

CONTROLLING A DIESEL ENGINE WITH ENGINE MANAGEMENT BASED ON STRUCTURE-BORNE SOUND

M. Decker¹, K. Hintz², J. Nobis³ and C. Gühmann¹

¹TU-Berlin, FG Elektronische Mess- und Diagnosetechnik, 10587 Berlin, Deutschland, E-Mail: marco.decker@tu-berlin.de

²Otto-von-Guericke-Universität Magdeburg, Institut für Mobile Systeme (IMS), 39106 Magdeburg, Deutschland, E-Mail: karsten.hintz@ovgu.de

³IAV GmbH, Gifhorn, Entwicklungszentrum, 38518 Gifhorn, E-Mail: juergen.nobis@iav.de

Abstract: An engine management system based on cylinder pressure provides the means to optimize, control and monitor the release of heat in any individual cylinder. The aim here is to reduce the resultant emissions as well as their scatter band. The paper demonstrates the relationships between structure-borne sound signals and cylinder-pressure signals using Wigner-Ville transformation. Subsequent feature extraction provides the capability of extracting features of combustion and injection that can be used in engine management. This makes it possible to replace cost-intensive cylinder-pressure sensor systems with structure-borne sound sensors that cost less and are more robust. Discourse concludes by presenting the results of engine management based on structure-borne sound and provides an outlook of further work.

Keywords: Signal processing, structure-borne sound, diesel engine, engine management based on structure-borne sound.

1. INTRODUCTION

Future exhaust emission standards will demand measures targeted at reducing emissions. Wherever possible, any measure applied must avoid increasing consumption and noise emissions. Involving the Chair of Electronic Measurement and Diagnostic Technology, the “Noise-Controlled Diesel Engine” research project being conducted within the Forschungsvereinigung Verbrennungskraftmaschinen (Research Association for Combustion Engines – FVV) aims to meet this objective. The project sets out to examine how consumption, noise and emissions can be improved by integrating appropriate acoustic sensor signals into the diesel engine management system. Achieving these goals demands detailed signal analysis. Examination reveals which combustion, cylinder-pressure, injection and engine-noise information is contained in a structure-borne sound signal and how to extract it.

If significant features of combustion and noise emissions can be determined using structure-borne sound, an engine management system based on structure-borne sound can be produced that delivers benefits similar to those of cylinder-pressure-based management.

After describing the test set-up, section 3 illustrates how to compute significant features from structure-borne sound as the basis for determining combustion and injection parameters. In this context, it also describes the preliminary studies in the time and frequency range as well as subsequent extraction of combustion and injection features. The models used for estimating the controlled variables for the engine management system are then explained. Finally, the paper presents results of the control system implemented and provides an outlook of further work.

2. TEST-BENCH SET-UP

For the purpose of testing, a modern 4-cylinder production diesel engine with direct-injection common-rail system was set up on the acoustics test bench of the Institute for Mobile Systems at the University of Magdeburg and fitted with measuring equipment.

Proceeding from preliminary studies, 18 sites were determined for positioning structure-borne sound sensors at which good cylinder-pressure transmission behavior is given. These positions on the intake and exhaust side of the engine block as well as at the front end of the engine bearing and in the vicinity of the injection valves above the cylinder head were used for further investigations.

The engine was fitted with four cylinder-pressure sensors and an ammeter clamp at the injector of cylinder 1 for recording cylinder pressures and generating a reference signal for injection.

To obtain maximum flexibility in terms of controlling the diesel engine and to permit fast integration of new algorithms, IAV GmbH's MPEC[®] (Modular Prototyping Engine Controller) Rapid Prototyping System [14] programmed with MATLAB/Simulink[®] was then integrated

in the test-bench set-up for controlling the test engine. The cylinder-pressure-based combustion features or acoustic features are fed into the control loops of the diesel engine control system on a cycle-resolved basis.

