IMPACT OF EMISSION REDUCTION STRATEGIES ON TORSIONAL VIBRATIONS

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Abstract

The need for emission reduction strategies for large bore combustion engines has been a main driver in engine development over the last few years. The technologies applied have different impacts on torsional vibrations.

In the first part of this paper a short overview of the relevant rules and methods to reduce engine emissions is presented. These reductions can be achieved by a combination of different measures for example by increasing the engine and power train efficiency, by using exhaust gas after treatment systems and by using different fuels for example natural gas (NG) or synthetic fuels. Although a reasonable portion of the above-mentioned examples only have a minor influence on the TV, it is necessary to study them, to avoid operational problems.

In the main part of this paper, the test setup of a high speed one cylinder test engine is described, which was used to measure pressure curves of the combustion of hydrogen and natural gas. After that, these pressure curves are applied to the torsional model of a 16V genset application to study the effects. These simulations help us to understand the impact of alternative fuels on torsional vibrations.

Nevertheless, the large variety of possible fuels and other measures lead to a high number of configurations and possible operation modes which need to be investigated at present and even more in the future. Therefore, the question: “How to prepare for a complex future in terms of engine excitation / operation” is discussed and a short outlook is given at the end of the paper.

INTRODUCTION

The need for emission and greenhouse gas reductions of large bore combustion engines is a main driver for engine development. The technologies applied have different impacts on torsional vibrations. This variability obviously leads to a large variety of possible combustion schemes and operation strategies.

RULES AND EMISSION REDUCTION TECHNIQUES

Relevant rules:

There are numerous exhaust gas emission legislations for diesel and gas engines for example the IMO (International Maritime Organization) for sea going ships and inland waterway vessels, different rules for regions like the EU, USA, China, Russia, and so on. Similar regulations exist for stationary power plants, off-road mobile machinery, and railway vehicles (see summary in [1]). Figure 1 illustrates the global trend towards stricter emissions legislation using the example of stationary combustion plants with spark ignited (SI) gas engines > 1 MW. This engine type is also used for the TV study in the next chapter of this paper. Additional limits have been established for THC (Total Hydrocarbons), HCHO (formaldehyde) and NH_3 (ammonia) at the end of 2019. A reduction of NO_x emissions can be achieved by decreasing the combustion temperature. Unfortunately, this leads to a larger ratio of unburned hydrocarbons and formaldehyde. THC emissions have a strong greenhouse gas effect and formaldehyde is classified as carcinogenic. Therefore the use of a SCR (selective catalytic reduction) exhaust gas aftertreatment system for NO_x reduction is likely. However, NH_3 slip may occur with such a system but must be avoided due to its toxicity.

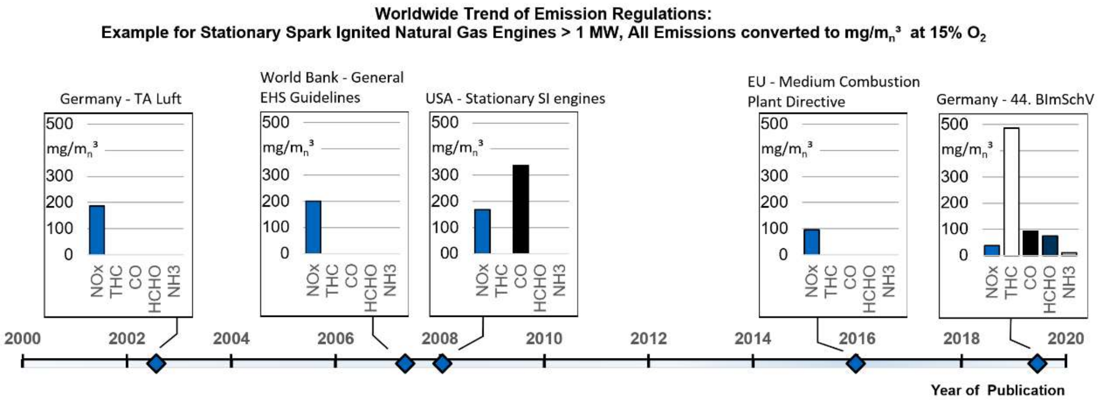


Figure 1: Global trend of emission regulations for investigated gas engine class, [1-6]

In addition to the above-mentioned regulated exhaust gas emissions, some regulations also limit sulfur emissions, and the IMO (International Maritime Organization) introduce ed the energy efficiency design index (EEDI) in 2011 and additional measures are already on the way for further emission reductions [7].

