A Signal Processing Detection Applied To Knock Intensity Measurement In Spark Ignition Engines

S. FEMMAM , B. LEMERCIER, R. MOKHNECHE and L. GEORGE
ECE, Rue de Grenelle Paris 75007
University of Haute-Alsace IUT de Colmar
Laboratoire Systèmes Complexes - FRE2494 CNRS Evry
FRANCE

Abstract: - Efficient performance control of Spark Ignition Engines has a great significance in today's competitive automotive industry. Engine cylinder pressure data has been proven to be the most suitable control variable used, however the complexities in the measurements and in the analysis of this signal are still under investigation. In the current work, normal and knocking cylinder pressure data measured from a research variable-compression-ratio engine over a wide range of operating conditions are analyzed. Both Frequency and Time domain analysis of the signals are extensively investigated and the results are compared. Similarly the effects of noise and interference are studied for both approaches and the results are processed and displayed for clearer comparison. The frequency domain analysis of cylinder pressure data provides more precise results, in particular for the cycles under knocking conditions. The frequency analysis can also be applied to multiple cylinders using the timing information from the electronics ignition system. Using the frequency analysis of the cylinder pressure data in conjunction with the ignition timing information from the electronic ignition system, knock intensity of each cylinder can be measured by a single knock sensor.

Key-Words: - Short time Fourier Transform, detection of abrupt changes, spectral subtraction, instantaneous frequency, channelized instantaneous frequency, time-frequency representations.

1 Introduction

All the problems of the engine knock has been widely studied during the past few years. It has been shown that knocking directly affects engine efficiency and excessive knocking can damage the combustion chamber and the engine body [1]. Auto-ignition theory is one of the most widely accepted theories that describe the sources of engine knock [3]. According to the auto-ignition theory, very high temperature and pressure at *TDC* can cause explosions in the combustion chamber end-gas. These explosions cause rapid oscillations in pressure signal that are known as knock. In this paper we start with the methods used to estimate and identify the characteristics of the signals extracted from the application in the time domain, frequency domain and both the time-frequency domain. The time-frequency domain is given to ensure us the robustness of our study and a proof of the accurate analysis on the measurement techniques. We introduce the uncertainty of time domain *KIC* calculation. The noise and perturbation sensitivity and finally we state steps for improving the knock detection. Some concluding remarks are given at the end of this paper.

2 Estimation and Identification of knocking cycles

In previous studies [2] the cylinder pressure signal was measured using a piezo-electric transducer. The data was sampled at 0.25 crank angle degree intervals over a wide range of engine operating conditions using two different fuels. Figure 1 shows a normal measured combustion cycle. The techniques used for estimation and identification are well stated and based over the classical theory. These techniques give us good results as we will see in the next steps of this paper [5].

3 Spectral analysis

Once we have the signal measure in time domain, we can study the frequency content of the signal. In frequency domain we can clearly see all the components of the knock signal. Using Fast Fourier Transforms (*FFT*), the power spectral density of the pressure signal is calculated from the following equation:

$$S(f) = \left|F\left\{P(t)\right\}\right|^2 \qquad (1)$$

Where *P(t)* is the time domain pressure signal and *S(f)* is the power spectrum in frequency domain. Figure 2 shows the power spectrum of the same pressure data. Since the knock ringing frequency is around 7-8 *kHz* [4], the power spectrum is only shown for the range of interest. By narrowing the range, we can eliminate the high power slow varying pressure signal, and focus in the lower powered oscillations of the pressure signal. Figure 3 shows a pressure-crank angle history of a heavily knocking cycle. The superimposed oscillations from *TDC* to 40º *ATDC* is characteristic of knocking cycles. This result has be well established in previous studies [2]. The power spectrum of the knocking cycle is shown in figure 4.