The cylinder pressure curve is generally regarded as a central variable for describing processes taking place inside the engine. Engine management on the basis of cylinder pressure provides the capability of optimizing, controlling and monitoring heat release development for each individual cylinder. This has the purpose of further reducing the resultant emissions. Figure 1 shows a schematic diagram of the structure of the cylinder-pressure-based engine management system as implemented in the MPEC system (IAV-AC3 control system).

Controlling the center of heat release (α_{q50}) has the purpose of stabilizing heat release [12]. The start of injection valve actuation (MI_{SOI}) is timed for each individual cylinder on the basis of the main center computed and a given setpoint value. To compute the center of heat release development was initially determined according to Hohenberg [11]:

$$\Delta Q_H(\alpha) = \frac{1}{\kappa-1} (p(\alpha)\Delta V(\alpha) + V(\alpha)\Delta p(\alpha)) + p(\alpha)\Delta V(\alpha), \quad (1)$$

with: p -cylinder pressure, V -volume.

The isentropic exponent was kept constant during computation ($\kappa = 1.37$). The next step involves computing integral heat-release development by numerical integration:

$$Q_H(\alpha) = \sum_{\alpha=-80^{\circ}KW}^{\alpha=120^{\circ}KW} \Delta Q_H(\alpha). \quad (2)$$

Finally, the center of heat release is computed as follows:

$$\alpha_{q50} = \frac{\max(Q_H(\alpha)) - \min(Q_H(\alpha))}{2} + \min(Q_H(\alpha)). \quad (3)$$

Load control provides the means for reproducibly delivering requested torque which is made up of driver request, compensation for auxiliaries and various other limitations. Here, the control system adjusts the time for which injection is actuated (MI_t) for each individual cylinder based on the indicated mean effective pressure ($imep$). Indicated mean effective pressure is computed from cylinder pressure p and change in volume dV as well as displacement V_h :

$$imep = \frac{1}{V_h} \int p \cdot dV \quad (4)$$

On reaching a maximum cylinder pressure calibrated for the operating point, mechanical limitation continues to retard the setpoint for the center of heat release until pressure falls below the maximum permissible cylinder pressure (p_{max}) applicable to the operating point.

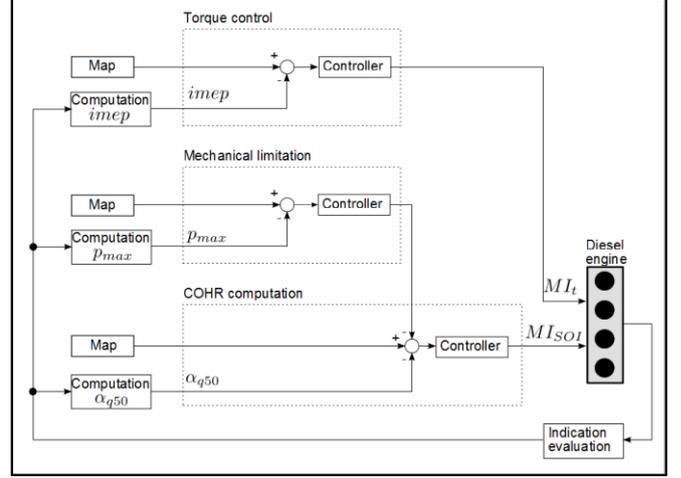


Figure 1: Schematic diagram of the AC3 control system in the cylinder-pressure-based engine management system

3. PRELIMINARY INVESTIGATIONS IN THE TIME AND FREQUENCY RANGE

In cylinder-pressure-based engine management, combustion is controlled on the basis of combustion features. Engine management systems controlled by cylinder pressure are not only being used in advance development and research but also in production vehicles. However, the high price and short life of the pressure sensors are significant impediments to using them at mass-production level. This is why the pressure sensors are to be replaced with acceleration sensors. Added to this is the possibility of modeling cylinder pressure from structure-borne sound signals.