Emission reduction techniques and future engine systems

Emission reductions can be achieved through a combination of different measures for example: by increasing engine and power train efficiency, by using exhaust gas aftertreatment systems and different fuels for example CNG (Compressed Natural Gas) and synthetic fuels.
In the case of conventional fuels, the planned emission limits of the BImSchV 44 [5], e.g. for nitrogen oxides, cannot be met with acceptable engine efficiency by only using internal engine measures. It can therefore be assumed that engines will be equipped with an appropriate exhaust gas aftertreatment system and will be designed for the highest possible engine efficiency and power output. Table 1 shows examples of the influence of different emission reduction strategies on torsional vibrations.

	Influence on Torsional Vibration*	
	Engine excitation	other
Increased specific engine power		
- Increased intake air pressure **	Up to ++	
- Valve train: Miller timing, …	Up to ++	
- Ignition or injection timing	Up to ++	
- Compression ratio	Up to +	
- Tribology, engine cooling	~	
- Cylinder cut off	Up to ++	
- Downsizing	Up to +	
Power train efficiency: gearbox, propeller		Gear and propeller excitation
Exhaust gas aftertreatment:		
- Exhaust gas recirculation (EGR)	~	
- SCR, particulate filter…	~	
Fuels: NG, hydrogen, ammonia, synfuels, etc.	Up to ++	Dual fuel: System complexity
Hybrid power train		Increased inertia, System complexity
Slow steaming	Up to ++	
*) Expected influence on torsional vibrations. … none, unknown, or almost no influence, + … medium influence, ++ … high influence expected **) Constant air/ fuel ratio assumed		

Table 1: Examples of different efficiency increase and emission reduction measures and their expected influence on torsional vibrations.

The highest impacts on the torsional vibrations from internal engine measures are expected to come from high intake air pressures followed by increased engine power output, valve, ignition and injection timing, see [8-11].

In addition, engine operation modes such as slow steaming, de-rating and cylinder cut off strategies are also expected to increase the torsional vibrations, see [12]. Finally, the use of innovative fuels, such as hydrogen or other synthetic fuels will also lead to a change in the engine excitations and the overall systems TV.

INFLUENCE OF HYDROGEN- AND CNG-COMBUSTION ON TVs

To study these effects in more detail, measured pressure curves with CNG (Compressed Natural Gas) with an indicated mean effective pressure (IMEP) up to 34.2 bar, low NOx emission and pure hydrogen up to 15.1 bar IMEP are applied to a 16V medium speed engine, this can be seen on the following pages.

Test Bench Setup

Figure 2 shows the 4.77 liter single-cylinder research gas engine of the Chair of Internal Combustion Engines from the Technical University in Munich (TUM) which is used to test different combustion processes. The engine is an in-house development based on the cylinder head and piston of an industrial gas engine. To realize combustion processes with high peak combustion pressures (PCP) up to 300 bar, the crankshaft, piston rod and bearings were reworked and reinforced. Numerous research studies on engine and emission performance have been successfully conducted with this engine e.g. [9-11,13,14,15].

Stroke	210 mm
Bore	170 mm
Displacement	4.77 l
Compression ratio natural gas	12.4
Compression ratio hydrogen	12.3
Valves	2 inlet valves, 2 exhaust valves
Engine speed	1500 1/min

Figure 2 & table 2: Specification of single-cylinder research engine

Test Bench Measurements

Natural gas from the public gas grid with an average methane content of 94.9% or hydrogen with a purity of 99.9% is used as fuel gas. An un-scavenged prechamber spark plug is used as the ignition system for natural gas and a standard spark plug is used for hydrogen. To evaluate the combustion process more accurately, the cylinder head is equipped with a pressure sensor for crank angle-resolved combustion chamber pressure recording.