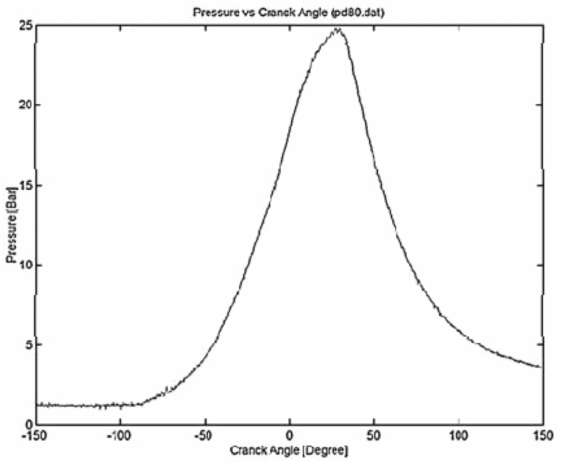


Figure 1: Pressure Signal of a knock free cycle

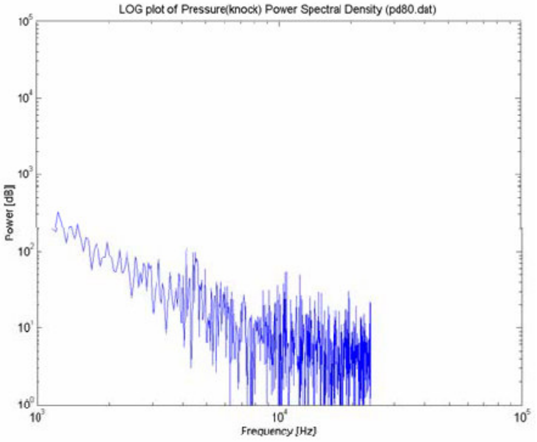


Figure 2: Power Spectral Density of a knock free cycle

In the above spectrum the knock peak occurs at 7.8 kHz and the noise floor of the system is much higher than the normal cycles. Next the knock intensity of the above pressure signals can be compared using the calculated power spectral densities. Figure 5 illustrates this comparison.

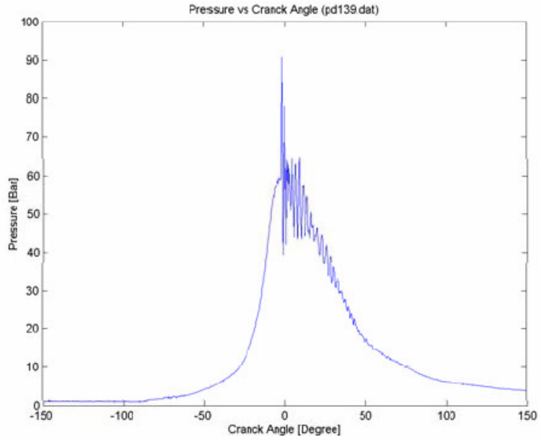


Figure 3: Pressure Signal of a heavily knocking cycle

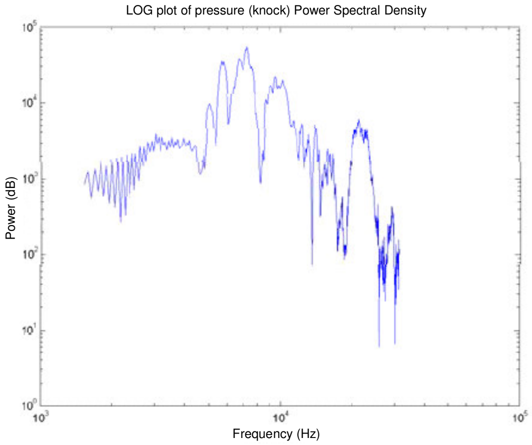


Figure 4: Power Spectral Density of a heavily knocking cycle.

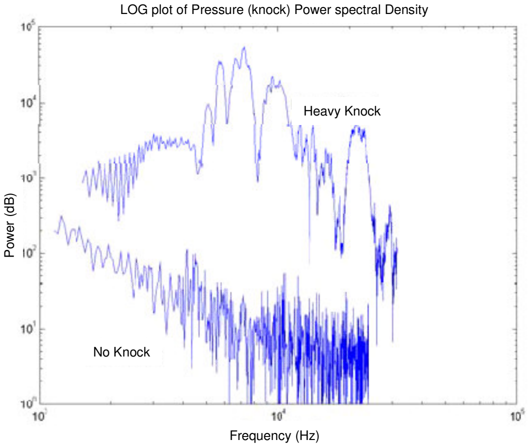


Figure 5: Comparing the power spectral density of a No-nock signal with a heavy knock signal

As we can see the heavy knock cycle has a higher overall power, and contains multiple high intensity peaks, while the no-knock cycle doesn't show any of these characteristics. Further analysis of many knocking cycles has shown that the spectral distribution and the intensity of the knock peaks vary from cycle to cycle, but the bandwidth of the knock signal is at 7-8 [*kHz*]. Figure 6 illustrates these relations.