Initial work on obtaining information on the low-frequency component of cylinder pressure by evaluating a structure-borne sound signal was published by Azzoni in 1997 [2]. For gasoline engines, Wagner [16] has presented a physically motivated approach to reconstructing the pressure signal independently of engine speed. Other approaches employ cepstral techniques [7], observer [3, 8] or neural networks [13] for reconstructing the cylinder pressure signal. The controlled variables from cylinder-pressure-based engine management must be available for configuring an engine management system based on structure-borne sound. The idea pursued in the project is not to model the entire cylinder pressure curve but to compute the necessary features directly. This objective was also pursued in [15, 1, 4]. It was possible to configure a bandpass filter for the acceleration signal and extract information about combustion from the filtered signal.

The features obtained from cylinder pressure ($\alpha_{q50}, imep, p_{max}$) are not reflected directly in the acceleration signal. Yet the structure-borne sound features contain information about the injection and the combustion process. Thus, using data-based models it is possible to estimate the controlled variables from the structure-borne sound features.

To achieve this objective, the acceleration signals must be examined in detail as the possibilities of analyzing

structure-borne sound in the engine management system essentially depend on the quality of the sensor signals. In an initial step, the measurement positions (sensor sites) were determined by way of experiments.

For this purpose, cylinder pressure and structure-borne sound were measured side by side on the engine test bench. In the second step, coherence analysis provided the basis for identifying suitable sensor positions delivering information on combustion [6].

Smoothed-Pseudo-Wigner-Ville distribution was used for selecting the frequency ranges (SPWV):

$$SPWV_{xx}(t, f) = \int_{-\infty}^{\infty} g(t - t') \int_{-\infty}^{\infty} h(\tau) z\left(t' + \frac{\tau}{2}\right) z^*\left(t' - \frac{\tau}{2}\right) e^{-j2\pi f\tau} d\tau dt' \quad (5)$$

The advantage over other time-frequency methods is high time-frequency resolution. This makes it possible to match up the points and frequency ranges from information present in the signal with a high degree of accuracy [9].

Figure 2 shows the evaluation of three measurements from the measurement series with strong combustion stimulation at an engine speed of $N = 1500$ rpm. The diagrams on the left show the evaluations for operating point $M = 54.4$ Nm, with operating point $M = 65.5$ Nm shown in the middle and operating point $M = 52.2$ Nm on the right. The time signals from acceleration sensor are presented in the diagrams at the top.

Smoothed-Pseudo-Wigner-Ville distribution is in each case shown in the middle for the range $f = 0 - 3$ kHz relevant to combustion. This is continued in the row below by the diagrams showing the time signals for cylinder pressure, cylinder-pressure gradients and injector current. The lower-most diagrams show the heating release curve and cumulative heat release curve.

Structure-borne sound is excited by direct and indirect combustion noise as well as mechanical noises. The cylinder-pressure gradient has a significant influence on the structure-borne sound signal as a result of the rapid rise in pressure $dp/d\alpha$ at the start of combustion. The SPWV analyses of the structure-borne sound signal clearly show the signal energy between $f = 0.5 - 2$ kHz and its direct correlation with the cylinder-pressure gradient.

At the operating points investigated ignition delay is varied by adjusting injection. This variation influences signal input for the rise in pressure in the structure-borne sound signal. Here, the correlations can be seen between the position of the maximum cylinder-pressure gradient as well as the position of the maximum heat release curve value. These correlate with the maximums in the lower frequency range of the acceleration pick-up. Noise also increases as the cylinder-pressure gradient rises.

The following investigations demonstrate the correlations between injection and structure-borne sound signal. Smoothed-Pseudo-Wigner-Ville distribution is used for examining the injection features in the time and frequency range. Figure 3 shows the time and frequency reading from the acceleration sensor at operating point

$N = 1000$ rpm with main injection actuated for $MI_t = 649$ μ s and a rail pressure of $p_r = 300$ bar. Wigner-Ville distribution shows the frequency range $f = 4 - 20$ kHz relevant to injection. In the frequency range $f = 4 - 15$ kHz signal inputs must be recorded directly after pilot and main injection are electronically actuated. The piezo injectors are lifted indirectly by a control valve. Here, excitation of the piezo crystal opens a control valve that closes a bypass, causing the needle to lift. One reason for the signal components observed could stem from the control valve opening. The needle also opens immediately after the start of actuation, resulting in the injection of fuel which induces injector excitation. The control valve opens completely at each operating point which means that it works almost digitally. As a result of the nozzle's ballistic configuration, the needle only goes to the lift stop in response to very long actuation times.