Figure 3 shows the lift curves of the camshafts used. The basis camshaft is common in similar forms in current gas engines in the industrial environment. The Miller-1 camshaft requires a high turbocharger pressure, but the peak combustion chamber temperatures and thus the nitrogen oxide emissions are reduced. The operating behavior of a gas engine in terms of efficiency and emissions is strongly influenced by the air to fuel ratio λ and the center of combustion, i.e., the crank angle at which 50% of the fuel mass is burnt (MFB50%). The engine load, as well as the related valve timing, have an equally strong effect. In addition to the trend towards increasing the specific power density of the engine, the NO_x emission behavior is of particular importance to the engine. The investigations on load increase for natural gas engines were carried out within the FVV project "BMEP > 30 bar with gas engines" (No. 1201) [10].
Starting from the Basis camshaft at low load, a considerable efficiency increase is possible by increasing the load to 32 bar IMEP. However, the achievable indicated efficiency η_i is limited by knocking. Furthermore, the boost pressure requirement increases from 3.5 bar to 6.0 bar and the peak combustion pressure (PCP) from 145 bar to 200 bars.

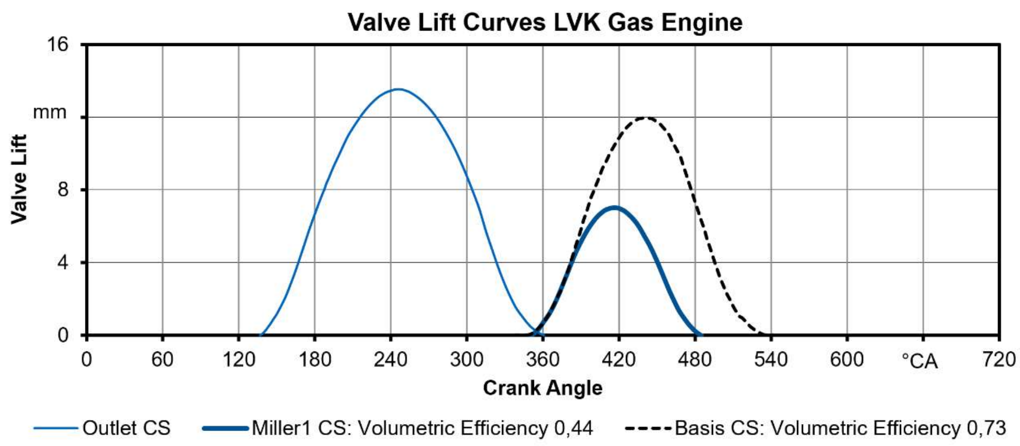


Figure 3: Camshafts and corresponding valve lift curves that were used in experiments.

The colder combustion chamber, due to the Miller effect of the Miller-1 camshaft, has a positive effect on the NO_x-η_i trade-off. On the one hand, less nitrogen oxide is produced at lower peak combustion temperatures, and on the other hand, the cooler charge shifts the knocking limit to access more efficient operating areas. The improvements come at the price of approximately 9.3 bar charging pressure and 240 bar PCP. All operating points investigated are summarized in Table 3.

With the use of alternative fuels, engine behavior can change considerably. One fuel that can be used in an engine with almost no generation of pollutants, if the correct operating strategy is adopted, is hydrogen. Due to further advantages, such as a good synthesis efficiency and the good availability of the educts, a growing spectrum of corresponding engines is likely. Existing natural gas engines can be operated with pure hydrogen with small to medium modifications. Typically, however, only a lower power density can be achieved this way. This is due to the fact, that the gas is easily ignited, which results in various types of pre-ignition. However, the wide ignition limits also allow very lean and thus nitrogen oxide-free combustion with good efficiency. The investigations to develop a hydrogen combined heat and power (CHP) engine are carried as part of the “MethQuest” project and are funded by the German Federal Ministry for Economic Affairs and Energy [16].

