FAST KNOCK DETECTION USING PATTERN SIGNALS

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ABSTRACT

In order to detect knock in spark ignition engines, usually structure-borne sound signals measured by acceleration sensors mounted on the engine housing are analyzed. Earlier investigations have shown that using linear, time variant filtered structure-borne sound signals as approximated pressure signal instead improves knock detection significantly. But this method is computationally too expensive for application in production vehicles. In this paper we propose to fit suitable pattern signals to structure-borne sound and use the estimated scaling parameters to approximate pressure. The new approach is applied to knock detection with measured data.

1. INTRODUCTION

Increasing environmental awareness, tightened laws and last but not least ascending fuel prices push the motor industry to develop more and more efficient internal combustion engines exhausting less pollutants. An important starting point is the optimization of the combustion process. For thermodynamic reasons engine efficiency depends on compression ratio: the higher the ratio the higher engine efficiency. Unfortunately, compression ratio is limited by the appearance of knock. Knock is an undesired spontaneous auto-ignition of the unburned charge causing a sharp increase of pressure and temperature. Knocking combustions produce more pollutants, and frequent and strong knock even can damage the engine. For a given compression ratio, efficiency of most modern engines reaches its optimum in working conditions with respect of ignition and injection timing where knock can appear. Therefore knock detection is an important task to enable engine management to adjust parameters optimally.

The sharp pressure increase excites combustion chamber resonances with frequencies depending on the absolute temperature and combustion chamber geometry [1]. Special pressure sensors mounted in the cylinder head or in the spark plug can be used to measure the excitation of the resonances. Fig. 1 (left) shows pressure resonances of a VW engine in the time-frequency domain by estimating the Wigner-Ville spectrum. Considering the pressure signal maximum or energy after highpass filtering gives a measure of knock intensity. But this method is very expensive and therefore not suitable for serial vehicles.

An accepted procedure in today's cars is to use acceleration sensors mounted on the engine housing which measure structure-borne sound as a distorted version of the pressure signal inside the cylinder. A common method to detect knock is to estimate signal energy in a relatively wide frequency band and compare it to a threshold. Structure-borne sound signals suffer from two drawbacks: They contain only a distorted version of the pressure signal and they are disturbed by additional noise caused by valves and other sound sources, see Fig. 1 (right). It was shown in [2] that increasing signal-to-noise ratio of the structure borne sound signals by linear, time variant filtering improves knock detection performance significantly. But the calculation effort is too high for serial engines. In this paper the advantages of the filtering are combined with a priori knowledge of the resonances.

The paper is organized as follows. Section 2 recalls the idea of improved knock detection. In Sec. 3 the approximation of pressure signals using pattern signals is derived and Sec. 4 describes a method how to obtain suitable pattern signals. In Sec. 5 the algorithm is applied to measured data before the paper is concluded with Sec. 6.

2. IMPROVED KNOCK DETECTION

A general idea to improve knock detection was presented in [2]: As mentioned before the highpass filtered pressure signal contains several components each corresponding to a resonance. Therefore, a general pressure signal model within the crank angle interval from 0 to 90 degrees with respect to top dead center is given by

$$Y(t) = \sum_{p=1}^{P} A_p(t) \cos \varphi_p(t) + W_y(t),$$

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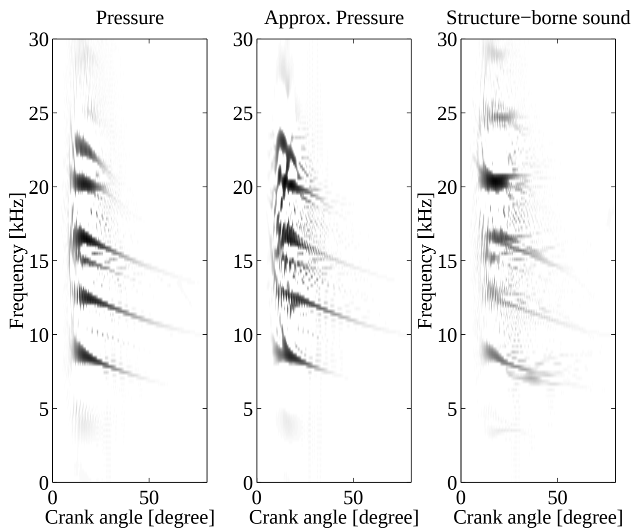

Fig. 1. Estimated Wigner-Ville spectra of measured pressure (left), measured structure-borne sound (right) and by pattern signals approximated pressure (middle) for a VW engine at 1750 rpm.

where P is the number of possible resonances, $A_p(t)$ and $\varphi_p(t)$ amplitude envelope and phase function of component p, and $Z(t)$ additional noise.

