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Real-Time Combustion Parameters Estimation for HCCI-Diesel Engine Based on Knock Sensor Measurement

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Abstract: Future internal combustion engine technologies require an accurate combustion monitoring and control. This can be performed through high frequency recordings of cylinder pressure. However, this solution is limited by the sensor cost and reliability. Another method consist in reconstructing combustion related variables from indirect measurements. In this paper, we propose a combustion indicator estimation method from the vibration trace of the engine block recorded with a standard knock sensor. The relevance of such a method is demonstrated through experimental results on an HCCI engine application.

Keywords: Diesel engine, knock sensor, combustion analysis, cylinder pressure, combustion diagnosis and control.

1. INTRODUCTION

Increasing legal requirements in engines regarding exhaust gas emissions, fuel economy, on-board diagnosis, together with a steady demand on performance, pushes the industry towards innovative solutions with reduced time-to-market. In addition with the introduction of new combustion concepts such as HCCI (Homogeneous Charge Compression Ignition) or CAI (Controlled Auto Ignition), the engine combustion, control, and diagnosis are becoming increasingly complex.

In order to perform closed loop combustion control, information about the combustion process can be investigated with in-cylinder pressure transducer. The cylinder pressure is a relevant feedback variable and internal combustion engine management systems relying on cylinder pressure signal became of a particular interest (see Leonhardt et al. [1999] for example). The combustion parameter for closed loop control are computed from the heat release analysis (Krieger and Borman [1966], Gatowski et al. [1984]). This solution has been investigated in many papers but is still not cost effective and commercial car implementations are thus limited. Other techniques relying on indirect measurement such as knock sensors, accelerometers, engine speed, torque sensor or ionization current measurements are possible to estimate combustion indicator for engine control.

In this paper, we focus on how to extract some information on combustion using knock sensors. The use of knock sensors is motivated by the cost and the number of sensor used to characterize the combustion in each cylinder (for example two sensors may be used for a 4 cylinder engine). The aim is to extract parameters which can be linked to the combustion phasing and to the combustion energy. These parameters will allow us to control the combustion thanks to the injection phasing, the mass of fuel injected and the EGR (Exhaust Gas Recirculation).

The accelerometer has multiple applications for IC engine. The first application was the detection of knock and the evaluation of its energy for SI engine, (see Boubal and Oksman [1998], Cerda et al. [2002], Zhekova and Guillemain [2004], ?]). Other studies focused on the reconstruction of the cylinder pressure signal. The signal processing tools used for that purpose were : deconvolution methods in Wagner et al. [1999], spectrum analysis in Gao and Randall [1999], cyclostationarity properties in Antoni et al. [2002] and methods using neural network models in Johnsson [2006]. Other studies tried to identify the different source signatures on vibration signal, see El Badaoui et al. [2005]. However, all of these methods cannot be implemented in real time and thus closed loop combustion control cannot be performed. Our aim is to estimate combustion indicators cylinder to cylinder on a cycle to cycle basis. For that purpose, on-line algorithms are required. Jargenstedt [2000] uses the analytic signal (Hilbert transform) to extract an envelope of the combustion. This method needs an accurate band pass filtering to extract the combustion signature and is very sensitive to contributions from other sources (due to low signal to noise ratio). The time frequency can be implemented by a recursive algorithm with the sliding discrete Fourier transform Ker et al. [2007]. It needs to choose an accurate time window length and the frequency band to look at. This frequency band may be too large and let the contribution of non combustion sources pollute the signal. This frequency band depends on the time window length. It is possible to model combustion from the vibration signal with an autoregressive moving average filter (ARMA filter). Souder et al. [2004] uses ARMA filter to estimate the start of combustion. However, the proposed model

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does not take low load operating points into account and has just been tested on single cylinder in steady state condition.

The paper is organized as follows : In Section 2 we detail the knock signal specifics and the difficulties to extract parameters related to the combustion phenomena. The proposed real time algorithm based on the Fourier periodic observer and the combustion indicator extraction technique are presented in Sections 3 and 4. In order to illustrate the relevance of our method, we compare the reconstructed combustion parameters with those computed from the reference cylinder pressure signal. Section 5 proposes an example of application based on HCCI engine. Conclusions are drawn in Section 6.

