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Diesel Engine Cold Start Noise Improvement

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ABSTRACT

The European as well as U.S. market share of modern Diesel engines has increased significantly in recent years, due to their excellent torque and performance behavior combined with low fuel consumption. The overall improved noise and vibration behavior of modern Diesel engines has also contributed to this trend. Despite overall improvements in Diesel engine noise and vibration, certain aspects of Diesel engines continue to present significant challenges. One such issue is the presence of Diesel knocking that is prevalent during cold start and warm-up conditions. This paper discusses a technique used to optimize the cold start noise behavior of modern Diesel engines.

The methods used in this study are based on optimizing the engine calibration to improve the vehicle interior and exterior (engine) noise, even at low ambient temperatures. Initially, the engine's combustion noise behavior is characterized by measuring the cylinder pressure (under various operating conditions) and developing appropriate transfer functions. Various engine calibration iterations are carried out using a structured Design of Experiments (DOE) and for each iteration, the measured cylinder pressure is used to calculate the combustion noise influence (based on existing transfer functions). At the end of this study, the influence of key calibration parameters on improving the cold start noise characteristics is demonstrated.

The acoustic optimization achieved in this way has no detrimental effects on the engine's ability to start, combustion stability, visible black or white smoke and emissions. Finally, the potential of using the developed technique in conjunction with other new technologies, such as exhaust gas after treatment systems and alternative preheating and boosting concepts, is discussed.

INTRODUCTION

The excellent torque and performance behavior of modern diesel engines combined with low fuel consumption and exhaust emissions has increased their market shares especially in Europe, but it is also expected for the U.S. market. The overall improved noise and vibration behavior of modern diesel engines has also contributed to this trend. However, during cold start and warm-up at low exterior temperatures, many diesel engines still produce an unpleasantly noisy knocking sound.

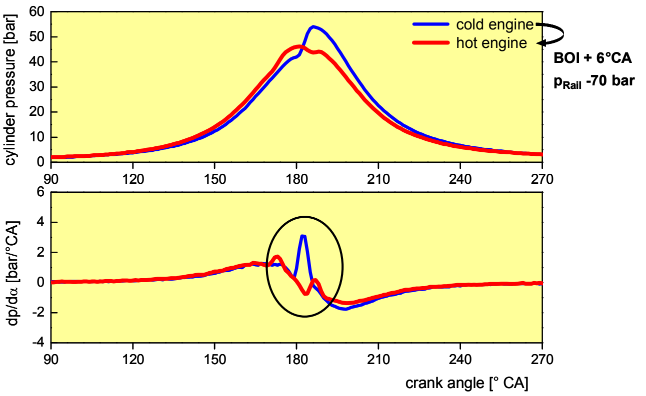

Figure 1: Cylinder Pressure Trace and Gradient for Cold and Hot Conditions

As an example, **Figure 1** shows the cylinder pressure curves and their first derivation over the crank angle of a Diesel engine with a common rail injection system and standard calibration at a cold and warm state, respectively. At a cold state, engine temperature amounts to 10°C and intake air temperature 0°C. At a warm state, it amounts to 85°C and 20°C, respectively. Both calibration states were using pre-injection and main-injection. The difference is caused by 6°C earlier timing as well as a rail pressure increase by 70 bar, during cold engine operation. Under cold operating conditions, a considerably higher cylinder pressure gradient results in a louder and more unpleasant combustion noise.

Recent investigations at FEV Motorentechnik showed that careful calibration optimization can significantly improve interior and exterior noise, even at low ambient temperatures. Based on these findings, a time effective method to optimize Diesel knocking was developed. It utilizes Design of Experiments (DoE), the prediction of combustion noise by FEV-CSL (FEV-<u>C</u>ombustion <u>S</u>ound

Level, procedure will be described later) as well as a new combination of the latest engine and vehicle cold-test rig capabilities.

The acoustic optimization achieved in this way does not have and detrimental effects on the engine's ability to start, combustion stability, visible black or white smoke and emission behavior. In the future, improved exhaust gas aftertreatment systems and alternative preheating and boosting concepts are expected to reduce Diesel cold start noise even further.

