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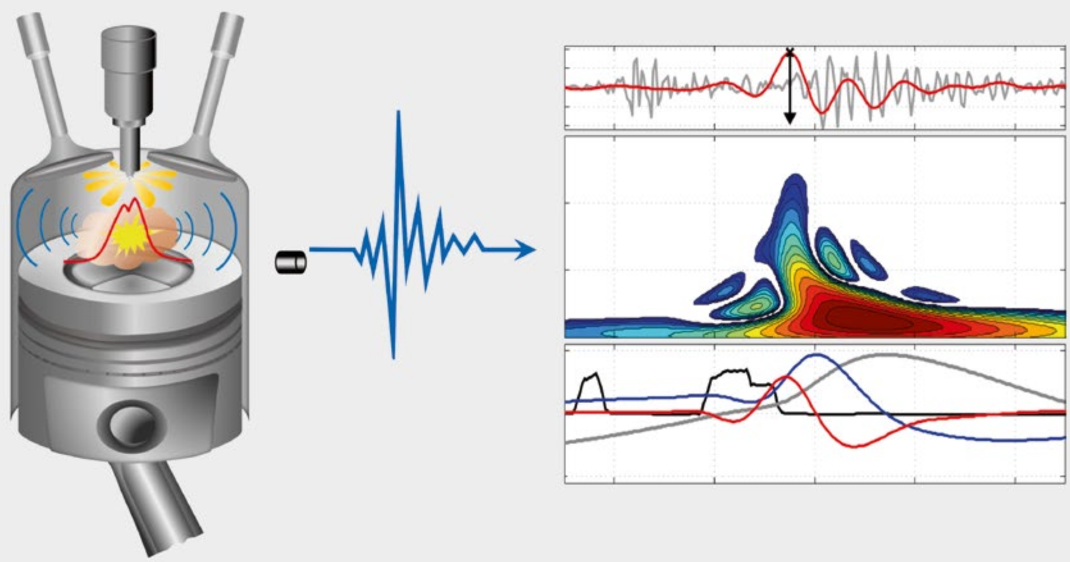
Structure-borne Noise Based Diesel Engine Control

Modern passenger cars are characterised by low noise emissions. In the lower load and engine speed range, however, dominant combustion noises are produced by the higher combustion delay, particularly during engine starts and during warming up. At the University of Magdeburg and the Technical University of Berlin, it is now possible to demonstrate through an FVV project that the structure-borne noise based methods developed in the predecessor project to control the centre of gravity of the combustion, also work well in a comprehensive speed-load range and during dynamic excitation. It can also be used for other diesel engines, and a regulation of the centre of combustion focus point is also possible.



1 MOTIVATION
2 DEVELOPMENT OF A VIRTUAL CYLINDER PRESSURE SENSOR
3 DEVELOPMENT OF A VIRTUAL NOISE SENSOR
4 CYLINDER-SELECTIVE NOISE-CONTROLLED DIESEL ENGINE
5 OPTIMISATION ALGORITHM FOR NOISE CONTROL
6 SUMMARY AND OUTLOOK

1 MOTIVATION

Today's passenger car diesel engines are distinguished by low exhaust emissions and low fuel consumption. In the lower load and engine speed range, however, dominant combustion noises are produced by the higher combustion delay, particularly during engine starts and warming up. Although, nowadays multiple pilot injections are used to reduce this type of irritating combustion noise. This clashes with the exhaust emissions, which have a higher priority. In the completed FVV project Noise-controlled Diesel Engine I and II [1], it was possible to control the noise behaviour by modifying the main injection on certain diesel grade values, but the pilot injections were not considered. In the following research project structure-borne noise based diesel engine control [2] the structure-borne noise signals were used, on the one hand, to achieve the same reduction of emissions like a cylinder-pressure-based engine control, and on the other hand, to evaluate combustion noises without using cylinder pressure sensors.

2 DEVELOPMENT OF A VIRTUAL CYLINDER PRESSURE SENSOR

In order to carry out the studies, at the IMS a series-production 1.6-l four-cylinder diesel engine was set up on the acoustic test bench. The algorithms required for processing engine speed, current, structure-borne noise and microphone signal data were provided by IAV's MPEC (Modular Prototyping Engine Controller) rapid prototyping system, **FIGURE 1**.

