REAL TIME KNOCK DETECTION WITH DFT-BASED TIME-FREQUENCY ANALYSIS

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ABSTRACT

New generations of spark ignition engines require a correct ignition adjustment to guarantee optimal performance. In this paper, we address the challenge of knock detection improvements with time-frequency analysis. Two real time knock detection methodologies based on the sliding Discrete Fourier Transform and the pseudo Wigner-Ville distribution are exposed. Their relative performances and robustness are compared in real time simulation on both production (vibration signals from accelerometer sensors) and modelled data.

1. INTRODUCTION

Correct ignition adjustment is crucial for new generations of spark ignition engines to guarantee optimal performance. A recent trend, towards finer engine settings adjustments, exploits the detection and characterization of knocking phenomena. The later are related to incorrect combustion behaviour happening close to the engine optimal operation point.

A proposed strategy consists in controlling spark advance by using closed-loop control algorithms with knocking condition detection, and in adapting the advance regulation optimally with respect to the detected knocking limit. Knock detection can be performed by using instrumentation in-cylinder pressure sensors. Nevertheless, their price and the environment hostility limit their practical use outside test beds. A more cost effective approach consists in using accelerometers located on the engine surface. Gasoline series vehicles are already equipped with knock sensors but the existing detection techniques require further improvements such as enhanced noise and speed robustness, adaptability to combustion conditions and, above all, a better characterization than standard binary classification in “knocking” or “not-knocking” modes.

This paper addresses the challenge of knock characterization improvements from noisy vibration signals with time-frequency analysis and exposes two real time knock detection methodologies suitable for closed-loop control. Their relative performance and robustness to additional noise are finally compared on actual production and modelled data.

2. KNOCK PHENOMENON

Several knock definitions exist, and we follow a generic one given in [1]: *“Knock is an undesirable mode of combustion that originates spontaneously and sporadically in the engine, producing sharp pressure pulses associated with a vibratory movement of the charge and the characteristic sound from which the phenomenon derives its name.”* The resulting impulsive pressure increase excites the cylinder cavity resonances, which are transmitted to the engine structure. It results in engine vibrations to the audible level. In the case of cylindrical combustion chamber, the resonant frequency can be approximated as [2]

$$f_{m,n,p} \approx \frac{c x_{m,n}}{2B}, \qquad (1)$$

where c denotes the speed of sound in gas and B the radius of the cylinder bore. The $x_{m,n}$ term is a mode constant. The indices m, n are integers denoting respectively the circumferential and radial mode numbers.

According to a thermodynamic relation, the velocity of sound can be approximated as:

$$c^2 = \gamma R T, \qquad (2)$$

where γ is the isentropic coefficient, R the gas constant and T the in-cylinder temperature. The frequency is thus a function of the chamber geometry, the temperature and the isentropic constant.

3. VIBRATION SIGNAL

The engine vibration signal exhibits non-stationary features due to different kind of sources such as valve openings and closures, piston slaps and additive disturbances. Transient waves generated by these sources often overlap and the challenge is to detect the components of the vibration signal associated to the knock phenomenon only. To help the identification of the knock related vibration, pressure trace acquired from in-cylinder pressure sensors are also studied. Thus, a simple comparison between spectrograms such as those presented in figures 1 and 2 derived from pressure traces and vibrations signals provides some useful insights on the behaviour of the transient event associated to the knock phenomenon. The resonance frequency generated by knocking conditions can be easily observed in the gradient pressure spectrogram. The vibration signal spectrogram shows a much more complex content with several transient events but the first resonance frequency at 8 kHz can be detected between 380° and 400° crank angle indexes.

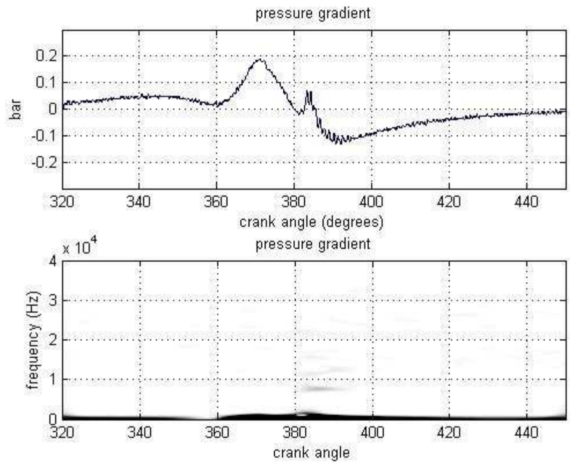

Fig.1: Pressure gradient (top) and its angular-frequency representation (bottom).

