IMPROVED KNOCK DETECTION BY TIME VARIANT FILTERED STRUCTURE–BORNE SOUND

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ABSTRACT

In order to detect knock in spark plug engines generally structure–borne sound signals measured by acceleration sensors mounted on the engine housing are used. At test bed engines additional pressure sensors measuring the pressure inside the combustion chamber deliver a reference signal to adjust the parameters of knock detection based on the sound signal. We show by experimental results that the approximation of pressure signals by time variant filtering of structure–borne sound increases the performance of knock detection significantly. These results can be regarded as an upper boundary of what can be achieved by knock detectors with less computational load.

1. INTRODUCTION

Increasing environmental awareness and raising political demands force an efficient dealing with energy and the avoidance of gratuitous pollutants. Inter alia combustion control of spark–ignition car engines can give a contribution to the demands. Thereby knock control is an important aspect. Knock is an undesired spontanious auto-ignition of the unburned charge causing a sharp increase of pressure and temperature. Generally rare knock has no effect to the engine performance but frequent or very strong knock can damage the engine. The efficiency of most modern engines reaches its optimum in working conditions with respect of ignition and injection timing where knock can appear. Therefore the detection of knock is important to control combustion parameters optimally.

The sharp pressure increase excites resonant oscillations of the gas with frequencies depending on the absolute temperature and the combustion chamber geometry. Special pressure sensors mounted in the cylinder head or in the spark plug can be used to measure the excitation of the resonances. This method is very expensive and therefore not suitable for serial vehicles.

One way is to use acceleration sensors mounted on the engine housing which measure the structure–borne sound as a distorted version of the pressure signal inside the cylinder. A common method to detect noise in today's cars is to estimate the energy in a relatively wide band of the structure–borne sound signal, [1], [2]. Of course, the sound signal is perturbed by mechanical noise, e.g. valve noise, which decreases the signal–to–noise ratio. Our aim is increase the signal–to–noise ratio and to equalize the sound signal with respect to the pressure signal by suitable time variant filtering.

This paper is organised as follows. Section 2 presents signal models for pressure and structure–borne sound and in Section 3 the approximation of the pressure signal by filtering the sound signal. Section 4 describes the knock detector. We present results with measured data in Section 5 before we conclude the paper.

2. SIGNAL MODELS

As mentioned before knock leads to the excitation of combustion chamber resonances, [3]. Following [4] we model the highpass filtered pressure signal within a crank angle interval between 0 and 90 degrees with respect to top dead centre (TDC) of the according cylinder as

$$Y(t) = \sum_{p=1}^{P} A_p e^{-d_p t} \cos(\varphi_p(t)) u(t - t_0) + Z(t) \qquad (1)$$

with

$$\varphi_p(t) = \omega_p(\alpha_0) \int_{t_0}^{t} m(\alpha_0, \alpha(\tau)) d\tau + \Phi_p \qquad (2)$$

The pressure signal is a superposition of P resonances. A_p and Φ_p are random amplitudes and phases of the oscillations, the damping term $e^{-d_p t}$ describes the decreasing of the amplitudes due to increasing combustion chamber volume and heat losses. $u(t)$ denotes the step function and t_0 the time instant of the excitation of the resonances. $\alpha(t)$

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is the crank angle at time t, $\alpha_0 = \alpha(0)$ serves as reference point for the modulation function $m(.)$ which takes the frequency modulation due to piston motion into account. $\omega_p(\alpha_0)$ denotes the pth resonance frequency at the reference point.

The engine block transfers the pressure resonances to its surface where they can be measured as structure–borne sound. Modelling the engine block by a linear, time variant transfer function $H(t,\omega)$ or the according impulse response $h(t,\tau)$, respectively, [5], [6], we get the model for the structure–borne sound

$$X(t) = \int_{-\infty}^{\infty} h(t,\tau)Y(t-\tau)d\tau + W(t) \tag{3}$$

where $W(t)$ denotes additional noise, e.g. valve noise. If the instantaneous frequencies $\dot{\varphi}_p(t)$ do not change to fast, (3) can be simplified using the quasi–static approximation, [7], to

$$X(t) \approx \sum_{p=1}^{P} A_p e^{-d_p t} \mathrm{Re}\left\{ H_p(t, \dot{\varphi}_p(t)) e^{j\varphi_p(t)} \right\} + W(t), \tag{4}$$

where

$$H_p(t,\omega) = \int_{-\infty}^{\infty} h(t,\tau) e^{d_p \tau} e^{-j\omega\tau} d\tau \tag{5}$$

and Re$\{.\}$ denotes the real part of its argument. In this case the structure–borne sound signal is a complex amplitude modulated version of the pressure signal containing the same resonances in principle corrupted by noise. Figure 1 shows the Wigner–Ville spectrum–estimate of experimental data described in Section 5.