Measure-ment No.	IMEP in bar	Fuel	MFB50% in °CA ATDC	NO_x @ 15%O2 in mg/m³	valve train	λ in -	P_{eng} in kW
NGM-34	34.2	CNG	10.2	315	Miller	1.78	191
NGM-33	33.2	CNG	14.9	118	Miller	1.78	185
NGM-29	29.4	CNG	28.7	48	Miller	1.65	164
NGB-33	32.7	CNG	16.7	127	Basis	1.85	179
NGB-29	28.9	CNG	16.2	147	Basis	1.85	158
NGB-23	22.4	CNG	15.8	111	Basis	1.86	120
NGB-20	19.5	CNG	15.4	114	Basis	1.83	116
H2-15	15.1	H2	14.2	~0	Basis	3.01	73

Table 3: Measurements with different fuels and engine settings

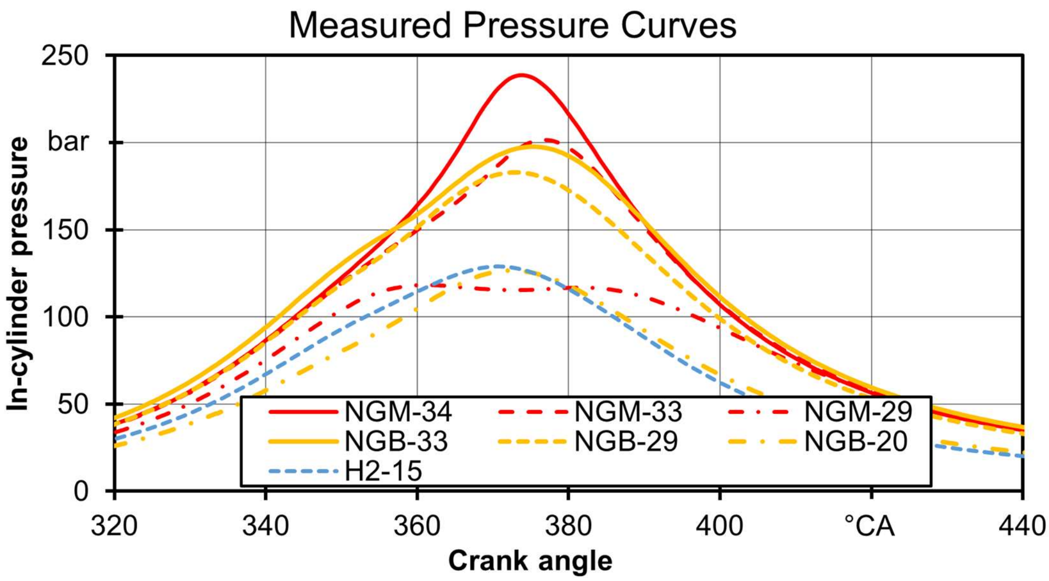


Figure 4: Measurements with different fuels and engine settings

The engine load of 15.1 bar IMEP can be achieved with the natural gas engine without major modifications using hydrogen as the fuel gas. At an air-fuel equivalence ratio of 3, no NO_x emissions are measurable in the exhaust gas and the efficiency is comparable to natural gas operation. If the specific load is further increased with hydrogen as fuel gas, backfire and preignition can occur. To give a short outlook: Experimentally and with more modifications, an IMEP up to 24 bars could be achieved. Since the hydrogen operating point with an IMEP above 20 bars can only be run with shorter-term stability, it is not included in these investigations.

Torsional vibration study with different fuels and IMEP

For the TV study three measurements are selected, which are listed in table 4. The engine power P_{eng} corresponds to a 16V engine.

Case	Description of measurement	PCP in bar	IMEP in bar	P_{eng} in kW
H2-15	Pure hydrogen	129	15.1	1168
NGM-34	NG, miller cycle, highest IMEP	236	34.2	3059
NGM-29	NG, miller cycle, lowest NOx	118	29.4	2624

Table 4: Selected cases for the TV study

In the second step of this study, a torsional system of a 16V industrial engine with similar bore and stroke as the testbed was built up, see figure 5. Because the measured pressure curves were taken for one engine speed, a genset application was used. In addition, the use of hydrogen seems to be more realistic for land-based applications due to the fact of the quite complex hydrogen storage systems in mobile applications.

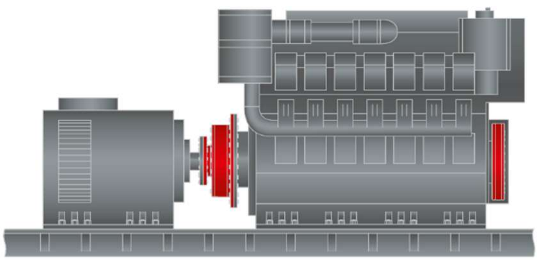


Figure 5: Engine with generator

Hydrogen:

Via the connecting rod ratio, the measured hydrogen pressure curve (H2-15) is converted to tangential pressure, see figure 6* and via Fast-Fourier-Transformation (FFT) an order-based resolution of the resulting excitation is achieved, see [17].