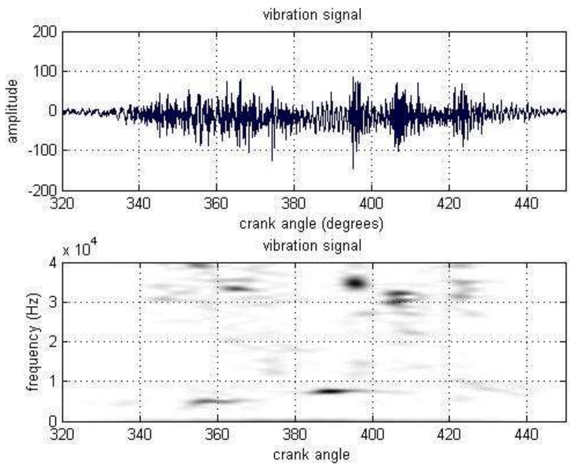

Fig.2: Vibration signal (top) and its angular-frequency representation (bottom).

If performing a time-frequency analysis by using the short time Fourier transform allows to get a first guess on non-stationary signal properties, the limitation of this kind of technique is quickly reached. [3] showed that most engine vibrations may be regarded as cyclostationary. Components of these vibrations are mutually not correlated and the cross-terms in the Wigner-Ville distribution can be removed by averaging several combustion cycles. Theoretically, the resulting mean Wigner-Ville spectrum (WVS) may converge to the WVS containing the auto-terms only. Nevertheless, the apparition of the knock phenomenon may be considered as random between 5° to 15° after the top dead center piston position. This stochastic nature of the knock apparition makes the cyclostationarity assumption not valid.

In order to attenuate the cross-terms interferences, the smooth pseudo Wigner-Ville spectrum (SPWVS) has been used. A careful analysis of the SPWVS (figure 3) reveals that a knock related component may be characterised by a time-varying amplitude modulation and a frequency content which may present no modulation. These conclusions may be surprising if Equation (1) is first considered. In accordance with this equation, the fundamental of the knock signal would be expected to be a chirp with a linear frequency modulation. For such signals embedded in noise, effective techniques exist to estimate chirp parameters [4]. But with respect to the results from SPWVS and the real time constraints, methods based on time-frequency analysis have been considered to process on-line vibration signals.

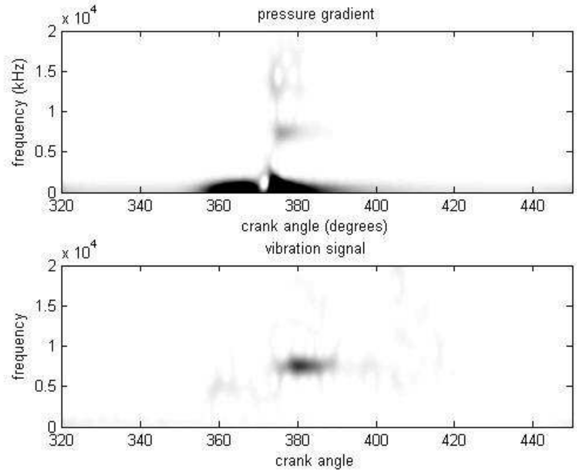

Fig.3: Smooth Pseudo Wigner-Ville distribution of pressure trace (top) and vibration signal (bottom).

4. REAL TIME ANALYSIS

Time-frequency representations are well suited to signal analysis for off-line diagnosis. Nonetheless, the computation time and the large number of operations needed to perform a Wigner-Ville distribution often exceed on-board processor capabilities. In practice, our purpose is to find a signal processing strategy which can be implemented in real time in order to identify the occurrences of the knock phenomenon. Two approaches have been considered, the first one is based on a sliding Discrete Fourier Transform (DFT) which can be implemented in a recursive way. The second approach is an extension of the first one, more precise in term of time/frequency resolution but requiring additional computations.