The needle is not to be expected to reach the lift stop during pilot injection. Although main injection is actuated for a long time, actuation time is not sufficient for the needle to reach the lift stop. Without relevant investigations on an injector test bench, however, it is not easy to reach any conclusions on needle lift and rate of injection – nor was any conclusions reached. The end of injection actuation also produces components in the structure-borne sound signal that could be caused by the control valve closing.

Although signal components also occur in the frequency range $f = 15 - 20$ kHz they come after the point at which injection actuation has stopped. Once the control valve closes, the valve chamber is filled through the bypass until such time as the needle meets the nozzle. Given the time lag from the end of actuation, the signal components in the acceleration signal must be ascribed to the needle meeting the nozzle or to it bouncing [5].

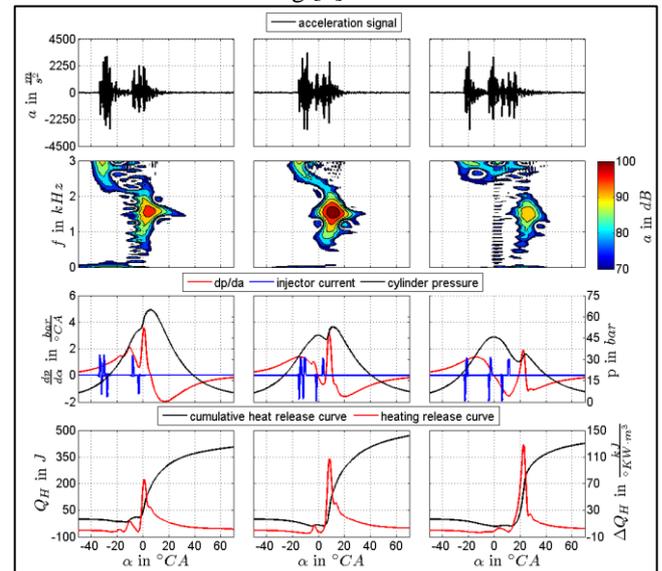


Figure 2: Time-frequency analyses using Smoothed-Pseudo-Wigner-Ville distribution; top: time signal from acceleration signal, middle: SPWV from acceleration signal; bottom: time signals for cylinder pressure, cylinder pressure gradients and injector current; lower-most diagrams: heating release curve and cumulative heat release curve; operating point $N = 1500$ rpm left: $M = 54.4$ Nm; middle: $M = 65.5$ Nm; right: $M = 52.2$ Nm

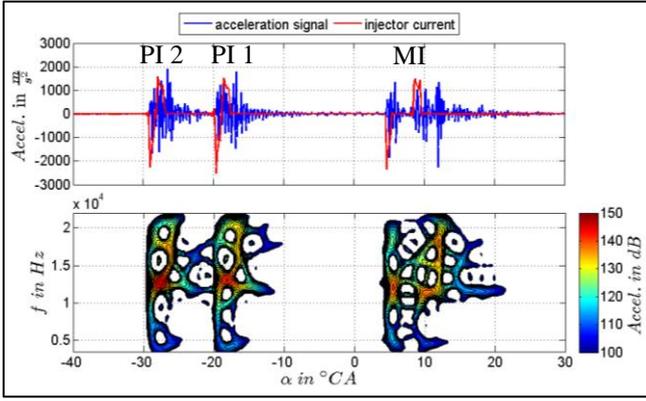


Figure 3: Time / frequency curve showing injection at $N = 1000$ rpm, $p_r = 300$ bar, $MI_t = 649 \mu s$ (below); acceleration signal and injector current (top)