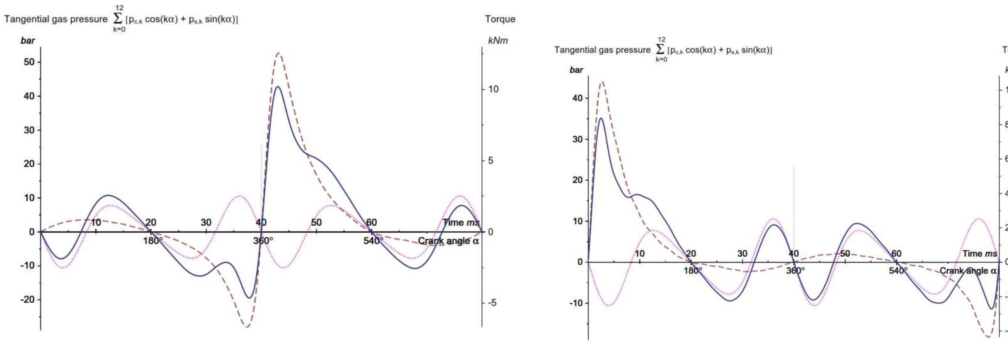


*Figure 6a: Tangential pressures H2-15 (hydrogen); 6b: Diesel-15 excitations; each at 1500 rpm with 15.1 bar IMEP**

*) Note: Combustion cycles are shifted by 360° in Figure 6.

In the third step, a genset power curve with an engine run up of 8 bar and 15.1 IMEP at a nominal speed of 1500 rpm was generated, see figure 7.

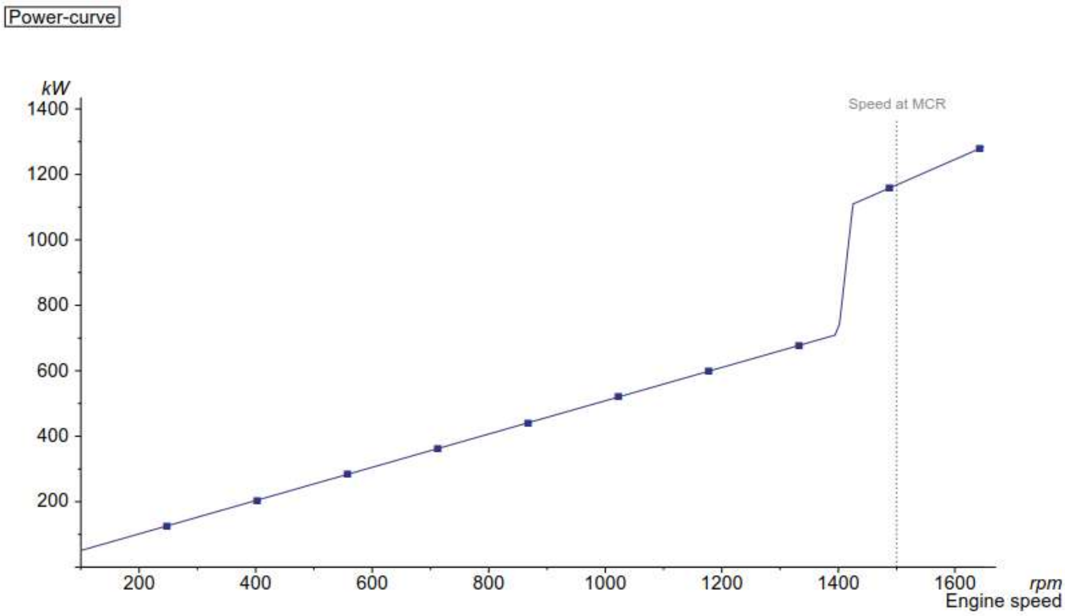


Figure 7: Genset power curve

In the fourth step a TVC with the following input data was performed:

1. TV model of an industrial 16V gas engine with a bore of 175mm,
2. without a torsional vibration damper (TVD),
3. power curve up to 15.1 bar IMEP (P_{eng} = 1168 kW) and
4. the hydrogen engine excitations derived from H2-15 measurements.