Information on the cylinder pressure profile is imperative for applying a cylinder-pressure-based engine control system, which was developed by the chair of electronic measurement and diagnostic technology at the TU Berlin. Unlike pressure sensors, the characteristic variables of indicated mean effective pressure p_{mi}, maximum cylinder pressure p_{max} and centre of heat release α_{q50} were to be determined by means of a virtual cylinder pressure sensor.

The coherence analysis [2] of the project engine has revealed a linear relationship between cylinder pressure signal and structure-borne noise signal in the frequency range up to 3 kHz. Determining the frequency bands excited in the structure-borne noise signal by combustion involves a time-frequency analysis, **FIGURE 2**. For this purpose, the Smoothed-Pseudo-Wigner-Ville distribution (SPWV distribution) was used for producing an angle-synchronous graph showing the relationship between structure-borne-noise and cylinder pressure signal. This was followed by an analysis of the time-based correlations between cause and effect or excitation by cylinder pressure and signal inputs in the structure-borne noise. The aim of this analysis was to extract a position information characteristic from structure-borne noise that correlates with the centre of heat release.

3 DEVELOPMENT OF A VIRTUAL NOISE SENSOR

The diesel noise rating computation method from FVV's Objectivising Subjective Assessment project [3] was used for evaluating diesel knock, **FIGURE 3**. Computing the diesel noise rating was based on recorded airborne noise signals using microphones. A model had to be created on the basis of the structure-borne noise signal that estimates the diesel noise rating for airborne noise (virtual noise sensor). The diesel noise rating is based on determining