Figure 6 shows 24 pressure measurements at varying conditions. Each of these measurements has different peak knock intensity due to the varying conditions (load, fuel type, engine speed etc…). Hence all of the above cycles experience the peak knocks in a relatively stable frequency range. Since the actual knock component of the pressure signal is contained in a narrow band around 7-8 [*kHz*], knock measurement and detection systems can take advantage of this to improve the signal to noise ratio by filtering out the unwanted frequency bands.

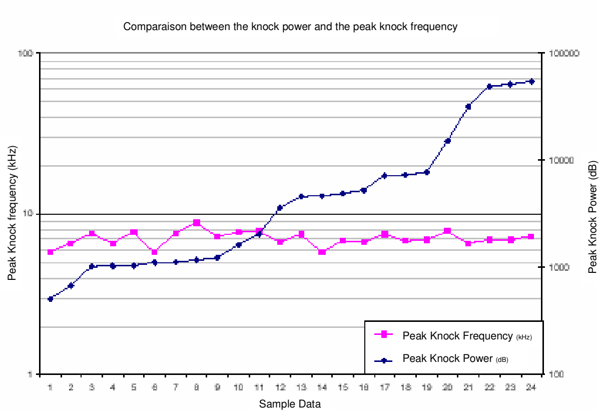


Figure 6: Comparison between the peak knock power and peak knock frequency

4 Temporally analysis

The time domain knock intensity measurement presented in [2] was performed over a window of 40 degrees of crank angle after the peak pressure. The knock intensity criterion (*KIC*) is the summation of all consecutive instantaneous pressure differences in the defined range.

$$KIC = \sum_{i=0}^{n} \left| P_{i+1} - P_i \right| \qquad (2)$$

Where $n = \left[\frac{40}{AI} \right]$.

Using the above formula the *KIC* for figure 1 is 17 [bars], and for figure 3 is 456 [bars] indicating normal and very heavily knocking cycles respectively.

5 Time frequency domain comparison

Using the time and frequency methods, the knock intensity is estimated for multiple data sets, and the results are showed in figure 7. As we can see the frequency domain results follow the same trend as the time domain estimates. The slight variations in the time domain estimated are due to the errors intrinsic to the calculation method that are discussed later in this paper.

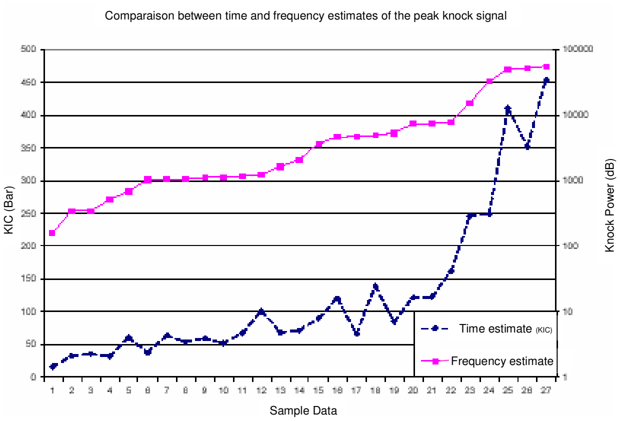
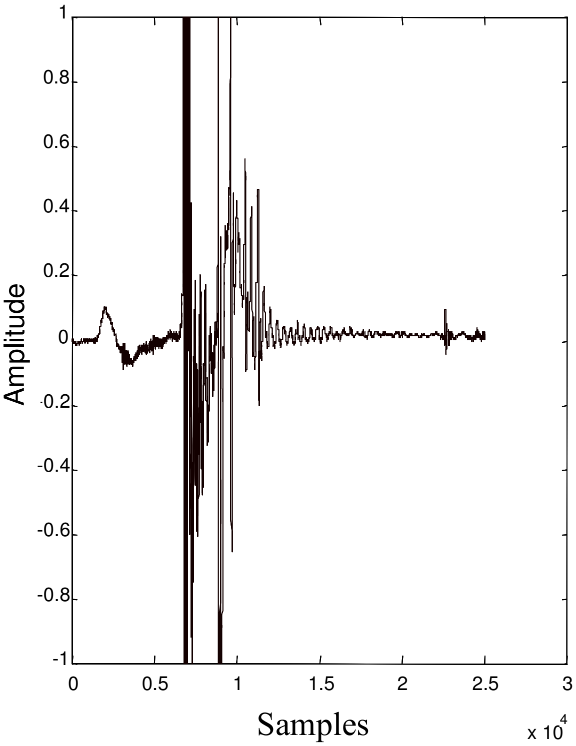