One result of this example is the TV stress within the crankshaft, see figure 8a.

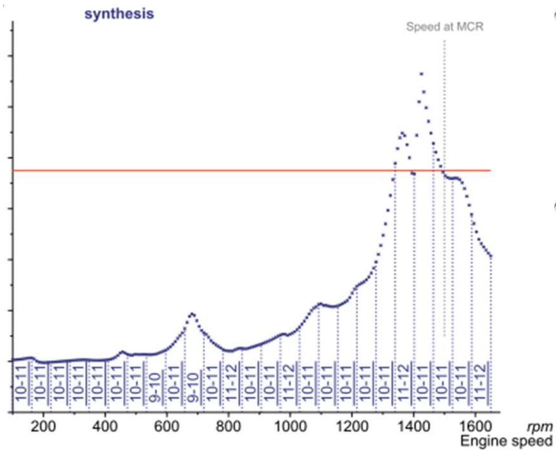


Figure 8a: Crankshaft stress with H2-15

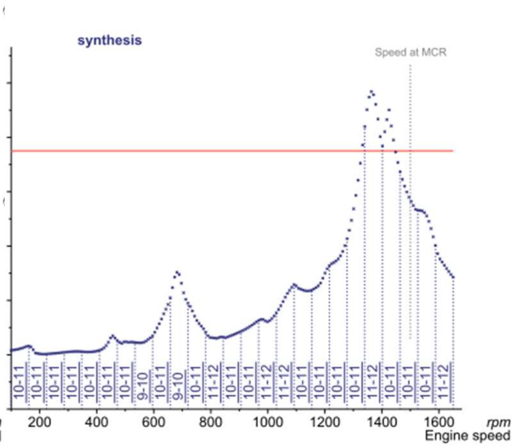


Figure 8b: Diesel-15 excitation (w/o TVD)

In the next step, a TVC was performed with a comparable diesel combustion. For a better comparison, the same TV model, power curve as for the hydrogen study (each with an IMEP of 15.1 bar at 1500 rpm) for the diesel excitations were used. Comparing figure 8a and 8b, it can be seen, that the resulting torsional stress in the crankshaft is lower with diesel than with hydrogen. For example, the max. stress is slightly lower and reasonably lower at the most important point, which is the engine's nominal speed at 1500 rpm.

After that, a TVC with a steel spring damper with an outer diameter of ca. 450 mm for Diesel and H2-15 were performed.

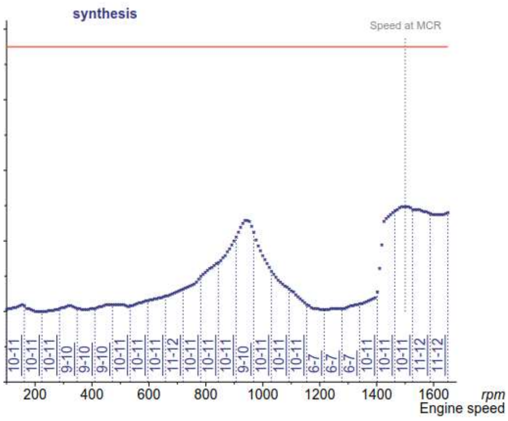


Figure 9a: Crankshaft stress with H2-15

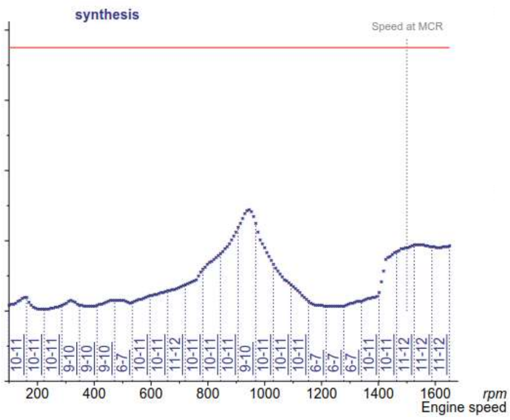


Figure 9b: Diesel-15 (both with TVD)

Like the TVC without damper it can be seen in figure 9a and 9b, that the use of the H2-15 excitation results in a 30 percent higher crankshaft stress than with diesel excitations at nominal speed.