4.1. SDFT based method

The rationale for this method is to analyze signals in a narrow bandwidth where the knock phenomenon appears. This strategy only requires the observation of a small number of frequency components. The sliding Discrete Fourier transform (SDFT) described in [5] is particularly well adapted to the computation of the spectral time variation in a few frequency bins, especially in real time applications. This algorithm uses the circular property of the DFT which states that if $X(k)$ is the DFT of N samples sequence, the DFT of the sequence shifted by one sample is $X(k)e^{j2\pi k/N}$. This property can be expressed with the following difference equation:

$$S_k(n) = S_k(n-1)e^{j2\pi k/N} - x(n-N) + x(n), \quad (3)$$

where S_k is the spectral component determined at each angular sample n for the frequency-domain index k in the range $0 \le k \le N-1$. Once the first spectral is obtained, only two real adds and one complex multiply per output sample are required to obtain the update value of the spectral component. Nevertheless, a particular attention has to be paid to the SDFT stability and applying this algorithm to a narrow bandwidth generally increases its robustness. In order to check the robustness of the SDFT, a comparison with the Goertzel algorithm has been performed. This algorithm [6] computes a single DFT with an implementation in the form of a second order infinite impulse response filter. A good agreement in the variation of the spectral component between both estimations validates our approach to use the SDFT algorithm for a knock detection application. If this method is well adapted to detect the knock resonance phenomenon, it also suffers from a lack of localization accurateness due to the Heisenberg-Gabor inequality, as the short-time Fourier Transform (STFT) case.

4.2. S-method based method

It has been shown in the section dedicated to the off-line vibration signal analysis that the pseudo Wigner-Ville distribution is well suited to the analysis of the knock related vibrations. A method that computes on-line an approximation of the pseudo Wigner-Ville distribution holds our attention; this distribution is referred to as the S-method. The S-method introduced in [7] and studied in [8] is a very effective way to estimate a pseudo Wigner-Ville distribution, avoiding cross-terms. It belongs to the general Cohen class of distributions and can be expresses as:

$$SW_x(t,\omega) = \frac{1}{\pi}\int_{-\infty}^{+\infty} P(\theta)STFT_x(t,\omega+\theta)STFT_x^*(t,\omega-\theta)d\theta, \quad (4)$$

where $P(\theta)$ is a finite frequency domain. The discrete form of equation 4 can be expressed as:

$$SM(n,k) = \frac{2}{N\pi}\left(|S_k(n)|^2 + 2\sum_{i=1}^{L} Real\left[S_{k+i}(n)S_{k-i}^*(n)\right]\right), \quad (5)$$

where $P(\theta)$ is a rectangular widow with a constant width L. We used the SDFT method described above to estimate the STFT term in Equation (4). A very efficient SW estimation can thus be obtained with a moderate computational increase. This method is better appropriate to the estimation of parameters such as the exact crank angle position of the beginning of the arrival or the maximum amplitude of the knock related resonance.

4.3. Results discussion

Figure 4 represents the on-line time-frequency analysis of a real knock signal with the SDFT and the S-method. The estimation of the resonance frequency power computed by both methods is also shown. One can observe the better time-frequency resolution obtained with the S-method. Another important conclusion concerning the application of the S-method is the potential to determine accurately the amplitude of the knock signal due to good focusing of the resonance frequency.