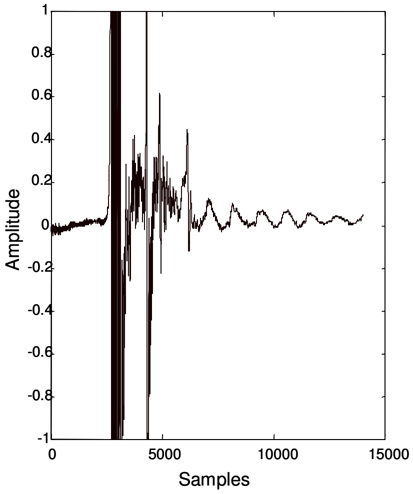
Figure 7: Comparison of Time and Frequency Estimates of the knock intensity

6 Time-frequency analysis

The time frequency analysis is used to ensure us that the methods used for measurements are accurate. The figure 8 presents the time varying signal of two different knocks, it is clear that the signal is pseudo-periodic and we can state that the FFT analysis can provide accurate results and since the component frequencies are limited in the 7-8 kHz bandwidth.



(a)



(b)

Figure 8 (a) and (b): Two different knocks time varying signals

Now we use the Morlet wavelets [5,8] to represent the distribution of the signal in time-frequency representation. We remark that the analysis with the FFT method still valid and accurate and it is simple to use this later method to minimize the time consuming processing.

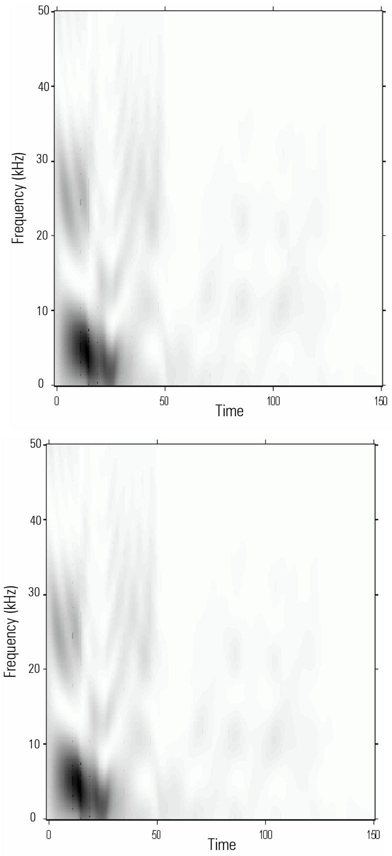


Figure 9: The Morlet time-frequency representations of the two knocks time varying signals of figure 8.

The figure 10 gives us the time-frequency distribution of the varying signal of figure 8 in three dimensional representation energy.

The figure 11 represents the three dimensional energy of the varying signal in surface distribution manner. These representations proof that the simple FFT analysis are accurate and confirm the results of the measurements techniques.

So we can conclude at this step that *FFT* analysis is sufficient to analyze and measure the knock intensity in spark ignition engines.

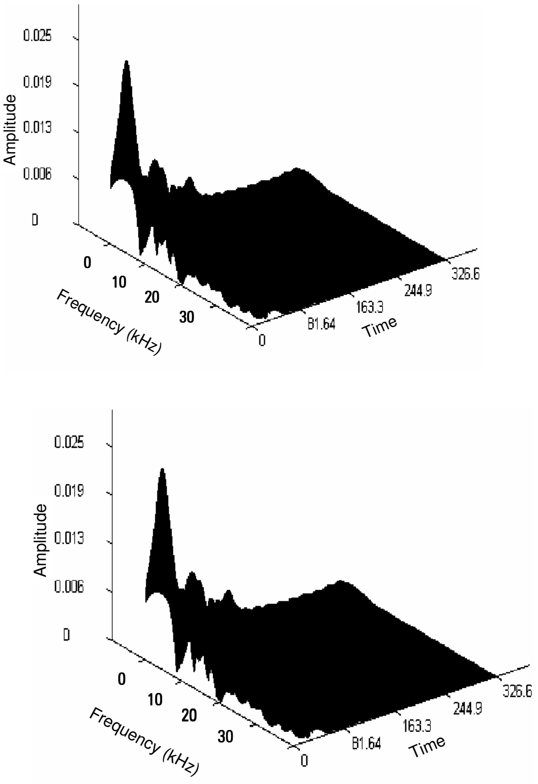


Figure 10: Three dimensional representation of the energy of the time varying signals of figure 8.