4. FEATURE EXTRACTION AND MODELING

After identifying the sensor position and frequency range that reveal significant combustion and injection features, a real-time algorithm must now be implemented to extract these features (α_{SBS_max}, MI_t) for estimating the controlled variables. Recorded in synchrony with crank angle, the time signal from the acceleration sensors on top of the cylinder provides the basis of the algorithm for determining the combustion features. The range of the time signal (relevant to computation) in relation to position in a combustion cycle is cut out by means of a window. Windowing takes place after the main injection event and shifts in relation to the start of injection. The maximum acceleration amplitude and associated crank angle α_{SBS_max} are determined within this window (Figure 4). Filtered with a band pass, the structure-borne signal is used for detecting the start of injection in the main injection event. On the basis of the signal's envelopes, it is possible to determine the start/end of injection in the main injection event MI_{SOI}/MI_{EOI} . The duration of main injection MI_t can be ascertained from the start and end of injection [10].

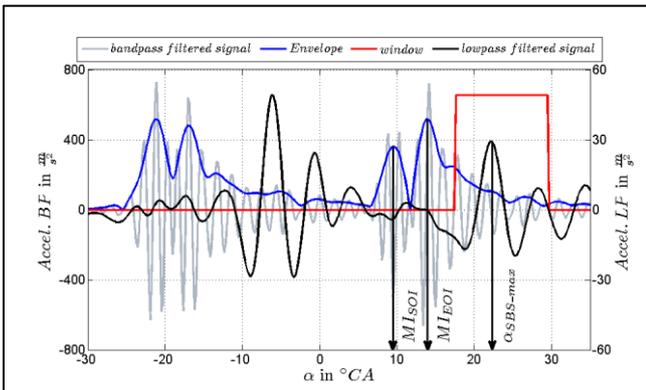


Figure 4: Time signals from the acceleration signal for determining combustion and injection features

The controlled variables ($\alpha_{q50}, imep, p_{max}$) obtained from cylinder pressure are not reflected directly in the acceleration signal. For this reason, polynomial models,

which use structure-borne sound signals (α_{SBS_max}, MI_t) and control unit variables ($N - rpm, rail\ pressure - p_r$) as input signals, were able to provide the means for estimating the controlled variables. The model approach for the center of heat release reads:

$$\widehat{\alpha}_{q50} = f(\alpha_{SBS_max}, MI_t, N, p_r). \quad (6)$$

The same model approach was used for indicated mean effective pressure:

$$\widehat{imep} = f(\alpha_{SBS_max}, MI_t, rpm, p_r). \quad (7)$$

In modeling maximum cylinder pressure, a better model quality was obtained by adding the start of main injection:

$$\widehat{p}_{max} = f(\alpha_{SBS_max}, MI_{SOI}, MI_t, rpm, p_r). \quad (8)$$

The Design of Experiments (DoE) method was used for generating a measurement series to train the model. Proceeding from application status ($\Delta MI_{SOI} = +6 \dots -8 \text{ } ^\circ CA$) engine speed ($N = 1000 \dots 1500 \text{ rpm}$), load ($M = 50 \dots 230 \text{ Nm}$) and start of main injection were varied in 48 measurements in the experiment.

5. CONTROL SYSTEM

The control system with engine management based on structure-borne sound could be put into operation after modeling the controlled variables for cylinder-pressure-based engine control from structure-borne sound signals and control unit variables. Steady-state operating points were measured for ascertaining the setpoint values. The associated control unit variables were taken from the calibration control unit. Using the example of a steady-state operating point, the mode of procedure is described below for controlling the center of heat release. Although $imep$ and p_{max} control were not activated, these model outputs were recorded in the measurement log.

