Acoustic Diesel Cold-Start

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Introduction

Over the past few years, the noise and vibration behavior of diesel passenger cars has been further improved, thereby continuously diminishing the disadvantages of diesel engines compared with gasoline engines. However, during cold start and warm-up at low ambient temperatures, many diesel engines still produce an unpleasantly loud knocking sound, resulting from a significantly higher combustion excitation.

As an example, Figure 1 shows the cylinder pressure curves and their first derivation versus crank angle of a diesel engine with common rail injection system and standard calibration at cold (approx. 0°C) and warm condition (approx. 85°C), respectively. At cold state, a considerably higher cylinder pressure gradient results in louder and more unpleasant combustion noise.

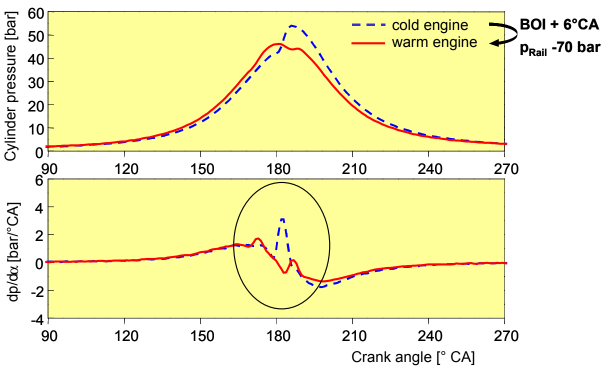

Figure 1: Cylinder pressure trace and gradient for cold and hot condition.

Based on internal research at FEV Motorentechnik, it could be shown that even at low ambient temperatures, systematic acoustic-related optimization of the calibration significantly reduces combustion excitation and thus the unpleasant knocking sound. It improves interior as well as exterior vehicle noise. At the same time, disadvantages regarding startability, combustion stability, visible black or white smoke and emission behavior (for instance in the MVEG test) are avoided. FEV-CSL (Combustion Sound Level) is an important development tool in the acoustic optimization of the calibration which facilitates combustion noise prediction in the optimization process based on a special cylinder pressure analysis /1/.

Basic Investigations on the Engine Cold Test Bench

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

The influence of injection parameter variations for a turbocharged 4-cylinder common rail diesel engine was investigated on an engine cold test bench. The test bench allows the variation of intake air, oil and coolant water temperature as well as boost pressure. Timings and quantities of pilot and main injection, rail pressure as well as exhaust recirculation rate were systematically varied. Aside from exhaust gas raw emissions (HC, CO, NOx and particulates), the cylinder pressure was measured to predict the engine noise level by means of FEV-CSL.

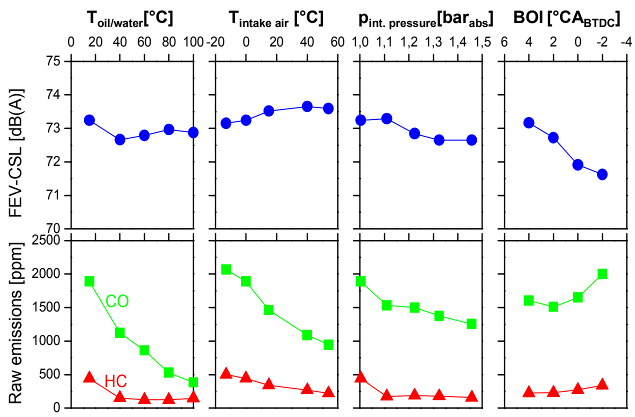

Figure 2: Engine noise and exhaust gas emissions at cold conditions.

As documented in Figure 2 the variation of coolant water, intake air temperature as well as boost pressure shows no significant influence on noise (FEV-CSL), whereas hydrocarbon and carbon-monoxide emissions are considerably diminished, especially by increased oil/water temperature and intake air temperature. By delaying BOI, combustion noise is – as expected – reduced, however, HC and CO emissions are simultaneously augmented.

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 (/2/). However, it can be explained by the pre-injection which has become customary today. Especially at low temperatures, ignition delay is drastically reduced by pre-injection. With the start of pre-injection, 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.

Combustion Noise Optimization at Cold Start and Warm-up Phase

By using modern measurement and analysis methods (engine or vehicle cold test bench, noise prediction by FEV-CSL, DoE guided measurement programs) calibration adjustment and thus noise quality can be considerably improved with respect to cold start behavior.