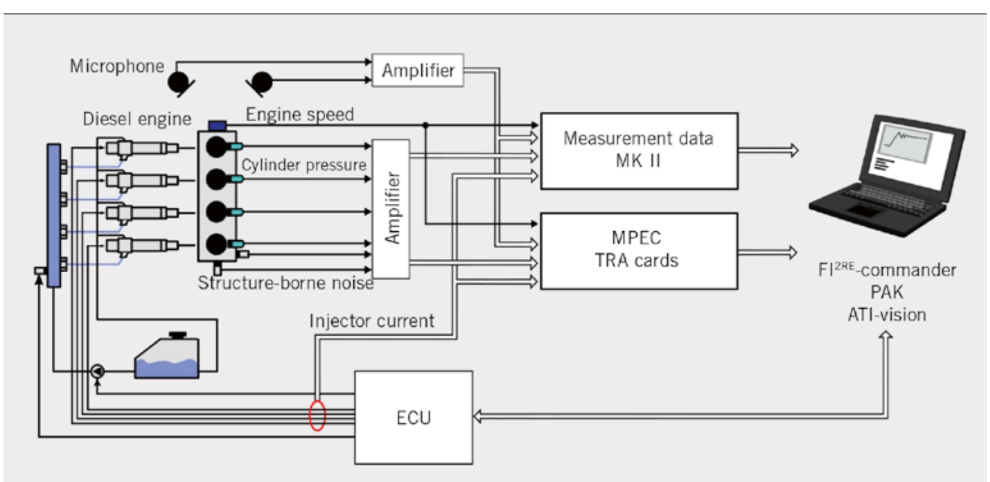


FIGURE 1 Schematic diagram of test bench configuration

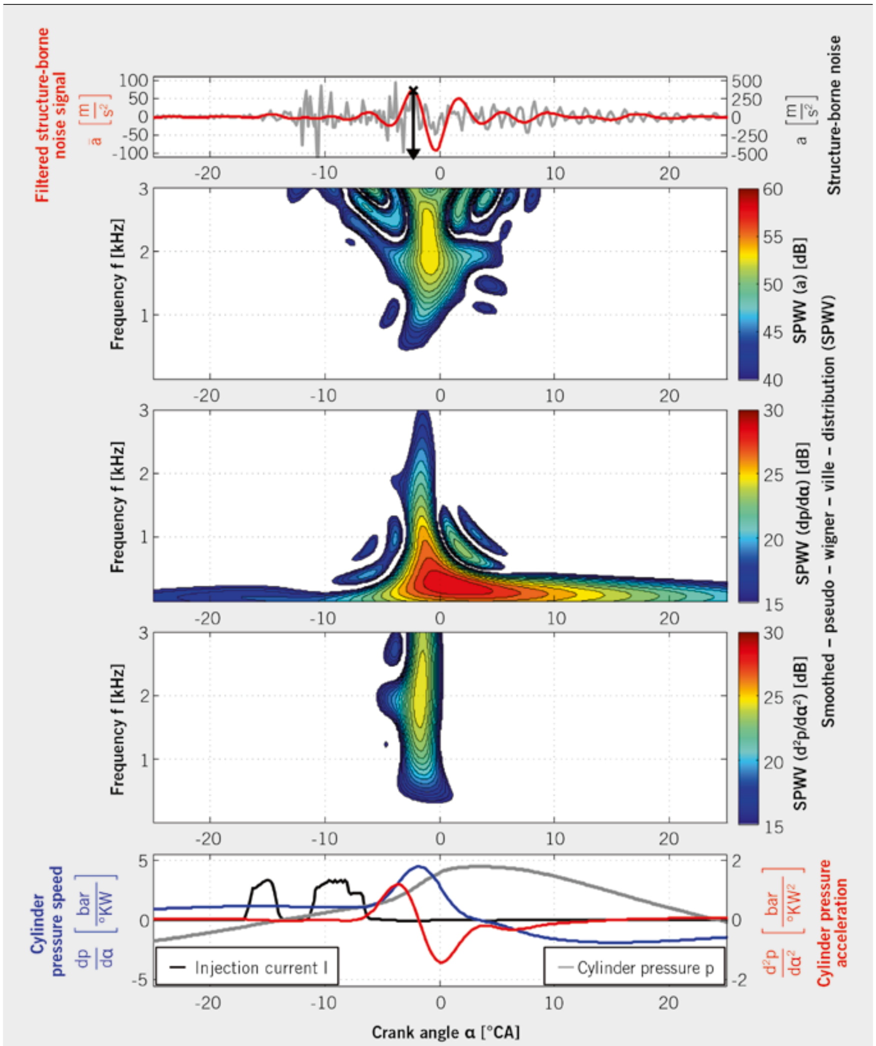


FIGURE 2 Time-frequency analysis of structure-borne noise signal a of sensor O_1 in comparison to cylinder pressure p of the first cylinder, cylinder pressure speed dp/dα and cylinder pressure acceleration d²p/dα² (1250 rpm, 25 Nm) (© IMS)

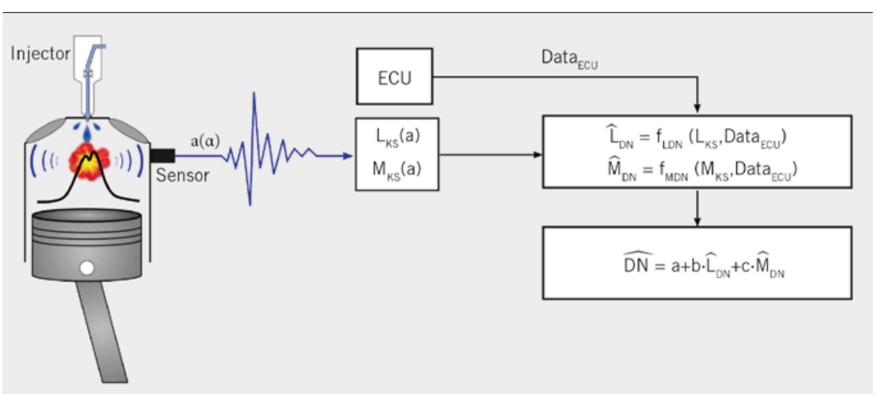


FIGURE 3 Methods for determining diesel noise rating (© IMS)

loudness and modulation. Given the need for airborne-noise signals, however, determining the diesel noise rating is limited to acoustic test benches interfering noises, such as driving noises, superimpose the signals when being used in the vehicle. Estimating the diesel noise rating provides a way of evaluating combustion noise irritation online and integrating it into the cylinder-pressure-based engine control system.