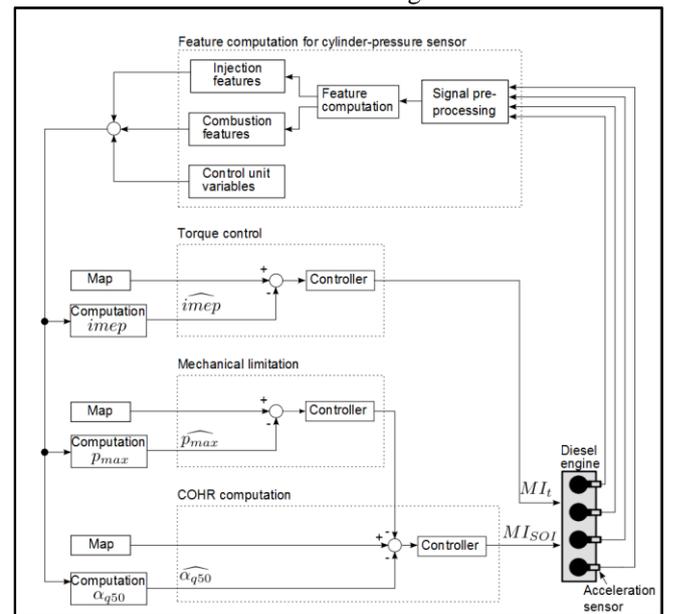


Figure 5: Schematic diagram of engine management based on structure-borne sound

As part of the investigations, a setpoint step change $\alpha_{q50} = +2^\circ\text{CA}$ was applied at operating point $N = 1500\text{ rpm}$, $M = 50\text{ Nm}$, for each individual cylinder. The control system delays the start of main injection (controlled variable). The top of Figure 7 compares the centers of heat release between measurements from cylinder-pressure signals and structure-borne model as well as the given setpoint. The controlled centers of heat release reach the setpoint for all four cylinders, demonstrating that the heat-release center can be controlled and corrected by the start of main injection. Table 1 summarizes the RMS errors (e_{rms}) for the combustion models. The slightly higher errors for cylinder 1 and cylinder 3 result in main injection being retarded. Investigation also produced a good estimate of indicated mean effective pressure and maximum cylinder pressure. It was also possible at steady-state operating points to model good results for combustion variables from structure-borne variables and control-unit variables.

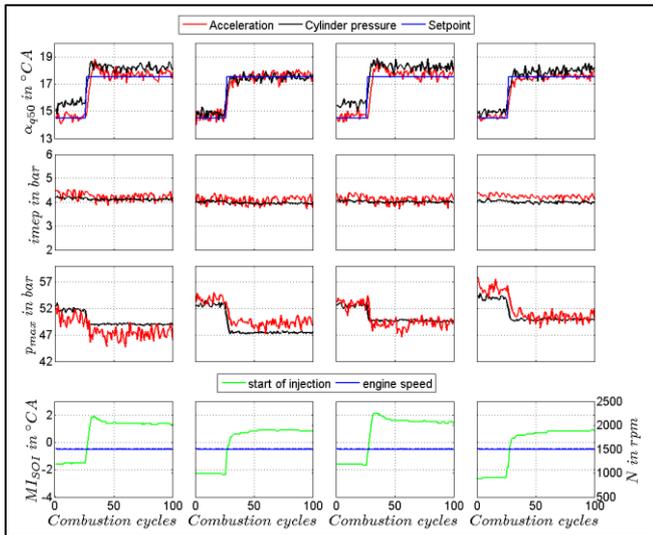


Figure 6: Setpoint step change in center of heat release and control on the basis of structure-borne sound signals for cylinders 1 (left) – 4 (right) at operating point $N = 1500\text{ rpm}$, $M = 50\text{ Nm}$

Table 1: RMS error between structure-bore sound and cylinder-pressure-based combustion management at a steady-state operating point

	e_{rms_Zyl1}	e_{rms_Zyl2}	e_{rms_Zyl3}	e_{rms_Zyl4}
α_{q50}	0.79°CA	0.45°CA	0.8°CA	0.47°CA
$imep$	0.19 bar	0.16 bar	0.16 bar	0.18 bar
p_{max}	2.34 bar	2.43 bar	1.21 bar	1.03 bar

The next step demonstrates the model quality during steady-state operation. For this purpose, load was increased from $M = 50$ to 175 Nm at an engine speed of $N = 1500\text{ rpm}$ (Figure 7). The combustion management RMS error is presented in Table 2. As load builds up, indicated mean

effective pressure runs from $imep \approx 4.3 \dots 12\text{ bar}$. In contrast to the steady-state operating point, the errors for maximum cylinder pressure show higher values. Altogether, it was also possible to demonstrate for transient operation that the models are capable of estimating the combustion variables with good results.