Pre-Optimization on the Engine / Vehicle Cold Test Bench with the help of FEV-CSL and DoE

The investigations on the cold test bench were supported by the Design of Experiments (DoE) method, as exemplarily shown in Figure 3. Begin of pre- and main injection, pre-injection quantity, exhaust gas recirculation rate and rail pressure served as variation parameters (factors). Optimization parameters (responses) were hydrocarbon, carbon monoxide, nitrogen and particulate emissions as well as the predicted engine noise level (FEV-CSL).

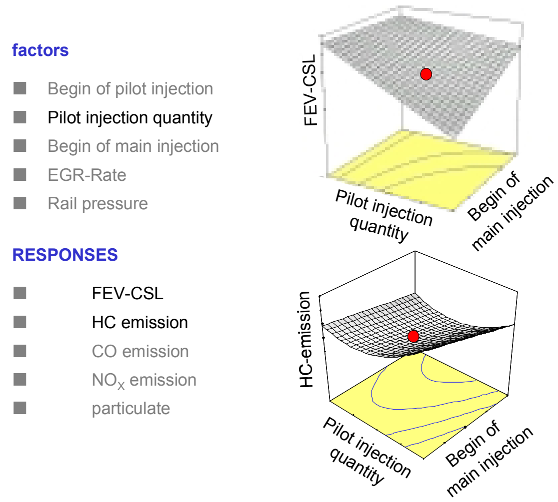

Figure 3: Use of DoE for cold start optimisation.

Application and "Fine-Tuning" in the Vehicle

After the calibration potential for the reduction of diesel knocking was determined on the cold test bench, series application into the vehicle was carried out on a conditioned vehicle cold test bench.

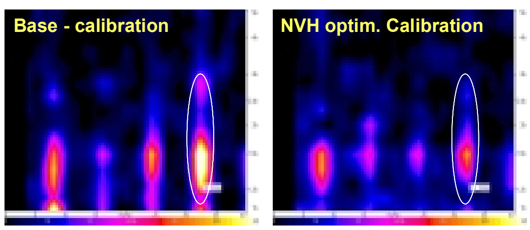

Figure 4: Comparison base /optimised calibration: Modulation analysis interior noise.

With the optimized calibration, emission targets were achieved. 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 as can be seen in Figure 4. The depicted modulation analysis of the interior noise shows that with optimized calibration the noise amplitudes could be considerably lowered in the frequency range (1 – 3 kHz) that is characteristic for knocking sound.

The demonstrated significant optimization potential was verified in principle with a number of other vehicles with modern common rail diesel engines.

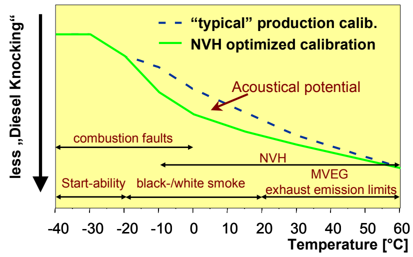

Figure 5: Sketch of calibration NVH-optimisation potential and limitation demands at cold start.

Figure 5 illustrates the 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, startability is by far the major requirement. 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, MVEG relevant exhaust emission regulations must be achieved.

Summary

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 during cold start. As a consequence further acoustic improvement in many vehicles is possible without negative drawback onto startability, combustion quality, visible smoke or emission behavior, which could be proved for a number of common rail diesel engines. The methodology developed by FEV – combustion noise prediction by FEV-CSL supported by DoE – as well as state-of-the-art engine and vehicle cold test benches play a vital role in the optimization process.

References

[1] Prediction of Combustion Process Induced Vehicle Interior Noise. Alt, N.; Nehl, J.; Heuer, S.; Schlitzer, M., SAE 2003-01-1435

[2] Abschlussbericht zum Sonderforschungsbereich 224 "Motorische Verbrennung". URL: http://www.vka.rwth-aachen.de/sfb_224/bericht.htm

[3] DoE in der Motorenentwicklung: Multiple Diesel Vehicles Calibration Based on Space-Filling DoE and Kriging Modelization. Figueres, F.; Raynaud, Y.: HdT Essen, Fachbuch Band 26, 2003