A high level of correlation between airborne and structure-borne noise signals, or loudness, modulation and diesel noise rating, was verified in [2]. The next step aims to show the diesel noise rating value range from airborne sound using structure-borne noise signals. This uses the idea of creating a regression model that estimates characteristic airborne sound values on the basis of structure-borne noise signals. This model was referred to as a virtual

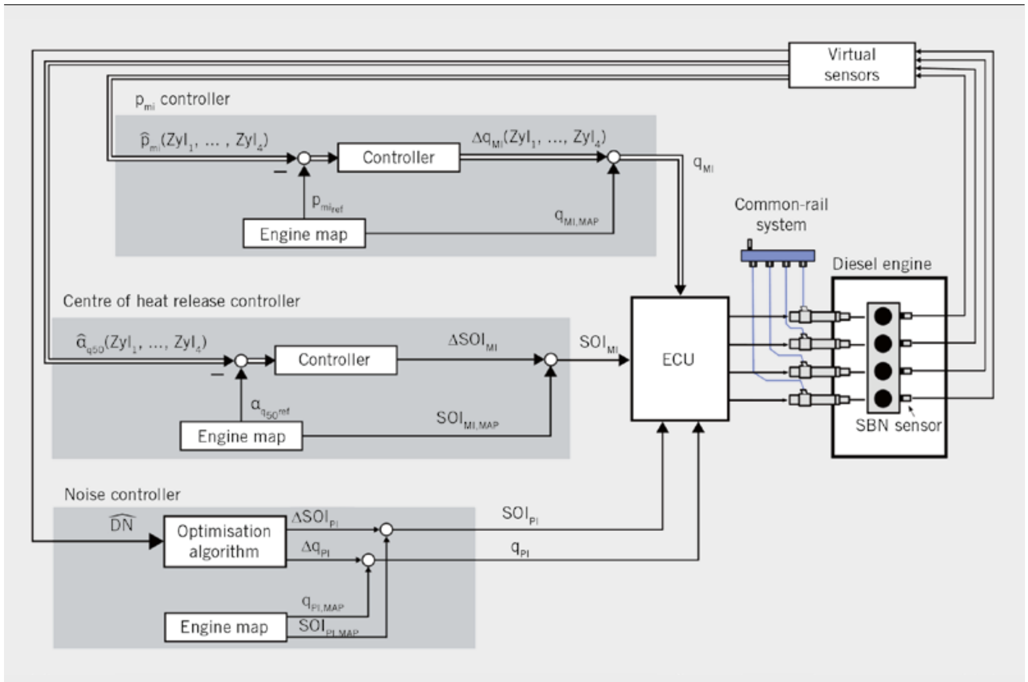


FIGURE 4 Diagram illustrating the principle behind the control structure (© IMS)

noise sensor. The approach reflects the concept for virtual pressure sensors. The diesel noise rating can be determined indirectly by L_{KS} estimated and M_{KS} modulated from structure-borne noise. Regression models were defined for these two variables. The diesel noise rating $\hat{DN}$ can then be calculated from:

Eq. 1 $$\hat{L}_{DN} = f_{LDN}\ (L_{KS}, Data_{ECU})$$

Eq. 2 $$\hat{M}_{DN} = f_{MDN}\ (M_{KS}, Data_{ECU})$$

Eq. 3 $$\hat{DN} = a + b \cdot \hat{L}_{DN} + c \cdot \hat{M}_{DN}$$

Control unit data ($Data_{ECU}$) can be used for determining regression models f_{LDN} and f_{MDN}.

4 CYLINDER-SELECTIVE NOISE-CONTROLLED DIESEL ENGINE

The models developed for estimating cylinder-selective combustion variables $\hat{\alpha}_{q50}$, $\hat{p}_{mi}$ and $\hat{p}_{max}$ were to be used to realise a cylinder-selective combustion control system. Here, the control strategy involved giving all cylinders equal status in relation to indicated mean effective pressure and controlling the main centre of heat release, **FIGURE 4**. Main injection fuel quantity q_{MI} and main injection angle SOI_{MI} served as the control variables.