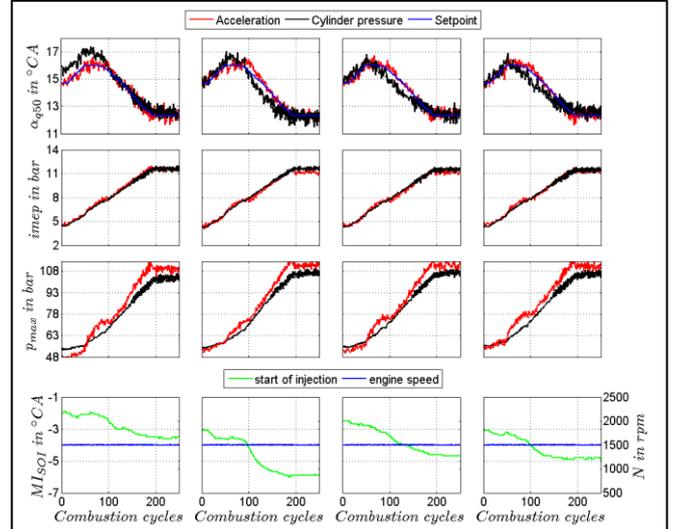


Figure 7: Increasing load from $M = 50$ to 175 Nm while controlling center of heat release on the basis of structure-borne sound signal for cylinder 1 (left) – 4 (right) at operating point $N = 1500\text{ rpm}$

Table 2: RMS errors between controlling combustion on the basis of structure-borne sound and cylinder pressure while increasing load

	e_{rms_Zyl1}	e_{rms_Zyl2}	e_{rms_Zyl3}	e_{rms_Zyl4}
α_{q50}	0.67°CA	0.51°CA	0.48°CA	0.47°CA
$imep$	0.27 bar	0.25 bar	0.25 bar	0.27 bar
p_{max}	6.27 bar	5.05 bar	5.23 bar	5.98 bar

5. SUMMARY AND OUTLOOK

This paper presents an engine management system based on structure-borne sound. It begins showing the Smoothed-Pseudo-Wigner-Ville distribution between cylinder-pressure features and structure-borne signals in the time and frequency range. It was also possible to detect injection features in the time and frequency range. It then goes on to describe the feature system for determining combustion and injection parameters in real time. After extracting combustion and injection features models were generated that are capable of providing a good estimate of combustion variables for managing the engine. Finally, the combustion management system was put into operation. Comparing structure-borne and cylinder-pressure-based control of the

center of heat release shows no significant differences for the operating points selected.

Further-reaching investigations, possibly in the running vehicle, must be carried out to show whether the algorithms developed can be applied to other diesel engines.

It would also be beneficial to extend the algorithms in order to extract injection and combustion information with just one acceleration pick-up.

Also conceivable are further investigations on compensating for aging effects with an engine management system based on structure-borne sound.