EFFECTIVE METHOD FOR NVH ORIENTATED CALIBRATION OPTIMIZATION

The disturbing diesel knocking is caused by hard combustion, as explained earlier. Therefore, cold start optimization must aim at reducing combustion excitation. By using modern measurement and analysis methods (engine or vehicle cold test bench, noise prediction by CSL and DoE guided measurement programs), calibration adjustment and thus noise quality can be considerably improved. However, apart from the dependence on the quality of the base calibration, the acoustic optimization potential is also limited by requirements (e.g. reliable start-up at 30°C) and the combustion calibration data set is processed based on the pre-optimized mapping points. It is then verified and fine-tuned on the vehicle, using a cold test bench with regard to NVH and emission behavior, stability, acceptable black and white smoke quantities as well as relevant emissions (e.g. like European or American test cycles like NEDC- / U.S. Tier-II, III, IV, …..).

PRE-STUDY ON ENGINE TEST BENCH - BASED ON AN INTERNAL RESEARCH PROJECT

The combustion noise is mainly determined by the cylinder pressure excitation, which in turn is characterized (aside from fuel characteristics) by the injection parameters (quantity and timing of pre- and main injection respectively, injection pressure, etc.). Also of significant importance is the engine structure as a transfer system; therefore, in the engine design process a careful acoustic optimization is necessary to specifically avoid structural weaknesses with respect to combustion excitation.

The influence of different injection parameters was investigated in this research project for a turbocharged 4-cylinder common rail Diesel engine (2.0L displacement) on a cold engine test bench. The test bench allows the variation of intake air, oil and cooling water temperature, as well as load pressure (for a schematic test bench layout, see **Figure 2**). Cooling water and oil temperatures can be freely adjusted between -25°C and 90°C and intake air temperature between -30°C and 60°C. Boost pressure could be increased up to 1.4 bar (absolute). The time of injection and the quantity of pre- and main injection, the rail pressure as well as the exhaust recirculation rate was also varied. In total, five (5) representative operation points from the load and rpm range were examined. A 15°C engine temperature and 0°C intake air temperature were defined as the base. Pre-injection was activated in all operation points. Aside from exhaust gas raw emissions (HC, CO, NOx and particulates), the cylinder pressures were measured to predict the engine noise level by the CSL.

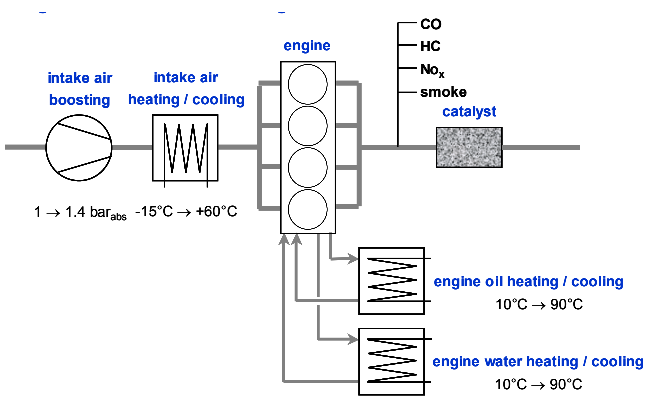

Figure 2: Boundaries of the Engine Cold Test Cell

Figure 3 shows the effects of varying oil/cooling water temperature, intake air temperature, boost pressure and start of main injection (BOI) on engine noise (CSL) and cold start relevant carbon monoxide and hydrocarbon emissions.

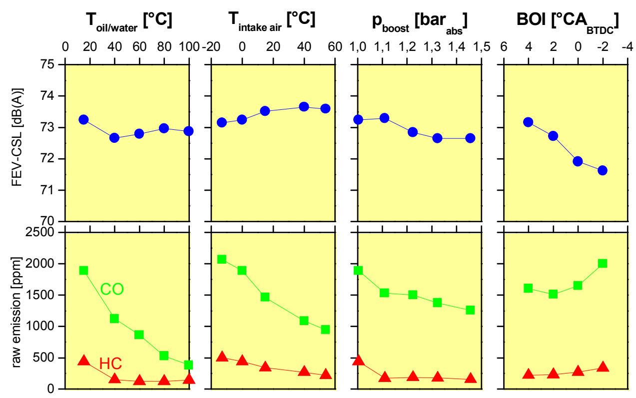

Figure 3: Basic Engine Test Cell Investigations for Cold Testing

The variation of cooling water, intake air and boost pressure shows no significant influence on noise; whereas, hydrocarbon and carbon monoxide emissions are considerably diminished, especially by increased oil/water temperature and intake air temperature. This creates additional freedom for acoustic optimization. By delaying BOI, combustion noise is - as expected – reduced; however, HC and CO emissions are simultaneously increased.