Indicated mean effective pressure is a direct measure of engine work. In an initial approach, therefore, a system was to be provided for controlling indicated mean effective pressure. Here, indicated mean effective pressure was to be recorded on a cylinder-specific basis and corrected for each cylinder by means of the main injection fuel quantity. This was necessary because the injected fuel quantity can vary depending on the condition of the solenoid injectors. This must be expected in particular if aging effects are at play or the injectors are damaged. Particularly when it comes to minimising exhaust emissions, it was essential to maintain the main centre of heat release. At commercial level, the centre of heat release can be determined by cylinder pressure sensors. However, the virtual pressure sensors developed in section 2 provided the alternative for ascertaining the centre of heat release on the basis of structure-borne noise sensors.

The generated regression models provided the basis for estimating the respective main centres of heat release $\hat{\alpha}_{q50}$ $(Cyl_1,\ldots,Cyl_4)$ for each cylinder for each working cycle synchronously. Adapting the centre of heat release involved controlling the injection angle. A PI controller was configured for control purposes. To verify the control structure, a step measurement of 1 bar (p_{mi} (Cyl_1) = 2.8 bar) was carried out around the 1250 rpm, 25 Nm operating point, **FIGURE 5**. It can be seen that the steady-state final values are reached after approximately 40 working cycles.

5 OPTIMISATION ALGORITHM FOR NOISE CONTROL

The aim was to optimise the diesel noise rating irrespectively of the operating point selected. Studies carried out so far have shown that combining angular position and pilot injection quantity can optimise the diesel noise rating across the board. The optimisation idea was based on using a search algorithm that has the task of detecting the maximum diesel noise rating by gradually varying the injection parameters. The gradient descent method increased the current injection parameter by a fixed increment. If the diesel noise rating increased, the injection parameter continued to increase until the gradient of the diesel noise rating between old and new injection parameter was zero. When the gradient turned negative, the last injection parameter set was adopted at the point at which the gradient produced a

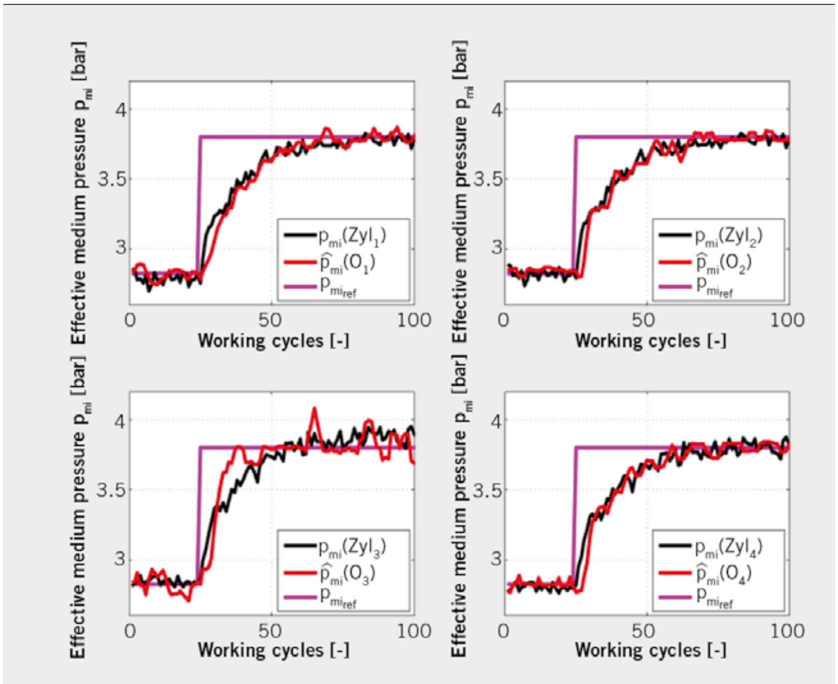


FIGURE 5 Step response of p_{mi} control to positive setpoint, plotted as a function of the working cycles (WC); the diagrams show the reference value, the measured and estimated p_{mi} value in relation to the individual cylinders and structure-borne noise sensors (© IMS)