Similar to the previous results, the torsional vibration torques at the flywheel for the four investigated cases are higher with the hydrogen- than with the diesel-excitations, shown over one working cycle in figure 10.

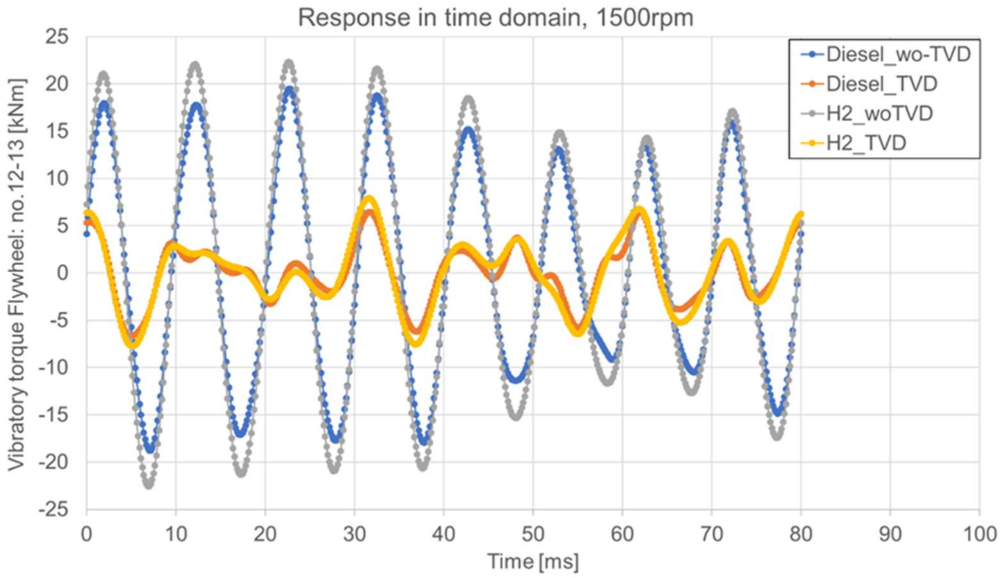


Figure 10: Vibratory torque at flywheel in time domain over 720°

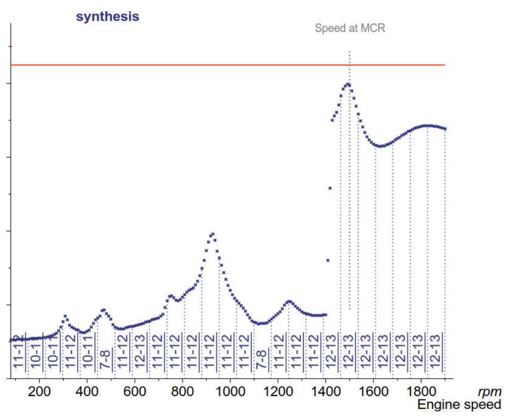
Natural Gas:

In this part the following CNG pressure curves are investigated:

Case	Description of measurement	PCP in bar	IMEP in bar	P_{eng} in kW
NGM-34	NG, miller cycle, highest IMEP	236	34.2	3056
NGM-29	NG, miller cycle, lowest NOx	118	29.4	2624
H2-15	*Pure hydrogen*	*129*	*15.1*	*1168*

Table 5: Investigated NG measurements in the TV study

Due to the higher PCP a different, reinforced TV engine model was used, but still a 16V diesel engine with a 175mm bore and a nominal speed of 1500 rpm. Calculating with an IMEP of 29.4 and a corresponding genset power of P_{eng} 2624 kW, an engine power curve like figure 7 was used.