The engine housing transfers the pressure resonances to its surface where they are measured as structure-borne sound. Since the amplitudes are relatively low, a linear transfer function is assumed. The movement of the piston motivates a time variant transfer function because the surface of the combustion chamber increases with time. Modeling the engine housing as a linear, time variant filter with impulse response $h(t,\tau)$ yields a model for the structure-borne sound

$$X(t) = \int_{-\infty}^{\infty} h(t,\tau) Y(t-\tau) d\tau + W_s(t)$$
$$= \sum_{p=1}^{P} \int_{-\infty}^{\infty} h(t,\tau) A_p(t-\tau) \cos\varphi_p(t-\tau) d\tau + W(t)$$

where $W_s(t)$ is additional structure-borne noise and $W(t)$ is the sum of $W_s(t)$ and the filtered pressure noise $W_y(t)$.

The idea for improved knock detection is not to use the structure-borne sound signal directly but to first approximate the pressure signal and then apply the knock detection algorithm, e. g. by estimating the inverse impulse response $h^{-1}(t,\tau)$ to $h(t,\tau)$ so that

$$\hat{Y}(t) \approx \int_{-\infty}^{\infty} h^{-1}(t,\tau) X(t-\tau) d\tau.$$

Figure 2 visualizes the approach. Unfortunately, it is computationally expensive. But good results motivate to find faster algorithms based on this idea.

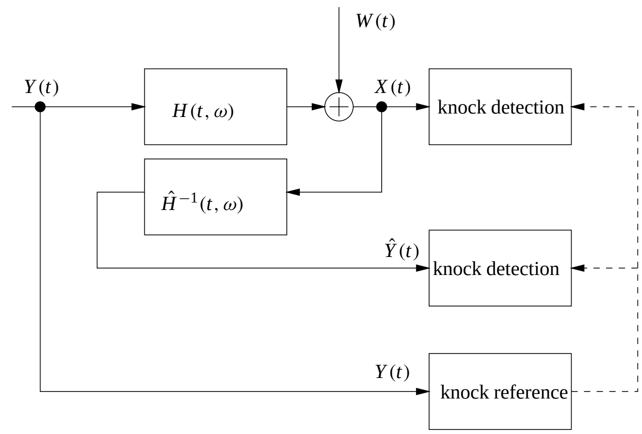

Fig. 2. Improved knock detection by linear, time variant filtered structure-borne sound.

3. FAST PRESSURE APPROXIMATION

Finite element simulations, [3], [4], and time frequency analysis, [5] show that the frequency modulation as well as the amplitude modulation of each resonance are basically a function of crank angle for constant engine speed while the scaling of the resonances depends on knock intensity. Therefore, each component of the pressure signal can be expressed by the multiplication of a pattern function $M_p(t)$ containing amplitude and frequency modulation and a scaling factor a_p representing knock intensity:

$$Y(t) \approx \sum_{p=1}^{P} a_p M_p(t) + Z(t).$$

Since the engine housing is assumed to act as a linear filter, the structure-borne sound signal can be regarded as the sum of pattern functions, too:

$$\begin{aligned} X(t) &= \int_{-\infty}^{\infty} h(t,\tau) Y(t-\tau) d\tau + W_s(t) \\ &\approx \sum_{p=1}^{P} \int_{-\infty}^{\infty} h(t,\tau) a_p M_p(t-\tau) d\tau + W(t) \\ &= \sum_{p=1}^{P} a_p N_p(t) + W(t) \end{aligned}$$

with the structure-borne sound pattern signals

$$N_p(t) = \int_{-\infty}^{\infty} h(t,\tau) M_p(t-\tau) d\tau.$$

Note that pressure signal and structure-borne sound signal are described by the same linear parameters a_p. Having the pressure pattern function $M_p(t)$, see Sec. 4, and the engine housing impulse response $h(t, \tau)$, see [5], the structure-borne sound pattern signals can be calculated. These calculations can be done offline with data obtained from test bed engines.