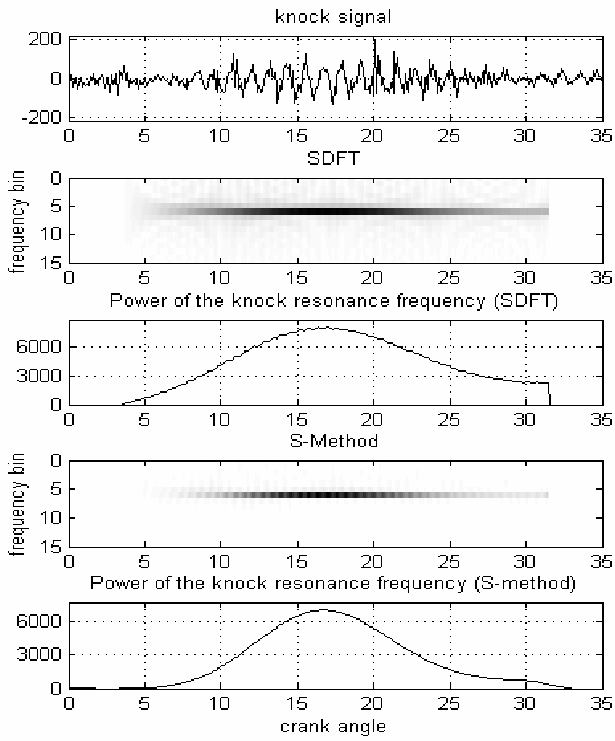

Fig.4: Knock signal, SDFT and S-method based time-frequency analysis with the associated estimation of the power of the resonance frequency.

5. KNOCK SIGNAL AMPLITUDE DETERMINATION

To investigate the accuracy of the estimation of the amplitude modulation by the S-method of the knock signal a simple model has been introduced. In accordance with the analysis of the angular-frequency representation the knock signal can be expressed as:

$$y(\alpha) = A_0 \alpha e^{-d\alpha^2} cos(c\alpha + \varphi). \qquad (6)$$

The damped sinusoid begins at $\alpha = 0$ and is located within the normalised angle period $0 \le \alpha \le 1.5$. The parameters of the damped sinusoid are chosen so as to get a very good match with real knock signal. These parameters are $A_0 = 240$, $d = 2$, $c = 34\pi$ and $\varphi = 0$.

To be more realistic this knock signal is embedded in centred additive Gaussian white noise. The test of accuracy consists in estimating the amplitude modulation for a set of simulated signal with an increasing noise variance (and so a decreasing SNR). The figure 4 (left) presents a single realisation of the noisy knock signal for three different SNRs. One can observe in the right part of this figure the good fitting of the S-method even in the worst case.

The figure 5 presents the mean square error between estimated and real amplitude modulation calculated for 16 SNRs varying from -3dB and 12dB. One hundred realisations for each SNR have been computed in order to perform a statistical study which confirms the good behaviour of the S-method.

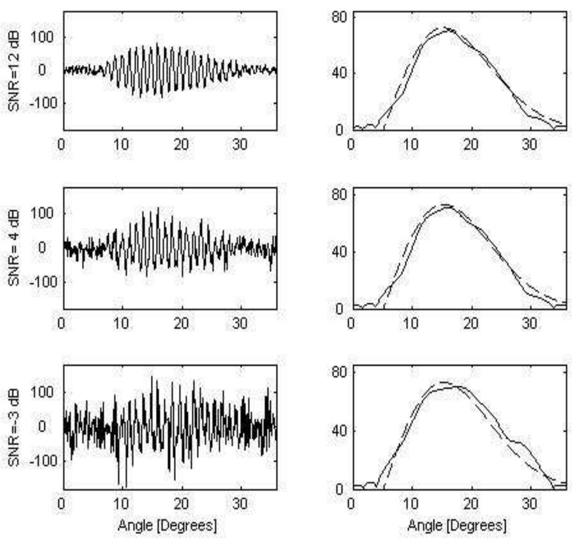

Fig.4: Synthetic signals on the left, on the right exact (dash) and estimated amplitude modulation from the S-method (solid).

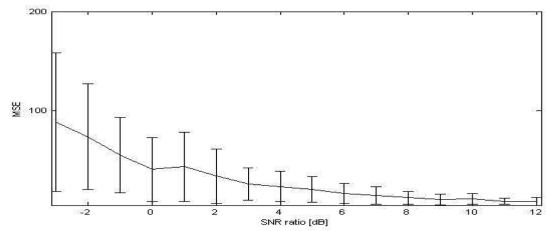

Fig.5: Performance evaluation (the bar indicates the standard deviation).

6. CONCLUSION

Engine performance optimization can be performed with spark advance control with a strategy based on knocking detection. An economical approach for knock detection consists in using accelerometer sensors located on the engine and in extracting information on the occurrence of the knocking phenomenon from vibration signals. Two time-frequency approaches based on DFT can be used to the knock detection. It has been demonstrated on both synthetic and real signals the efficiency of the S-method to estimate the amplitude modulation of the knock related resonance. Nonetheless, a trade-off between computation limitation, time-frequency resolution and also knock signal complexity drive the choice of one of these methods.

7. REFERENCES

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