The minor dependency of combustion excitation on intake air and combustion chamber wall temperature (oil/water temperature), as well as boost pressure, seems to contradict literature (/3/, /4/) and also the common understanding. However, it can be explained by pre-injection, which currently has become customary. Respectively, the injection timing delay is predominant, not the ambient temperature. Especially at low temperatures, ignition delay is drastically reduced by pre-injection. With the start of pre-injection, the first pre-reactions (for instance radical formation) occur, which at the onset of main injection facilitate a quick ignition of the induced fuel with a subsequent smooth combustion process.

The results of the basic investigations on the engine cold test bench show that boost pressure and intake air temperature increase and both exhibit a significant potential for the reduction of exhaust gas raw emissions, which can be used for acoustic calibration (**Figure 4**). Combustion excitation acts against HC and CO raw emissions. This trade-off is represented by a gray area. However, in most cases a moderate increase of HC and CO is acceptable for acoustic calibration (white arrow).

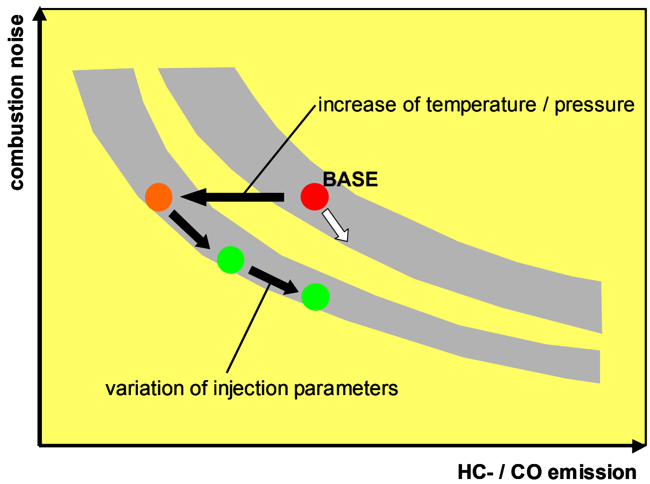

Figure 4: Potential of Pre-heating and Boost Pressure Increase

By increasing the boost pressure or temperature, HC and CO emissions are reduced, while the combustion noise remains nearly unchanged. The injection parameters can now be modified in such a way that a part or the entire emission potential can be used for noise reduction (black arrows).

So, in the mid and long term, alternative boosting and pre-heating concepts could contribute to noise reduction during cold start and warm-up. For increased supercharging during idle or lower load and rpm range, electric chargers, electrically supported chargers or two-phase chargers (like just introduced into the market for series production) could be implemented. The intake air can, for example, in principle be pre-heated electrically.

Additionally, the increased flexibility of injection systems and the possibility to control the combustion process even more precisely promises more freedom for further acoustically orientated calibration optimization in the future. In this context, multi-injection and injection curve shaping needs to be mentioned. Increased processor and storage capacity of the control units also contribute to this trend. In the heat-up behavior, more advanced heating elements can improve conditions for a smooth starting and running combustion process.

Nevertheless, the calibration potential is limited. Therefore, non-engine approaches for the exploitation of additional NVH optimization potentials are discussed in the following text.

Considering that some exhaust system components act against combustion excitation and thus combustion noise, even more efficient exhaust aftertreatment systems (particulate filters, oxidizing catalysts etc.) are desirable. This would result in further noise and vibration optimization potential through NVH-oriented vehicle calibration, while increased pollutant emissions would be compensated for by the aforementioned optimized exhaust gas aftertreatment systems.