An estimation $\tilde{a}_p$ of the scaling parameters a_p can be estimated easily by least squares fitting the structure-borne sound pattern signals to the measured structure-borne sound signal,

$$X(t) \approx \sum_{p=1}^{P} \tilde{a}_p N_p(t),$$

and the pressure signal can be approximated applying the scaling factors estimated by structure-borne sound signals to the pressure pattern signals:

$$\tilde{Y}(t) = \sum_{p=1}^{P} \tilde{a}_p M_p(t).$$

4. PATTERN FUNCTION GENERATION

There are several possibilities how to obtain suitable pattern signals. Finite element simulations allow to estimate frequency modulation and amplitude modulation, [4], but they need detailed information about combustion chamber geometry. Much easier is the exploitation of measured pressure signals. The simplest method is to apply bandpass filters to separate the resonances. But often the resonances are too close together or even cross in the time-frequency plain so that this method is not advisable. A proven approach is the application a subspace method, proposed in [6]. The subspace method estimates instantaneous amplitude and phase for a given number of resonances whereas analytic signals are considered. For finding pattern signals the subspace method was extended by following iteration:

From a set of pressure signals the subspace method is applied to the signal with the highest energy searching for four resonances. The first pattern signal is then obtained by reconstructing the time signal of the resonance with highest energy. The pattern signal is optimally fitted to and then the subtracted from each pressure signal. The residua form the new set of pressure signals and the iteration starts again until the desired number of pattern functions is found.

In order to estimate the number of resonances P, the correlation between measured pressure $Y(t)$ and approximated pressure $\tilde{Y}(t)$ of an other set of knocking combustions were calculated. Fig. 3 shows the result for the VW engine at 3500 rpm. It also shows the correlation between measured pressure and structure-borne sound $X(t)$ whereas the sound signals were optimally time-shifted in order to compensate phase delay. This correlation does not depend on P. The same holds for the correlation between measured pressure and filtered structure-borne sound $\hat{Y}(t)$. At first, the mean correlation between time signals $Y(t)$ and $\tilde{Y}(t)$ increases with increasing numbers of pattern signals. The

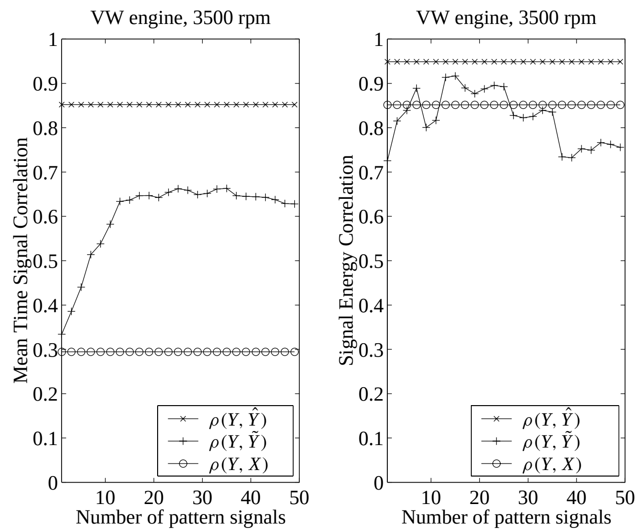

Fig. 3. Correlation between pressure $Y(t)$, structure-borne sound $X(t)$, time variant filtered structure-borne sound $\hat{Y}(t)$, and by pattern signals approximated pressure $\tilde{Y}(t)$ depending on number of pattern signals.

curve comes to saturation at about a pattern signal number of 13. From this number on, the correlation is relatively independent on the pattern signal number. The signal energy correlation has a maximum at a pattern signal number of 15. But it has high values from 13 to 15 pattern signals. The same investigation at 1750 rpm indicated a optimum pattern signal number of 14. Therefore, this number was chosen for further investigation. Figure 4 shows the first six pattern signals from 0 to 50 degree crank angle. Obviously, the number of pattern signals is larger then the number of resonances visible in Fig. 1. On the one hand there are resonances with similar frequencies that could not be resolved in Fig. 1, on the other hand the time instant of knock may vary so that more than one pattern signal have to be used to describe a resonance.