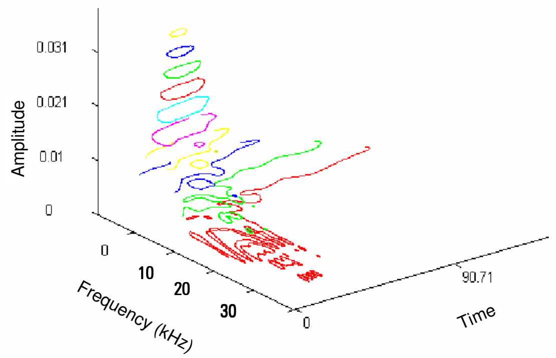


Figure 11: Three dimensional surface representation of the energy of the time varying signals of figure 8

7 Uncertainty of Time Domain *KIC* calculation

It can be seen that the larger oscillations will result in a higher *KIC* value. These oscillations also include the slowly decreasing variation in the pressure signal. Hence the *KIC* value will contain a portion of this variation that is inherent to the pressure signal For example in an ideal knock free system, the *KIC* will still record a small number directly proportional to the slope of the pressure signal.

This number will always offset the *KIC* results, and will vary depending on the slope of the pressure signal. Since the slope of the pressure signal varies depending on many factors, this inherent error cannot be accurately estimated and eliminated in time domain *KIC*.

8 Sensitivity to noise

The two methods to detect knock are both sensitive to noise. White noise can worsen the performance of both methods, but with improving the signal to noise ratio the sensitivity to white noise can be reduced. Due to the moving parts of high-speed SI engines, considerable amount of colored noises are generated. Since we have already established the knock peak frequency, colored noise can be filtered out from the signal, using band pass filters [6-7,9].

9 Multiple Cylinder Knock Intensity Measurement

In ideal conditions one piezo-electric transducer inside each cylinder would measure the most accurate results. Yet this may not be feasible for commercial production. If a knock sensor is used in the engine body instead, the measured signal will include the pressure or vibration information from all cylinders. In this case the signal to noise ratio (*SNR*) is much lower, but appropriate filtering can reduce the noise and interference from the signal. Since in 4 cylinder engines the combustion periods of different cylinders do not overlap, the knock information can easily be recovered from the measured signal. The figure 12 shows the pressure signal for one cylinder. The figure 13 shows the power spectrum of the above signal. The pressure information from figure 5 is used to generate the pressure data that would be measure by a single knock sensor in a 4-cylinder engine. The figure 14 illustrates this result. The figure 15 shows the power spectrum of the above pressure data. As we can see the frequency content of the signal has not changed.