3. TIME VARIANT FILTERING

From physical point of view the structure–borne sound resonances are the result of the pressure resonances filtered by the engine block. In order to approximate pressure by sound we have to solve the inverse problem. Neglecting the physical aspect and changing to discrete processes $Y_n = Y(n\Delta)$ and $X_n = X(n\Delta)$ we set

$$Y_n = \sum_{k=k_1}^{k_2} \bar{h}_{n,k} X_{n-k} + U_n. \tag{6}$$

$\bar{h}_{n,k}$ is the inverse impulse response, U_n noise and k_1 and k_2 denote the time interval boundaries, whereas k_1 is negative to allow non–causal filtering. Actually k_2 should be 0, but we got better results with $k_2 > 0$. We can estimate the parameters $\bar{h}_{n,k}$ for each n of interest by least–squares estimation if we observe the engine for a large number of cycles and thereby making use of the cyclostationarity of Y_n and X_n, [4], [6].

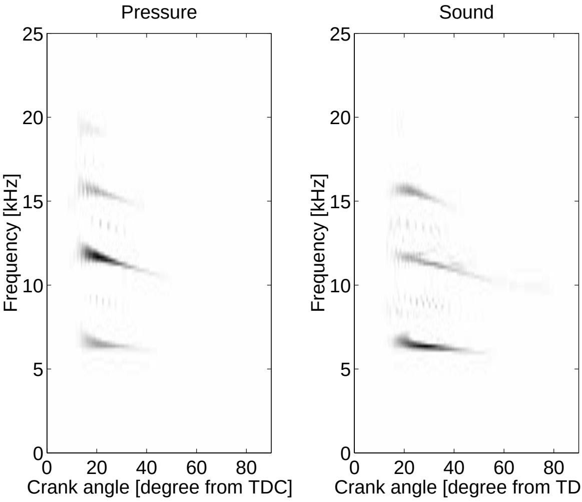

Figure 1: Wigner–Ville spectrum–estimate of pressure and structure–borne sound signal of a BMW engine at 2000 rpm.

4. KNOCK DETECTION

There are several different approaches for knock detection, see e.g. [8], [9], [10], [11], [12], [13] using sturcture–borne sound to detect knock. The new idea is to apply the approximated pressure signal instead of the sound signal to the knock detectors. Since the pressure signal serves as reference the use the approximated pressure should deliver better results than the sound signal. To show the advantages of this method we chose a detector described below. For theoretical background and details see [13].

We assume to have P possible resonance modes and to be able to estimate the according resonance energies. For, we can apply non–equidistant sampling for compensating the frequency modulation and narrow band energy measurements, see [4], [12]. The detector compares the energies of the actual combustion x_p $p = 1,\ldots,P$ with the energies of the last M non–knocking combustions x_{pm} ($p = 1,\ldots,P; m = 1,\ldots,M$). Therefore we calculate the relative resonance energies

$$\hat{\xi}_p = \frac{x_p}{\sum\limits_{m=1}^{M} x_{pm}}, \quad p = 1,\ldots,P. \tag{7}$$

If the sum $t = \sum_{p=1}^{P} \hat{\xi}_p$ of the relative resonance energies exceeds the threshold κ the combustion is classified as knocking otherwise as non–knocking. In the latter case the oldest reference combustion is replaced by the actual combustion in order to adapt the detector to possible changes of engine working conditions.

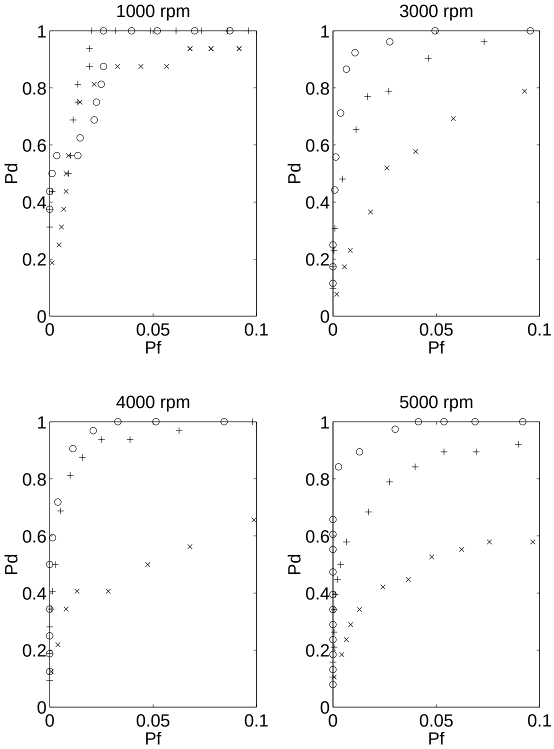

Figure 2: ROCs of the adaptive knock detector based on structure–borne sound ($\times$), time variant filter sound (+), and pressure ($\circ$).