2. ACCELEROMETER SIGNAL

The engine block vibration is due to several sources such as valve openings and closings, piston slaps, combustion process and additive noise. Transient waves generated by these sources overlap each other and the issue is to isolate the contribution of the combustion phenomena. The comparison with the pressure sensor is performed through recordings with the combustion sensing platform presented in Grondin et al. [2007]. Examples of acquired pressure and knock sensor frames for a 4 cylinder Diesel engine are represented in Figure 1. In that case, the pilot injection and the combustion effects on the engine block vibration can be observed from the knock sensor recording. In order to help this identification, pressure traces from in-cylinder pressure sensors and vibration signals are jointly analyzed by time-frequency analysis. Different time-frequency representations may be used allowing good resolution for off-line diagnosis. Classical examples are Wigner-Ville or Choi-Williams Flandrin [1993]. Here we apply the Wigner-Ville distribution, defined, for a signal x, as:

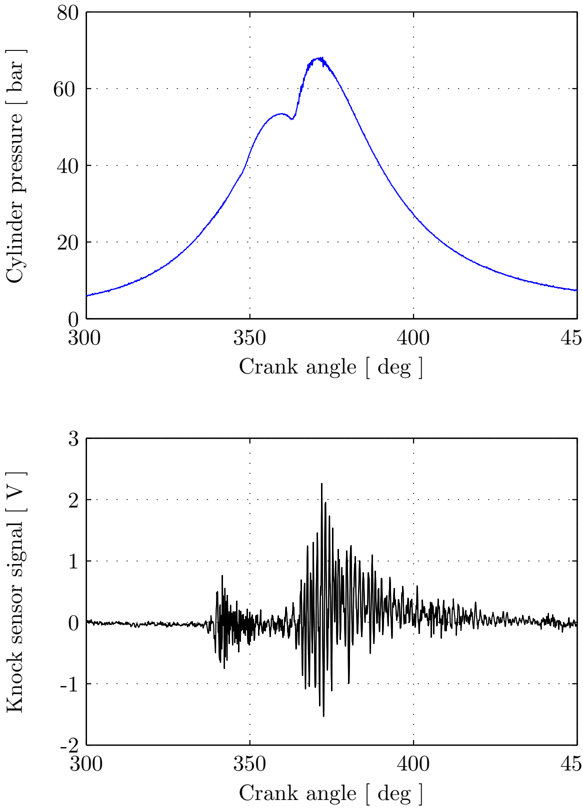

Figure 1. *Experimental results. Cylinder pressure (top) and knock sensor acquisition (bottom) at 1500 rpm, 7 bar of IMEP. The angular resolution is 0.1 crank angle degree.*

$$\mathrm{WV}_x(t,\nu) = \int x(t+\tau/2)x^*(t-\tau/2)e^{-j2\pi\nu\tau}d\tau.$$

Examples of time-frequency maps on the same operating point are represented in Figure 2. This time-frequency analysis has been performed in a test recorded on a 4 cylinder engine at 1500 rpm, 3 bar of IMEP in HCCI mode, with a single injection. One can observe in the first angular-frequency representation (due to the crank angle based x-axis) that the pressure gradient signal exhibits three different components within a crank angle window where the combustion process occurs. Each component is related to the auto ignition and appears few crank angle degrees before the TDC. The low frequency component has the higher amplitude and is related to the rapid increase of the cylinder pressure after the auto ignition. The two others are characterized by narrower frequency content (respectively at 7 kHz and 11 kHz). These components correspond to resonances due to the excitation of the cylinder cavity. A careful study of the angular-frequency map of the vibration signal demonstrates the relevance of the low frequency band width of the knock signal. This method allows to identify each component of the knock signal. However, these components show some differences due to the propagation path (convolution by the transfer function of engine structure). The two resonances are amplified in comparison to the low frequency component which is strongly distorted (only the very low frequency content less than 2 kHz is preserved). An angular shift between both representations is introduced by the offset of the knock sensor. At last, a component located near to 20 CAD and at 3 kHz is related to a mechanical source and must be removed.

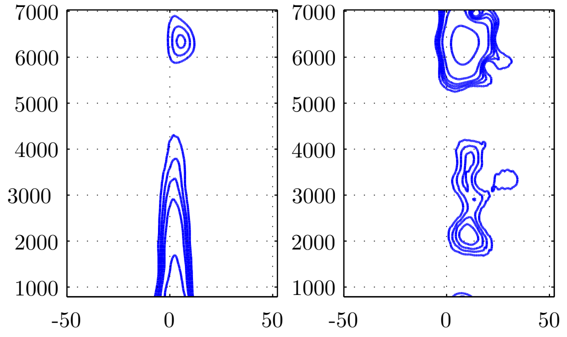

Figure 2. *Time-frequency (in Hz) analysis of pressure and knock signals : (Left) Wigner-Ville spectrum on pressure gradient, (Right) Wigner-Ville spectrum on knock signal. X and y axis units are crank angle degree and frequency respectively. The* 0 *represents the TDC.*

The frequency band and the angle window where it is possible to extract the combustion signature from the knock signal depends on two parameters :

(1) The amplitude of the combustion source. The pressure gradient must be high enough to be detected among the other sources (see Figure 2).
(2) The transfer function of the engine block. We observe that the pressure gradient energy is located under 2kHz. The engine block act as a high pass filter with a cut frequency around 2kHz for a 4 cylinder (see ?]). Thus, the combustion related component on the knock signal is located at higher frequency.

The combination of these two parameters determines the operating region of the engine where the combustion can be extracted. With the timing of the combustion (modulo a propagation delay) which can be determined with the pressure gradient, we deduce that the energy of the combustion is prevailing in the frequency band $1500-3000$ Hz. A time-frequency study of the impact of injection noise shows that the injection energy is prevailing in the frequency band $3000-4500$ Hz. These results are the same than in Leclère et al. [2005] where the injection noise due to the common rail injection system is studied. Our objective is to estimate the parameters of combustion extracted from the bandpass of interest. In the next section, we present the Fourier periodic observer which will give us the combustion energy according to the crank angle.

3. VIBRATION SOURCE OBSERVER DESIGN

On a fixed operating point, the accelerometer signal is periodic with respect to the angular domain. Moreover, this signal is directly linked to the combustion. Indeed, it is a filtered version of the combustion vibration. The filtering is due to the propagation of the signal in the mechanical structure. The signal we are interested in is this "source" signal. To estimate this signal, we consider that the mechanical structure is a finite dimensional linear filter where the input is the vibration we want to estimate, and the output is the accelerometer measurement.

Consider the linear system driven by an unknown periodic input signal $w(t)$

$$\begin{cases} \dot{x} = Ax + A_0 w(t) \\ y = Cx \end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state and A, A_0, C are matrices in $\mathcal{M}_{n,n}(\mathbb{R})$, $\mathcal{M}_{n,1}(\mathbb{R})$ and $\mathcal{M}_{1,n}(\mathbb{R})$ respectively. The goal of our study is the estimation of the T_0-periodic continuous input signal $w(t) \in \mathbb{R}$, with $1 = dim(w) = dim(y) \leq n = dim(x)$, through its Fourier decomposition over the h harmonics

$$w(t) \triangleq \sum_{k\in\mathcal{I}_h} c_k e^{\imath k\omega_0 t} \quad \omega_0 \triangleq \frac{2\pi}{T_0}$$

where $\mathcal{I}_h = \{-h, \ldots, h\}$ is the set of h modes. We assume that the following hypothesis holds

Hypothesis 1. (Injectivity of A_0 and $C^\dagger$). $\mathrm{Ker}(A_0) = \{0\}$ and $\mathrm{Ker}(C^\dagger) = \{0\}$.

We note † the Hermitian transpose that reduces to standard transpose for matrices with real entries.

Hypothesis 2. (Observability). The only solution $t \mapsto (x(t), c_k(t))$ of

$$\begin{cases} \dot{x} &= Ax + A_0(\sum_{k\in\mathcal{I}_h} c_k e^{\imath k\omega_0 t}) \\ \dot{c}_k &= 0, \quad \forall k \in \mathcal{I}_h^+ \end{cases} \tag{2}$$

for which the output $y(t) = Cx(t)$ is identically zero on $[0, T_0]$, is the zero solution.

3.1 Reference model

The reference system writes

$$\begin{cases} \dot{x} &= Ax + A_0(\sum_{k\in\mathcal{I}_h} c_k e^{\imath k\omega_0 t}) \\ \dot{c}_k &= 0, \quad \forall k \in \mathcal{I}_h, k \geq 0 \\ y &= Cx \end{cases} \tag{3}$$

Generically we denote by $\mathcal{F}_l(x)$ the l^{th} coefficient of the Fourier decomposition of a periodic signal $x(t)$, i.e. $\mathcal{F}_l(x) = \frac{1}{T_0}\int_0^{T_0} x(s)e^{-\imath l\omega_0 s}ds$. When x is real, the complex-conjugate of $\mathcal{F}_l(x)$ satisfies $\mathcal{F}_l(x)^\dagger = \mathcal{F}_{-l}(x)$. his explains the fact that we consider only $k \in \mathcal{I}_h$ positive: $c_k \in \mathbb{C}$ when $k > 0$ and $c_k \in \mathbb{R}$ when $k = 0$.

3.2 Observer structure

Corresponding to state-space model (3), we define a time-varying Luenberger type observer

$$\begin{cases} \dot{\hat{x}} &= A\hat{x} + A_0(\sum_{k\in\mathcal{I}_h} \hat{c}_k e^{\imath k\omega_0 t}) - L(C\hat{x} - y) \\ \dot{\hat{c}}_k &= -e^{-\imath k\omega_0 t} L_k(C\hat{x} - y), \quad \forall k \in \mathcal{I}_h, k \geq 0 \end{cases} \tag{4}$$

L and $\{L_k\}_{k\in\mathcal{I}_h}$ are defined later through the convergence analysis. The error-state is $\tilde{x} = x - \hat{x}$ and $\tilde{c}_k = c_k - \hat{c}_k$, and the error dynamics is

$$\begin{cases} \dot{\tilde{x}} &= (A - LC)\tilde{x} + A_0(\sum_{k\in\mathcal{I}_h} \tilde{c}_k e^{\imath k\omega_0 t}) \\ \dot{\tilde{c}}_k &= -e^{-\imath k\omega_0 t} L_k C\tilde{x}, \quad \forall k \in \mathcal{I}_h, k \geq 0 \end{cases} \tag{5}$$

3.3 Observer definition

L is chosen such that $A - LC$ is asymptotically stable. Assuming that for all $k \in \mathcal{I}_h$,

$$P_k \triangleq C(\imath k\omega_0 - P)^{-1}A_0$$

is full rank, we choose the gains $L_k(t)$, $\beta \neq 0$ and

$$L_k(t) \triangleq -\epsilon\beta^2((\imath k\omega_0 - (A - LC)))^{-1}A_0)^\dagger C^\dagger \tag{6}$$

For $\epsilon > 0$ and small enough, convergence is proved Chauvin et al. [2007].

Thus, we have a real time estimation of the source signal and its Fourier decomposition. Based on this information, in the next section, we estimate combustion parameters.

4. FROM INSTANTANEOUS ENERGY TO COMBUSTION PARAMETER

The observer leads to an estimation of some of the frequencies of the vibrating source. In this section, we propose a method to use these estimations to characterize the combustion in each cylinder. For that purpose, we estimate in real time a set of Parameters of Combustion (PoC) from the instantaneous energy of the estimated source vibration. We note the energy :

$$E(\alpha) \triangleq \sum_{k\in\mathcal{I}_h} \|\hat{c}\|_k^2$$

where $\hat{c}_k$ are the Fourier coefficients corresponding to the harmonics on the Fourier decomposition. Only the harmonics included in the bandwidth of interest are kept. The energy signal computed from the knock signal has a physical meaning, it corresponds to the instantaneous energy of the combustion. This parameter will increase with respect to the energy released during the combustion transferred to the knock sensor through the engine block.