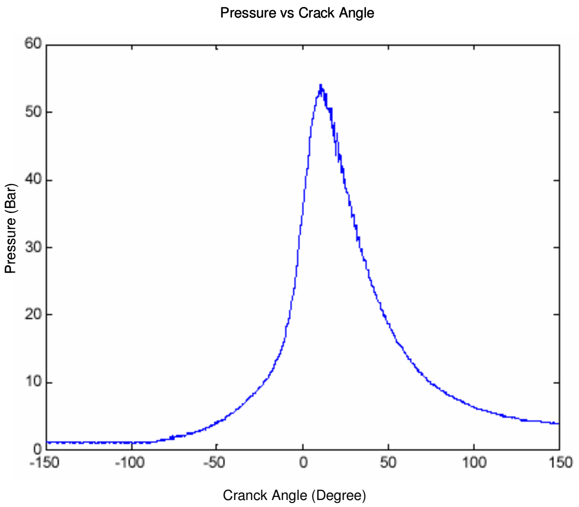


Figure 12: Single Cylinder pressure signal

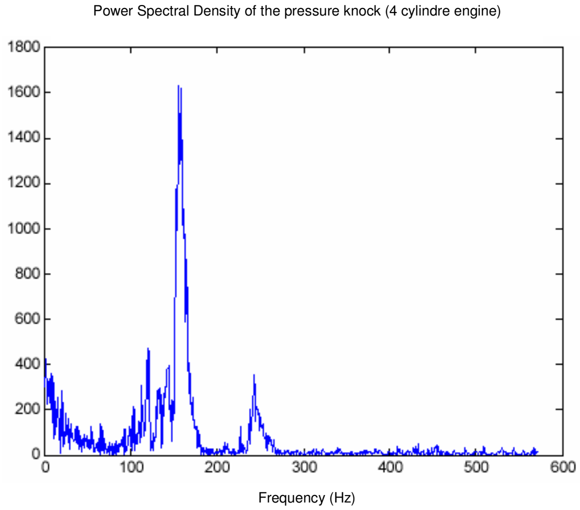


Figure 13: Power spectrum of the pressure signal of a single cylinder

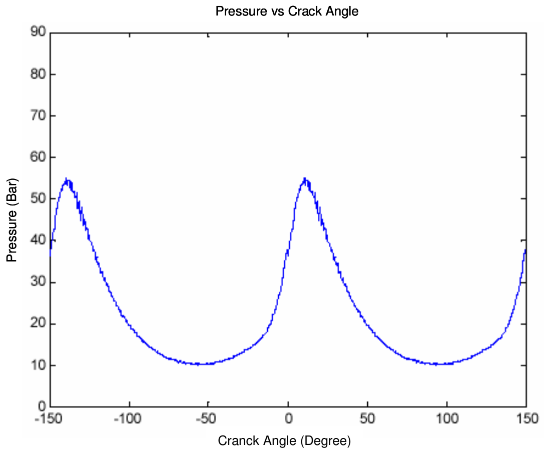


Figure 14: Pressure signal of a hypothetical group of cylinder in a 4-cylinder engine

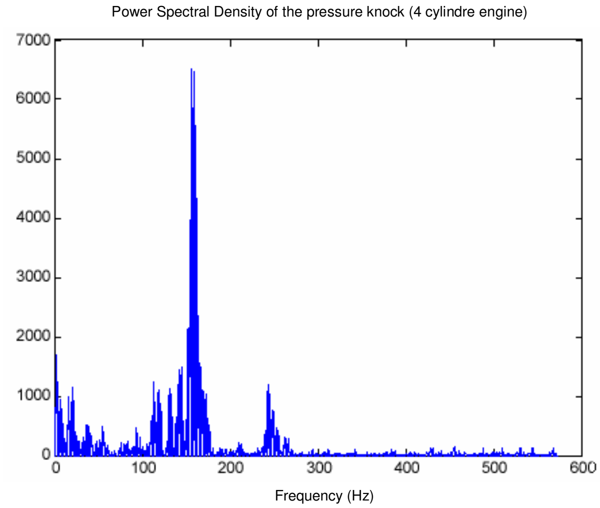


Figure 15: Simulated Power spectrum of the Cumulative Pressure signal of a 4-cylinder engine

10 Improving the knock detection

In electronic ignition (distributor less) systems, the timing of the spark plugs is control by a computer. The computer referred as the Engine Control Unit (*ECU*) has accurate information about the position of the pistons measured by sensors. The ECU controls the ignition via transistor switches by breaking the coil circuit ground. This gives the *ECU* very accurate control over spark timing. In these systems precise timing data is available from the ignition control system, and this timing information can improve the knock intensity measurement and control. In practical cases where one knock sensor is designed in the engine block, this timing information allows the cylinder with the knocking cycles to be identified. Hence the electronic ignition unit (*ECU*) can accurately adjust the ignition angle to overcome knock conditions or improve efficiency.

11 Concluding Remarks

The frequency analysis of the cylinder pressure data showed accurate levels of knock intensity. The suggested approach eliminates the errors intrinsic to the time domain approach. It was demonstrated that frequency analysis could improve the knock intensity measurements, by reducing the effect of noise and interference and eliminating the residual error in the time-domain analysis. The implications of the spectral analysis were analyzed for 4 cylinder engines with electronic ignition control. It was shown that ignition-timing data provides sufficient information to allow knock detection of multiple cylinders using a single knock sensor.

References:

[1] Douaud, A. and Eyzat, P. (1977) "DIGITAP-AN on-line Acquisition and Processing System for Instantaneous Engine Data-Applications.", S.A.E. paper 770218

[2] Westbrook, M. H., "Automotive sensors",Bristol ; Philadelphia : Institute of Physics Pub., c1994.

[3] Carstens-Behrens S, Böhme J, "Fast Knock Detection Using Pattern Signals", