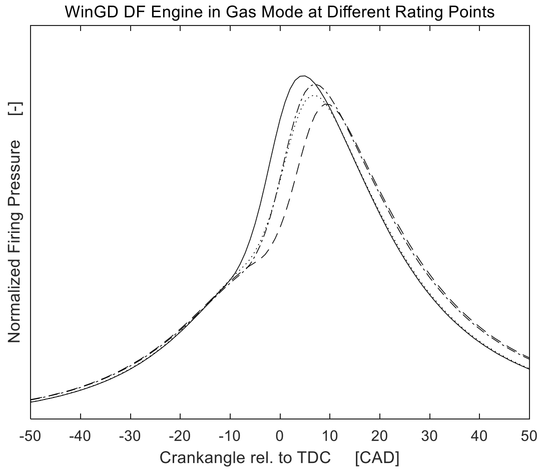

Figure 7 - Firing Pressure Curves for WinGD DF Engine in gas Mode.

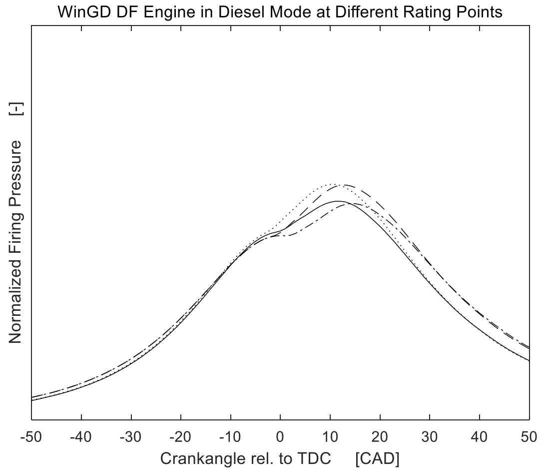

Figure 8 - Firing Pressure Curves for WinGD DF Engine in diesel Mode.

When comparing the effects of these different combustion modes on the tangential excitation forces an interesting observation here is that the tangential excitations of lower orders (1-4) at full engine load are higher in diesel than in gas mode despite the much lower firing pressures. The harmonic orders >4 however are considerably higher in gas mode (Figure 9). The reason for this phenomenon becomes obvious when considering what the decomposition of the cylinder pressure curve into its Fourier components actually means: As the pressure peak of the gas mode is sharper more of the higher-frequency components are needed for its representation whereas the relatively flat diesel pressure curve can be represented with low orders.

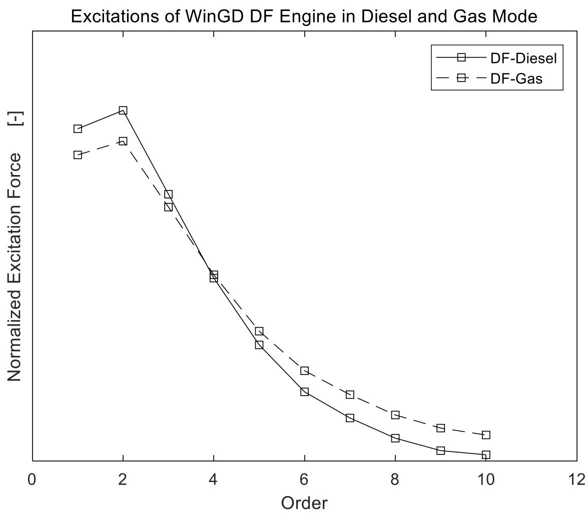

Figure 9 - Comparison of Excitations in gas and diesel Mode at same Rating Point.

Finally, these differing characteristics (whilst apparent throughout the load range but only presented at full engine load in this paper), must be considered when doing the Torsional Vibration Calculation (TVC) for a specific DF installation: The engine and shaft line must comply with the limitations in both operation modes, thus the worst case must be considered. Often, the nominal operation range up to 100% load & speed can be well covered by the gas excitations. At conditions above the nominal speed however the engine will trip to diesel mode which in turn makes it necessary to use the diesel excitations for this range.

EFFECT OF RATING POINT

Two-stroke marine engines can traditionally be ordered with any speed/power combination within a given rating field (Figure 10) - the engine type, cylinder number as well as speed and power depend amongst others on the type of ship and the foreseen service speed. Any point within the rating field must comply with IMO regulations regarding NOx emissions and must also adhere to the contracted BSFC. NOx emissions are traditionally established as and limited through a weighted average of the four load points 100%, 75%, 50% and 25% (Figure 11).

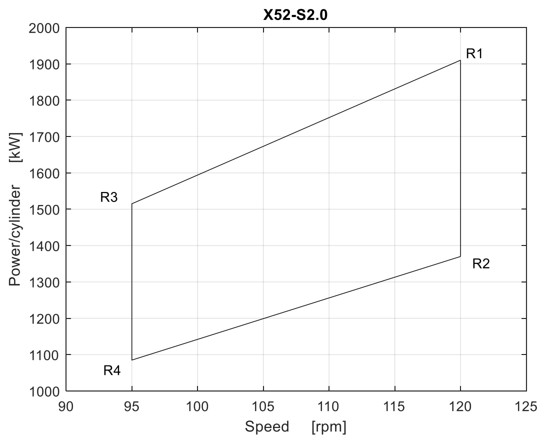

Figure 10 - Rating Field forp X52-S2.0.

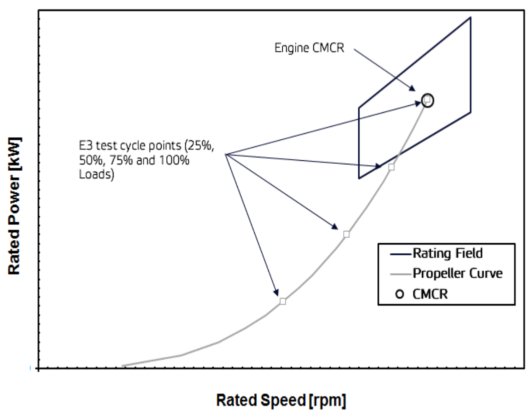

Figure 11 - IMO E3 Test Cycle for NOx Compliance.

Generally, the output of an engine family is limited, amongst other factors, by the maximally allowable firing pressures (crankshaft, bearings, hot parts etc) as well as the abovementioned NOx requirements. As the formation of NOx mainly depends on temperatures, residence time and the availability of oxygen it is obvious that NOx will increase when running at lower speeds (longer residence time) and mep (combustion is more concentrated close to top dead centre) than R1. This can be mitigated by optimizing certain parameters such as the fuel injection settings and hardware as well as shape & dimensions of the combustion chamber and the in-cylinder flow field which leads to large differences in the firing pressure curves (Figure 12) and resulting excitations (Figure 13).

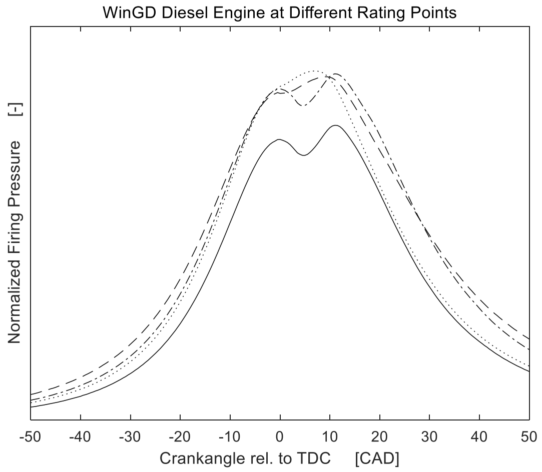

Figure 12: Firing Pressure Curves for X52-S2.0 at full load for different Rating Points.

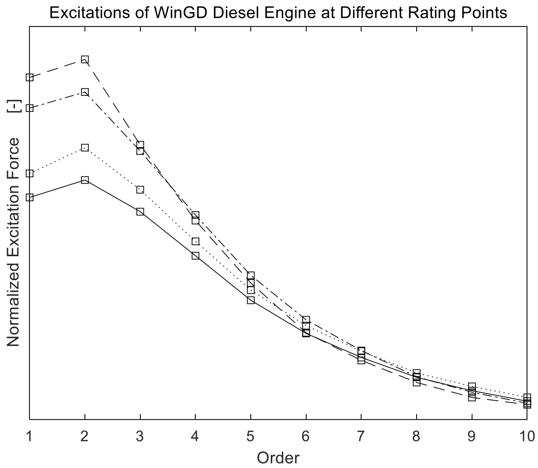

Figure 13 - Excitations for X52-S2.0 at full load for different Rating Points.

As the rating fields of different engines (bore) sizes can have a certain overlap the speed and power combination desired for a specific vessel can potentially be fulfilled with two completely different engines – with the obvious difference in excitations. This is another aspect that should be considered during the layout of a vessel besides the more obvious ones such as BSFC, engine size or EEDI.

SUMMARY (OR CONCLUSIONS)

As exemplarily laid out in the previous three chapters torsional vibrations are a direct result of the thermodynamic process taking place in the combustion chamber. There is a contradicting trade-off between the requirements regarding emissions, fuel consumption (BSFC) and tangential excitations: Tuning layouts which are beneficial for BSFC are disadvantageous for NOx and tangential excitations and the other way around. For these reasons a careful compromise has to be made between the different aspects for each rating point, operating range and fuel mode – this requires more and more interaction between thermodynamic and vibrations specialists.

REFERENCES

[1] International Maritime Organisation IMO, *Energy Efficiency Measures*, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx

[2] von Rotz, B., Schmid, A., Hensel, S., Herrmann, K., Boulouchos, K., Comparative Investigations of Spray Formation, Ignition and Combustion for LFO and HFO at Conditions relevant for Large 2-Stroke Marine Diesel Engine Combustion Systems, CIMAC Congress, Helsinki, June 6-10 2016.