In this section we define the combustion indicators or estimated combustion parameters. The goal is to define a set of parameters from the harmonic signal returned by the periodic observer which can be used as closed loop variables for combustion control. These parameters must be correlated with the combustion parameters computed from the cylinder pressure signal. The main issue regarding the energy signal processing is to avoid false detection due to small fluctuation before and after the main peak.

In order to obtain robust indicators, the computation of the PoC is not performed on the raw energy signal. Here, we use a fitting method in order to smooth the harmonic energy returned by the periodic observer. We choose a Gaussian function, f, that represents the shape of the most relevant part of the signal.

$$f(\theta) = a_1 \exp\left(-\frac{(\theta - a_2)^2}{a_3^2}\right) \qquad (7)$$

The parameters, a_i, are identified online by using nonlinear recursive fitting method. The initial parameters for learning are updated for each engine cycle and chosen to be in the angular range where the combustion may occur. This is usually set a couple of degrees after the start of injection taking into account the auto-ignition delay and the propagation time of the shock wave. However, the initial values of these parameters do not need to be accurate since the fitting method is robust enough.

The PoC are defined according to the following definitions :

- The Start of Combustion (SoC) is related to the crank angle at witch the auto-ignition occurs. The estimated start of combustion SoC is defined as :
$$SoC = a_2 - a_3$$
- The Middle of Combustion (MoC) is related with the maximum of the reaction in the cylinder. It corresponds to the angular where the instantaneous energy is maximum. The estimated occurrence of the middle of combustion is defined as the center of the gaussian function :
$$MoC = a_2$$
- The Energy of Combustion (EoC), which is related to the total energy released by the source. The energy released by the combustion phenomena is :
$$EoC = a_1 a_3$$

The parameters of combustion are computed following these steps :

(1) Band-pass pre-filtering between 1500 Hz and 3000 Hz.

(2) Computation of the instantaneous energy with the periodic observer.

(3) Gaussian fitting of the instantaneous energy.

(4) Determination of the parameters of combustion.

Figure 3 describes this methodology on a steady state operating point for one engine cycle and one cylinder. Here, the Gaussian fitting allows to keep only the relevant part of the energy signal and avoid any false detection due to the small fluctuation before and after the main peak of energy du to cool flame or engine block resonances.

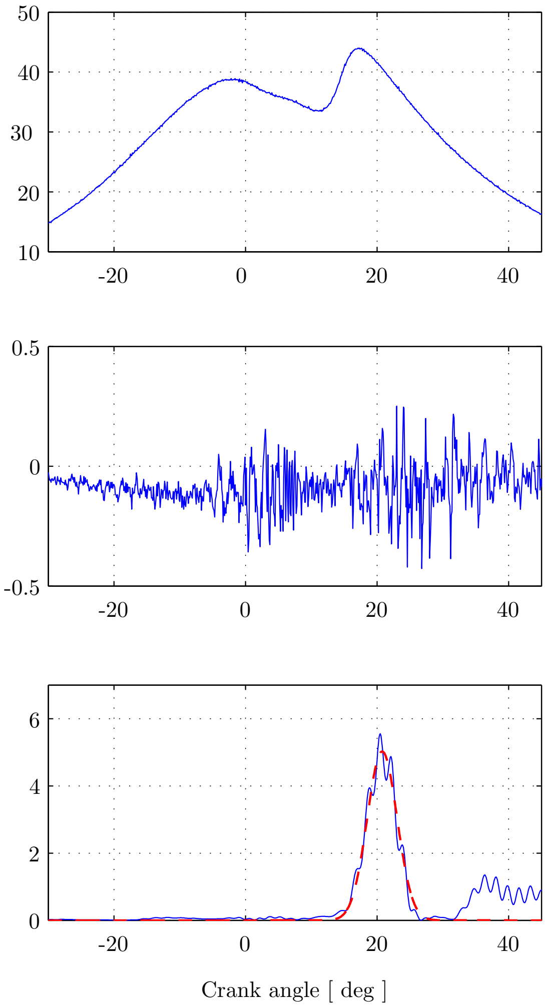

Figure 3. *Application of the observer on accelerometer data. Cylinder pressure (top), knock signal (middle), estimated knock energy (bottom solid line) and gaussian fit (bottom dashed line). The engine speed is 1000 rpm, the IMEP is 6 bar and the the mean AVL noise is 86 dB.*

5. EXPERIMENTAL RESULTS

The experimental setup is a four cylinders light-duty direct injection Diesel engine working in both conventional combustion mode and HCCI mode. This engine operates in HCCI mode until 7 bar of IMEP and in Diesel mode for higher load. The engine is equipped with high pressure injection system, variable geometry turbocharger (VGT), exhaust gas recirculation (EGR) vane and intake throttle. The full path engine control is developed at IFP. Airpath control are not presented here, more details are given in Chauvin et al. [2006a,b]. The engine is connected to a brake and is fitted with pressure and temperature sensors for intake and exhaust plenums. In-cylinder pressure are recorded using an AVL piezoelectric sensor mounted on the glow plug location. The charge yielded by the piezoelectric sensor is converted into a proportional voltage signal by the charge amplifier. Vibration signals are measured by industrial knock sensors which have same frequency response as instrumentation piezoelectric accelerometers in [0-6] kHz bandwidth . Their positioning has been chosen taking into account engine geometry and propagation ways.

A specific acquisition platform has been developed at IFP in order to acquire properly data of interest, cylinder pressure and knock signals in particular. This platform is composed of an industrial PC on which is running a real-time kernel. This computer contains a FPGA based timer board which uses TDC events and flywheel or coder signal to trigger and synchronize an acquisition module on specific crank angles. This gives the ability to get cylinder to cylinder and cycle to cycle data frames at up to 400 kHz or down to 0.1 crank angle degree (CAD). Eight independent channels per acquisition module are available with multi-windowing or continuous acquisition capacity. These data can be saved on PC hard disk drive for a specified number of consecutive engine cycles in order to be post-treated. Therefore it is possible to prototype and validate, off-line, combustion analysis and signal processing algorithms on high quality and resolution engine data. Moreover the amount of data (100 cycles per cylinder per engine set point) provide statistical analysis ability. For further details on this platform see in Grondin et al. [2007].

The results and the limits of the extraction method are shown on figure 5 and figure 7. On figure 5, we started with an engine calibration point and we modify the Burnt Gas Rate (BGR) level (ratio between the burned and the total gas mass in the intake manifold). Then we compute the start of combustion (SoC) from the cylinder pressure signal and the estimated start of combustion from the knock sensor and the rate of heat released from the cylinder pressure. The results on HCCI mode allows a combustion control. Indeed the standard deviation on SoC and MoC is under 0.4 crank angle degree and the mean on the ten cycles follows the combustion analysis mean. On figure 7, we worked on engine calibration points at 1000 rpm at different load in HCCI mode. Whereas the AVL Noise is very small (82dB), the extraction of the middle of combustion succeed. However, a little variation on MFB_{50} (Mass Fuel Burnt : 50 %) is amplified on MoC on knock sensor. Fourier observer can also estimate the combustion noise (EoC). Initially combustion noise is evaluated on cylinder pressure by applying structure and ear filters. AVL offer integrated system which calculate

Speed [rpm]	IMEP [bar]	Noise [dB]	BGR [%]	Cycle number
1500	3	92	10	1-10
1500	3	91	15	11-20
1500	3	90	20	21-30
1500	3	87	25	31-40
1500	3	85	30	41-50

Table 1. Experimental BGR variation (HCCI mode)

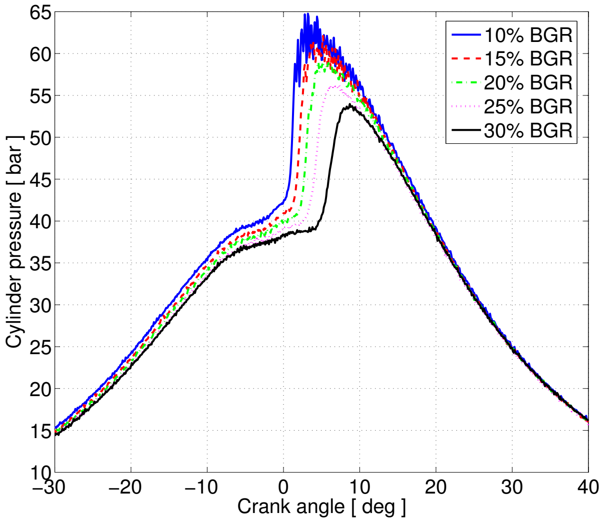

Figure 4. *Experimental variation of the BGR at* 1500 *rpm (see Table 1). Effect on the cylinder pressure.*

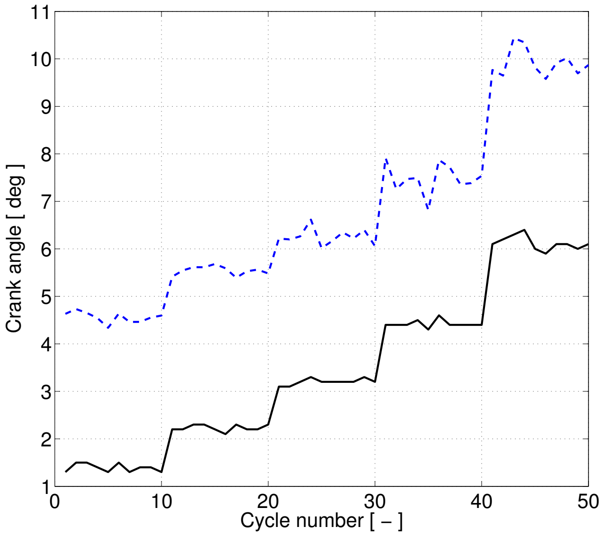

Figure 5. *Experimental variation of the BGR at* 1500 *rpm (see Table 1). Start of combustion estimation (dotted line) and real value (solid line).*

Speed [rpm]	IMEP [bar]	Noise [dB]	SoP [CAD]	Cycle number
1000	1	78	-21	1-40
1000	2	80	-18	41-80
1000	3	80	-10	81-120
1000	4	82	-2	121-160
1000	5	83	-1	161-200
1000	6	86	-17	201-240

Table 2. Load variation (HCCI mode)

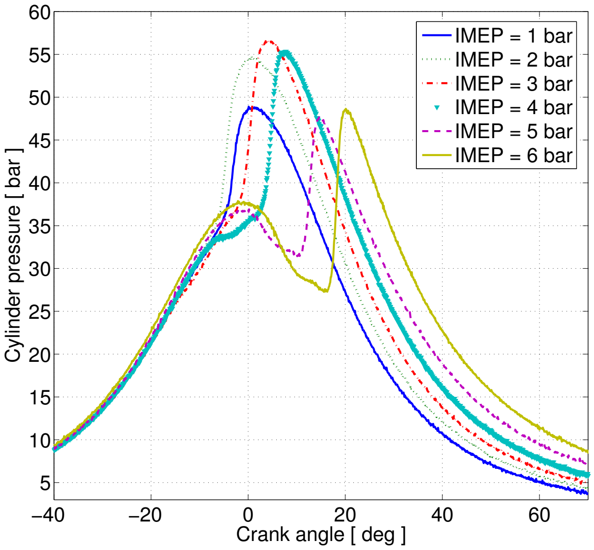

Figure 6. *Experimental load variation at* 1000 *rpm (see Table 2). Effect on the cylinder pressure.*