PREDICTION TOOL BASED ON CYLINDER PRESSURE TRACES - *FEV-CSL*

The engine Combustion Sound Level (CSL) is determined by combining thermodynamic parameters and structure evaluation functions, while also considering the mechanical noise. The engine noise can be divided into individual components, such as direct and indirect combustion noise, as well as flow noise and mechanical noise. Combustion noise is directly related to all load-dependent noise components, direct and indirect combustion noise as well as flow noise, which comprises surface radiation of the intake and exhaust system, resulting from air-mass flow.

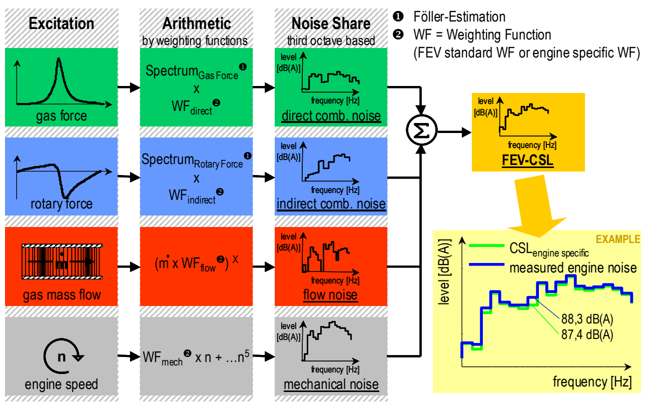

Figure 5: CSL: Prediction of Engine Noise Level

Not only direct gas force excitation, but also some other additional forces are exciting the structure-borne engine vibrations. These additional forces can be divided into two groups according to their time curves. Forces that follow the time curve of the cylinder pressure (gas force) cause direct combustion noise; whereas, indirect combustion noise is caused by forces that are following the rotating force curve. Those are mainly determined by the rotating excitation force of the crankshaft and lateral piston forces.

Based on this model (/1/), the individual combustion noise shares are determined by combining the excitation parameters (cylinder pressure, rotating force and air mass flow) with the associated structure evaluation functions (**Figure 5**). The excitation spectra for gas force and rotating force are not simply taken from a usual FFT but estimated by applying the Foeller procedure /2/.

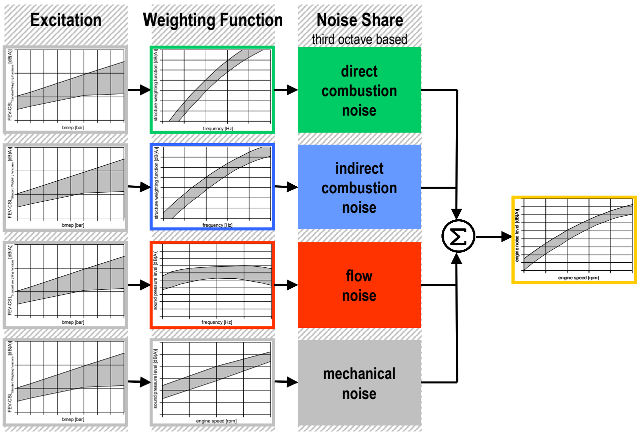

Figure 6: CSL: Evaluation of Combustion Excitation and Structure Attenuation

The evaluation of combustion noise excitation is performed by calculating the CSL and comparing it to the-state-of-the-art. For this purpose, standardized structure weighting functions have been used. By comparing the engine-specific structure weighting functions of the individual noise shares to the state-of-the-art, critical noise shares and critical frequency ranges can be identified. Thus, the noise contribution of the (measured) noise level can be divided into individual exciting and attenuating components (**Figure 6**). Based on this information, further NVH refinement strategies can be developed.

The individual disturbing noise components are ascertained based on the third-octave-selective addition of the excitation level and the level of the corresponding evaluation function. The total noise level of the engine results from the summation of all individual noise shares.

The comparison of calculated (CSL) and measured engine noise reveals very similar 3rd octave spectra and very small differences in the overall level.

OPTIMIZATION WITH A COMBINATION OF THE CSL AND DOE

The investigations on the cold test bench (conditioned engine or vehicle cold test bench /6/) were supported by the Design of Experiments (DoE) method. Start of pre- and main injection, pre-injection quantity, exhaust gas recirculation rate and rail pressure served as variation parameters (factors). The optimization parameters (responses) were hydrocarbon, carbon monoxide, nitrogen and particulate emissions, as well as the predicted engine noise level.