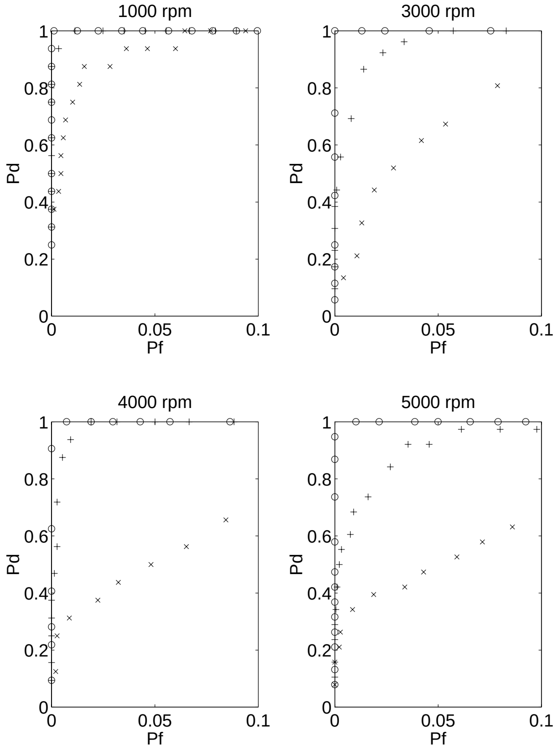

Figure 3: ROCs of the non–adaptive knock detector based on structure–borne sound ($\times$), time variant filter sound (+), and pressure ($\circ$).

5. EXPERIMENTAL RESULTS

The experimental data were recorded from a six cylinder BMW engine. The signal of a pressure sensor mounted in the cylinder head was recorded during time windows according to the interval from 0 to 90 degrees crank angle from TDC. The signal of an acceleration sensor mounted on the engine housing close to the cylinder was recorded in parallel. Speed and load were constant. For each speed between 1000 and 2000 cycles of the monitored cylinder were recorded. 150 to 200 cycles randomly chosen were used to identify the inverse impulse response of the engine block, the other cycles for knock detection.

For knock detection and knock reference the resonance frequencies at about 7, 12, and 16 kHz were taken into account, see Figure 1. The resonance energies were estimated by evaluating the periodogram of the signals in a band around the resonance frequencies with a bandwidth of 500 Hz without frequency demodulation for the sake of simplicity.

The reference was found by a non–adaptive version of the knock detector: Each resonance energy was related on the mean over all energies of the according frequency. If the sum of the relative energies of a combustion exceeded a threshold the combustion was defined to be knocking otherwise non–knocking. The value of the threshold was chosen so that about two percent of the combustions were defined as knocking.

The knock detection was done with three different signals: (a) structure–borne sound, (b) time variant filtered sound, and (c) pressure. The latter signal can be considered as optimal knock detector input signal because the pressure signal serves as the reference. To demonstrate the knock detection performance the results are presented as receiver operation characteristics (ROC).

Figure 2 shows the result of the adaptive knock detector for different speeds and memory length $M = 31$. Note that the axis showing the false alarm probability ranges from 0 to 0.1, the axis of the detection probability ranges from 0 to 1. Generally the knock detection based on the pressure signal works best although we do not get a detection probability of 1 for false alarm probabilities greater than 0. The reason is the adaptivity of the detector opposite to the non–adaptivity at the reference formation. That's why the results with the approximated pressure signal can be even better than that of the pressure signal, e.g. at 1000 rpm. For the other presented speeds the approximated pressure signal leads to worse results, but they are still significantly better than the results based on the (unfiltered) structure–borne signal which yields the worst results.

In some cases, e.g. when the working condition of the engine is definitely stationary as e.g. in our experiment, it can be useful to apply non–adaptive detectors ($M \to \infty$). Calculating the relative resonance energies analogous to the reference the knock detector yields results shown in Figure 3. In this case the ROC based on the pressure signal has the ideal shape which confirms the correctness of the algorithm. The results based on the approximated pressure are slightly better than in the adaptive case and those based on the structure–borne sound are similar. This means that the waiving of adaptivity in not necessary in case of stationary working conditions.

6. CONCLUSIONS

We have shown that a suitable processing of structure–borne sound improves the performance of a knock detector significantly. But the presented way of time variant filtering is not suitable for series cars because of the relatively high calculation effort. Generally there can be no better method of knock detection than to approximate the signal that serves as reference. But for knock detection it is not necessary to reconstruct the whole signal. The aim for further investigations is to find simpler methods to estimate only the resonance energies of the pressure signal from structure–borne sound signals in real time.

7. REFERENCES

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