5. RESULTS

The algorithm was applied to the VW engine at 1750 and 3500 rpm. The following relates to the 1750 rpm data. The total set of 1847 cycles, each sampled in the crank angle interval from 0 to 90 degree with a sampling frequency of 100 kHz, was divided in 616 cycles for estimation tasks and 1231 cycles for validation tasks. Pattern signals and transfer functions were estimated using the 100 signals with highest energy in pressure. In order to compare knock detection using structure-borne sound, time variant filtered structure-borne sound, and by pattern signals approximated pressure a commonly used knock detection scheme was applied: If the maximum value of a measured pressure signal

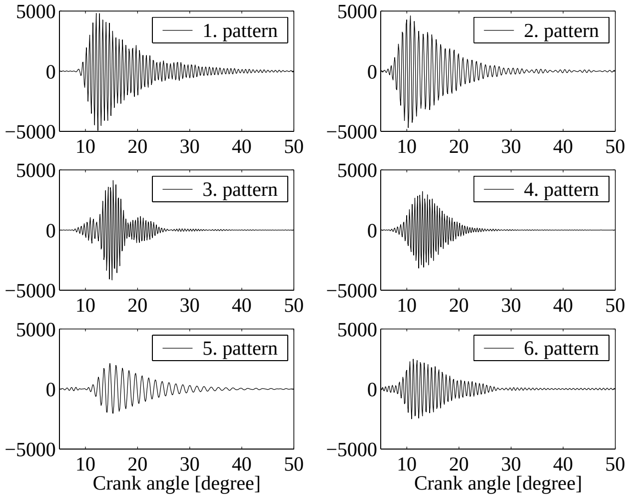

Fig. 4. Real part of the first pattern signals for the VW engine at 1750 rpm.

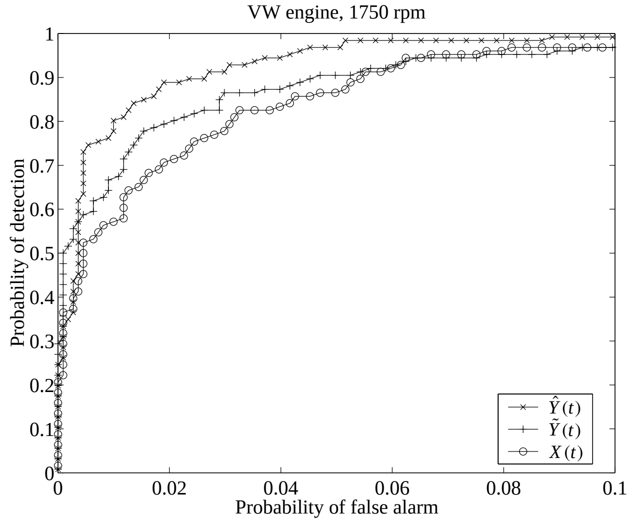

Fig. 5. ROC of the knock detection.

exceeds a given threshold, the combustion was defined as knocking. This decision serves as reference. The knock detection was performed by calculation signal energy of structure-borne sound, time variant filtered structure-borne sound and approximated pressure signal. If the signal energy exceeded a given threshold κ, the combustion was regarded as knocking. This procedure was repeated for a different values of κ yielding a so-called receiver operation characteristic (ROC). In a ROC, the probability of detection is plotted against the probability of false alarm, whereas detection means that a knocking combustion was detected correctly, and false alarm that a non-knocking combustion was regarded as knocking. Fig. 5 shows the ROCs of the three signals under consideration. As expected the time variant filtered structure-borne sound yields the best results, which means that for a given probability of false alarm it has the highest probability of detection. The structure-borne sound yields the worst results. The probability of detection using the pattern signal approximation generally is between that of both other signals. The results for 3500 rpm were similar but the improvement was less significant. Generally it turned out that the results strongly depend on the choice of pattern signals.

6. CONCLUSIONS

It was demonstrated that fitting suitable pattern signals to structure borne sound signals and using the estimated parameters for pressure approximation increases correlation between pressure and structure-borne sound. Applying the algorithm to measured data, it was shown that knock detection can be improved by this kind of pressure approximation. But there are some problems that should be investigated in future work, e. g. the influence of the choice of pattern signals, the problem of dealing with different speeds and the problem of varying time instant of knock.

7. REFERENCES

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