CSL can also be used to effectively support NVH-oriented vehicle calibration. In that case, it is typically used in combination with the DoE (Design of Experiments). In the first step, the calibration of noise-relevant injection parameters is pre-optimized on an engine or vehicle emission test bench, while paying close attention to exhaust gas emissions and fuel consumption targets. Noise generation is estimated by the CSL. In the second step, a complete calibration data set is processed, based on the pre-optimized mapping points. The NVH and emission behavior can then be verified and fine-tuned for the vehicle on a test bench.

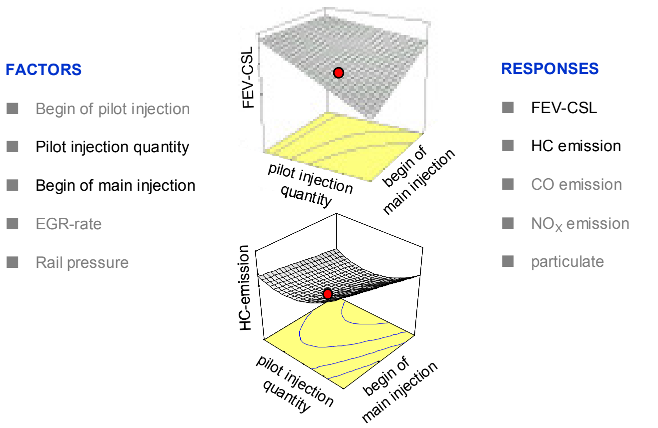

Figure 7: Use of the DoE for Cold Start Optimization in an Engine Test Cell for Cold Engine Testing

Start of pre- and main injection, pre-injection quantity, exhaust gas recirculation rate and rail pressure served as variation parameters (factors) in the investigation. The optimization parameters (responses) were hydrocarbon, carbon monoxide, nitrogen and particulate emissions, as well as the predicted engine noise level. **Figure 7** shows typical examples of regression models obtained by the DoE for two variation parameters (pre-injection quantity and begin of main injection) and two responses (CSL / HC -emissions).

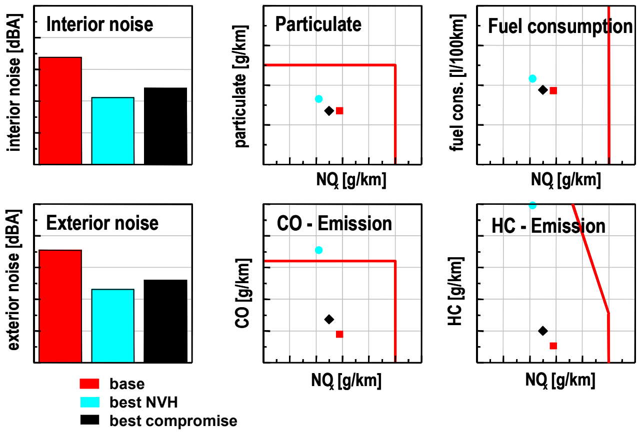

Figure 8: NVH Improvement at Idle (-10°C) and Exhaust Emissions

Figure 8 shows the results of a DoE optimization, based on investigations on a cold conditioned engine test bench. The vehicle cold conditions test bench can be operated at temperatures as low as -30°C. In this case, it was operated at -10°C.

The “Best NVH”-variant has maximum idle noise reduction potential with exhaust gas emission reaching legislative limits and a certain increase of fuel consumption within the MVEG cycle (a European cycle for emission and fuel consumption testing on vehicle dynamometers). In case of the “Best Compromise”-variant, fuel consumption remains unchanged and the increase in exhaust gas emissions is negligible, while vehicle interior noise as well as exterior noise are reduced by 2 dB(A).

NVH ORIENTATED APPLICATION AND FINE-TUNING IN THE VEHICLE

After the calibration potential for the reduction of Diesel knocking was determined using the CSL, series application into the vehicle was carried out on the conditioned vehicle cold test bench, which is also equipped for interior and exterior noise measurements.

The emission regulations were met, using the optimized calibration. Aside from a total level reduction in the vehicle interior and exterior noise (idle, -10 °C intake air temperature), the noise quality was significantly improved with regard to typical Diesel engine knocking (**Figure 9**). The depicted modulation analysis of the interior noise shows that with optimized calibration, the predominant amplitudes (especially the 2nd engine order) could be lowered considerably in the characteristic frequency range for knocking sound (1 - 3 kHz).

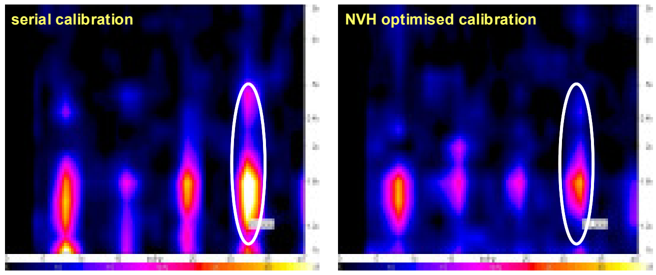

Figure 9: Modulation Analysis Interior Noise

The demonstrated significant optimization potential - which of course is also defined by the acoustic quality of the base calibration - was verified in principle with a number of other vehicles with modern Diesel engines equipped with common rail injection systems. This gives a lot of freedom for parameter variations. All these optimizations were also elaborated by using the presented method combined with the CSL and DoE. However, it needs to be mentioned in this context, that the calibration of the cold start and warm-up run at low ambient temperatures is extremely complex and determined by many - in part conflicting - parameters.

Figure 10 illustrates these basic interrelations and limitations with regard to the decisive requirements in cold start and warm-up for a typical series application. In the temperature range up to about -20 °C, the ability to start is by far the chief requirement. All other demands and development goals must be subordinated. This is superimposed by the requirement for the prevention of ignition/combustion faults, which is critical up to approximately 0°C. Reasonable acoustic optimization starts at about -10 °C, while black and white smoke must be avoided. From 20 °C onwards, test cycle relevant exhaust emission regulations must be met. Noticeable changes of the sound impression during warm-up must also be avoided.

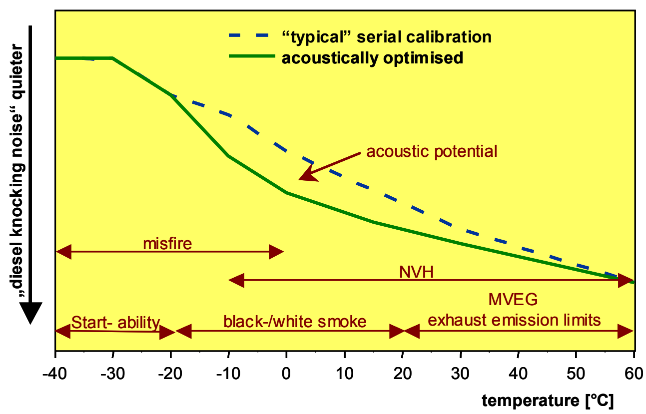

Figure 10: Calibration NVH-optimization Potential

CONCLUSION

During cold start and warm-up, many Diesel engines still produce an unpleasant loud knocking sound, due to harsh combustion compared to hot operation.

Within an internal research project at FEV Motorentechnik, it could be demonstrated that the acoustic optimization of the injection parameters has the largest potential for combustion noise reduction, especially under cold start conditions. It was demonstrated that acoustic optimization of the calibration can substantially reduce Diesel knocking at low temperatures, without any detrimental effects on the engine's ability to start, combustion quality, visible smoke or emission behavior. Through specific optimization - with acoustic demands as an integral part of the development process - a further acoustic improvement in many vehicles is possible. This could be proved for a number of common rail Diesel engines.

For the future, it is expected that further Diesel knocking improvement potential will be gained by improved exhaust gas aftertreatment systems (particulate filters allow more flexibility for raw emissions) and alternative pre-heating and supercharging concepts.

Therefore, the methodology developed - combustion noise prediction by FEV-CSL supported by the DoE – in combination with state-of-the-art engine and vehicle cold test benches play a vital role in the optimization process, with respect to both performance/emissions and objective as well as subjective NVH behavior.

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