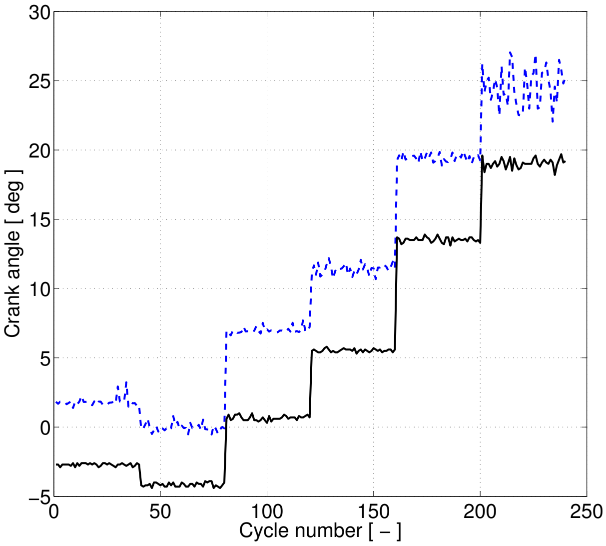

Figure 7. *Experimental load variation at* 1000 *rpm (see Table 2). Middle of combustion estimation (dotted line) and real value (solid line).*

combustion noise on pressure (www.avl.de). Combustion noise is calculated on knock sensor as explain in section 4. Results are shown on figure 8 for 40 engine cycle on a steady operating conditions in HCCI. The BGR level has been set near to the instability combustion limit in order to generate a small fluctuation of the engine noise (cycle to cycle). In these conditions, the estimated noise (EoC) is very close to the measured noise cycle to cycle. This proves the relevance of this indicator for closed loop combustion control.

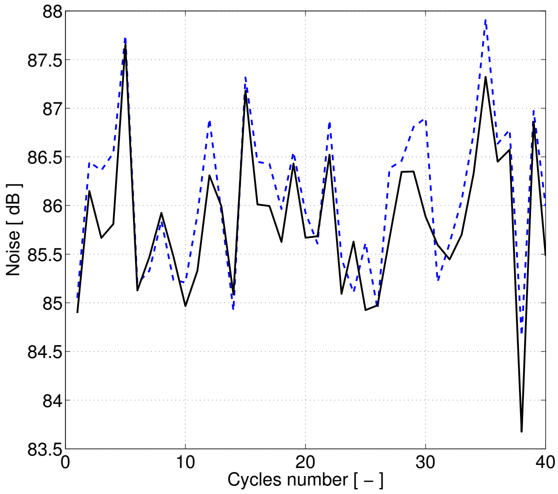

Figure 8. *Measured combustion noise (solid line) and EoC (dashed line) at* 1000 *rpm and* 6 *bar of IMEP.*

6. CONCLUSION

This paper has presented a tool for indirect combustion sensing. Instead of the direct measurement with cylinder pressure transducer, the combustion parameters (PoC) are computed from a knock sensor. This kind of sensor has the advantage to be cheaper than the cylinder pressure sensor. The method rely on a real time Fourier decomposition of the engine vibration trace. From this decomposition, an energy variable is computed and fitted with a Gaussian function. Then, the estimated combustion parameters are directly linked to the Gaussian function parameters. Our method has been illustrated through an example of comparison between direct and indirect combustion analysis based on cylinder pressure and knock signal for HCCI Diesel engine application. The signal processing rapid prototyping platform acquires the cylinder pressure and knock signals simultaneously and perform combustion analysis cycle to cycle and cylinder to cylinder. This allows a direct comparison of the combustion parameter reconstruction by direct comparison with the cylinder pressure sensor information. Algorithm have been optimized and the presented results show good agreement for the combustion phasing (SoC and MoC) and for the combustion noise (EoC). The main advantage of the proposed approach is that the algorithm can be implemented in real time. Then the PoC can be sent to the engine control system cycle to cycle and cylinder to cylinder. The next step of this study is to use the estimated PoC as feedback variables for closed loop combustion control. The main goal is to compensated the feedforward on start of injection in order to reduce engine noise due to thermal effects or to compensate cylinder unbalance due to BGR unbalance. Other applications are possible in the field of combustion diagnosis.

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