6. REFERENCES

- [1] ARNONE, L. ; MANELLI, S. ; CHIATTI, G. ; CHIAVOLA, O.: In-Cylinder Pressure Analysis through Accelerometer Signal Processing for Diesel Engine Combustion Optimization. In: *SAE 2009 Noise and Vibration Conference and Exhibition*. St. Charles, Illinois, United States, 2009
- [2] AZZONI, P.: Reconstruction of Indicated Pressure Waveform in a Spark-Ignition Engine from Block Vibration Measurements. In: *Journal of Dynamic System, Measurement and Control* 119 (1997), S. 614–619
- [3] CHAUVIN, J. ; GRONDIN, O. ; NGUYEN, E. ; GUILLEMIN, F.: Real-Time Combustion Parameters Estimation for HCCI-Diesel Engine Based on Knock Sensor Measurement. In: CHUNG, Myung (Hrsg.): *Proceedings of the 17th IFAC World Congress*, 2008, S. 8501–8507
- [4] CHIAVOLA, O. ; CHIATTI, G. ; ARNONE, L. ; MANELLI, S.: Combustion Characterization in Diesel Engine via Block Vibration Analysis. In: *SAE 2009 Noise and Vibration Conference and Exhibition*. St. Charles, Illinois, United States, 2010
- [5] CHRIST, Konrad: *Kalibrierung von Magnet-Injektoren für Benzin-Direkteinspritzsysteme mittels Körperschall*. Karlsruhe : KIT Scientific Publishing, 2011
- [6] DECKER, M. ; HINTZ, K. ; GÜHMANN, C.: Untersuchung von Körperschallsignalen im Zeit-Frequenzbereich für ein körperschallbasiertes Motormanagement. In: PUENTE, Fernando (Hrsg.) ; BEYERER, Jürgen (Hrsg.): *XXV. Messtechnisches Symposium des Arbeitskreises der Hochschullehrer für Messtechnik e.V. (AHMT)*. Aachen : Shaker Verlag, 2011
- [7] EL-GHAMRY, M. ; STEEL, J.A. ; REUBEN, R.L. ; FOG, T.L.: Indirect measurement of cylinder pressure from diesel engines using acoustic emission. In: *Mechanical Systems and Signal Processing* 19 (2005), Nr. 4, S. 751 – 765
- [8] GRONDIN, O. ; CHAUVIN, J. ; GUILLEMIN, F. ; NGUYEN, E. ; CORDE, G.: Combustion parameters estimation and control using vibration signal : Application to the Diesel HCCI engine. (2008), Dezember, S. 5621–5627
- [9] GÜHMANN, C. ; LACHMANN, S. ; RÖPKE, K. ; TAHL, S. ; LINDEMANN, M. ; JOERRES, M.: Messtechnische Untersuchung von Störgeräuschen in Klopfregelsystemen. In: *MTZ - Motortechnische Zeitschrift* 2006-1 (2006), S. 40–47
- [10] HINTZ, K. ; DECKER, M. ; NOBIS, J. ; TSCHÖKE, H.: Körperschallbasiertes Motormanagement unter Berücksichtigung von Verbrauch, Geräusch- und Abgasemission. In: *Motor- und Aggregate-Akustik III*, 2011. – ISBN 978–3–8169–3071–6, S. 228–239
- [11] HOHENBERG, G: Der Verbrennungsablauf - ein Weg zur Beurteilung des motorischen Prozesses. In: *4. Wiener Motorensymposium* (1982)
- [12] REMPEL, A. ; STÖLTING, E. ; PREDELLI, O. ; GRATZKE, R.: Flexible Motorprozessregelung für neue Brennverfahren. In: *at - Automatisierungstechnik* 57:1 (2009), S. 14–22
- [13] ROGER, J.: Cylinder pressure reconstruction based on complex radial basis function networks from vibration and speed signals. In: *Mechanical Systems and Signal Processing* 20 (2006), Nr. 8, S. 1923 – 1940
- [14] STÖLTING, E. ; SEEBODE, J. ; GRATZKE, R. ; BEHNK, K.: Emissionsgeführtes Motormanagement für Nutzfahrzeuganwendungen. In: *MTZ - Motortechnische Zeitschrift* 12 (2008)
- [15] TAGLIALATELA, F. ; CESARIO, N. ; PORTO, M. ; MEROLA, S. S. ; SEMENTA, P. ; VAGLIECO, B. M.: Use of Accelerometers for Spark Advance Control of SI Engines. In: *SAE International Journal of Engines* 2 (2009), Nr. 1, S. 971 –981
- [16] WAGNER, M.: *Rekonstruktion von Zylinderinnendruckverläufen aus Körperschallsignalen für Ottomotoren*. Shaker Verlag, 2004