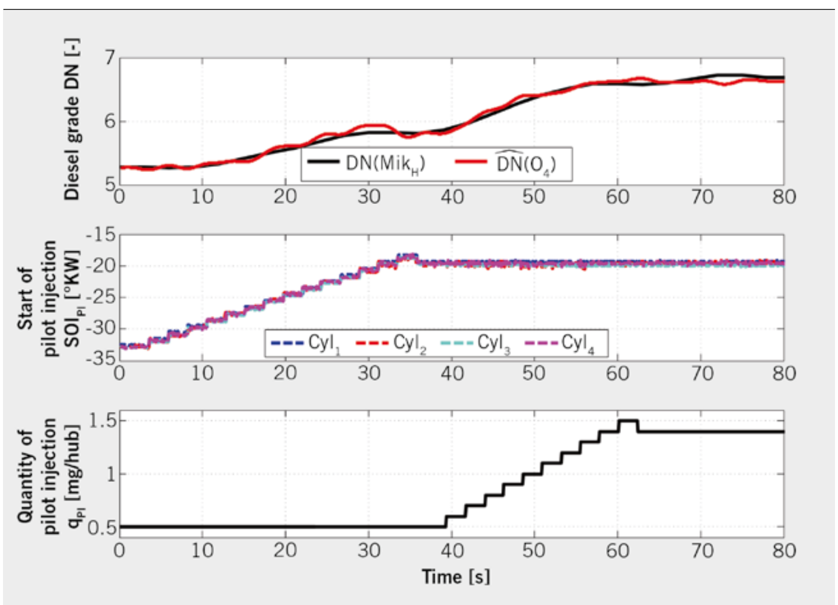


FIGURE 6 Development of the diesel noise rating (DN) and pilot injection parameter over time on running the optimisation algorithm (© IMS)

positive value. **FIGURE 6** shows the characteristic curve for iteratively optimising the diesel noise rating. After the initialisation the algorithm shifted the pilot injection angle from retarded to advanced. This increased the diesel noise rating from approximately 5.2 to 5.8. The diesel noise rating fell again from a pilot injection angle of -19 °CA. The pilot injection fuel quantity was then increased, resulting in a nearly proportionate rise in the diesel noise rating. From 1.5 mg/stroke, the diesel noise rating remained at approximately 6.9. Any maximisation of the diesel noise rating can no longer be identified by increasing the pilot injection, and the maximum permissible total injected fuel quantity was also reached. At this point the algorithm was stopped.

6 SUMMARY AND OUTLOOK

For cylinder-selective, noise-controlled engine management, a system has been developed to control indicated mean effective pressure as well as the centre of heat release. For this purpose, regression models were successfully used for estimating the controlled variables on the basis of structure-borne noise signals or their characteristics and control unit data. Step responses from the control loops verified that the models provide a level of sufficient quality to reflect the actual physical values, making them suitable for control purposes. This provided the basis for adapting combustion by varying the pilot injection parameters at predefined operating points. The regression models then were additionally used for computing the diesel noise rating from the structure-borne noise signals. The aim was to vary and, ultimately, optimise the diesel noise rating using the pilot injection parameters. By examining the underlying principles, it was established that particulary the pilot injection fuel quantity plays a sensitive part in affecting the diesel noise rating. Furthermore, the maximum diesel noise ratings fell within a relatively narrow pilot injection angle range that is governed by the engine's operating point. To reach the objective of optimising the diesel noise rating, a heuristic algorithm was used which is based on a gradient method. The nitrogen oxide and hydrocarbon emission levels and specific fuel consumption were also reduced at this optimised working point. The implemented control concepts showed a fundamental potential for reducing acoustic irritation from combustion noises.

Further studies will need to reveal whether the model quality of virtual cylinder pressure sensors can be optimised by integrating further measured variables, such as engine speed, which is also used in various research projects for directly estimating cylinder pressure. Engine speed signals could also be used for obtaining information on modulation of airborne noise and matching it directly to the specific cylinder. Also analysing the use of pilot injection parameterisation to minimise combustion noises provides very extensive research potential.

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THANKS

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