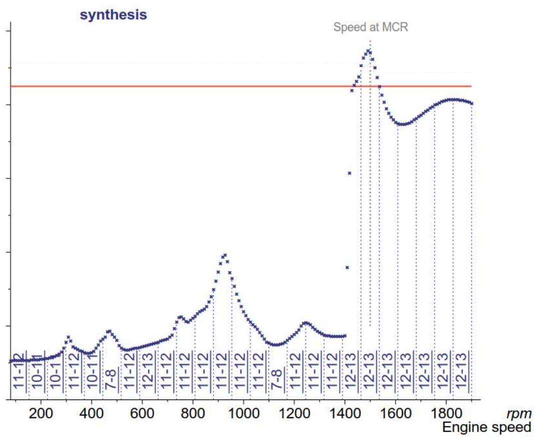


Figure 11a: Crankshaft stress with NGM-29 Figure 9b: and NGM-34 excitation

The resulting crankshaft stress with a steel spring TVD in the given space of close to 500 mm shows, that the stress is close to its limit, but fulfilled, see figure 11a. But for excitation NGM3-34 the limit is exceeded, and a new damper cannot easily be found. In that case, a discussion with the engine builder is needed to discuss further investigations to bring the TV stress below the given limit.

SYSTEM COMPLEXITY

The study in the previous chapter showed, that in all three investigations a torsional vibration damper is needed. In addition to that, the wide variety of possible fuels and other measures lead to a high number of configurations and possible operation modes which need to be investigated at present and even more in the future. Therefore, solutions to the question: “How to prepare for a complex future in terms of engine excitation and operation” must be found.

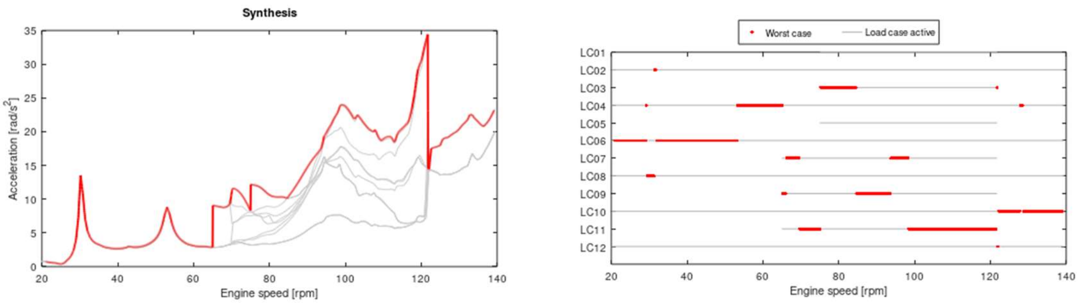


Figure 12: Max. Generator acceleration from 12 different load cases

One solution that supports TV damper manufacturers in their design process is showing graphs that give a good system overview in a limited number of diagrams. As an example, figure 12 shows the maximum acceleration on a generator. The vessel has 12 different operation cases: 6 operation modes (PTO, zero & full pitch) and two different engine exhaust gas stages.

CONCLUSION

Based on the current emission regulations, as well as political and social pressure, further emission reduction of large bore combustion engines is obvious. This trend is also reflected in the emission legislation for natural gas engines. In addition, the regulation of further exhaust gas components is to be expected, which are currently not considered. These reductions can be achieved by a combination of different measures. Whereby it can be expected that the use of different exhaust gas aftertreatment systems will have quite a small effect on the torsional vibrations (TV). On the other hand, an increase in the specific engine power and the use of different fuels for example natural gas or synthetic fuels can have quite a high impact on the TV of an engine.

In the main part of the paper different measured pressure curves of a single cylinder research gas engine using CNG up to an IMEP of 34 bar and hydrogen as fuel are used to study their effect on the TVs. To do so, these pressure curves were transferred to engine excitations and applied on a TV model of an industrial available 16V genset application. It was found that even for hydrogen with a fairly low IMEP of 15 bar, that the TV crankshaft stress limit is exceeded without a TV damper (TVD). Applying a steel spring TV damper, a 30% higher TV stress in the crankshaft for hydrogen can be seen compared to the diesel excitation. On the other hand, an IMEP of 34 bar shows, that even with a special tuned TVD the crankshaft is still overloaded. In such a case additional design loops for this application between the engine builder and the TVD supplier are needed for further design optimizations.

Nevertheless, the large variety of possible fuels and other actions lead to a high number of configurations and possible operation modes which need to be investigated at present and even more in the future. Therefore, one answer to the question: “How to prepare for a complex future in terms of engine excitation / operation”, can be diagrams with compressed information, based on different operation modes. To sum up, the operation modes of the engines and power trains will further increase and will need a more detailed system know-how to optimize these complex systems and avoid operational problems in their application.

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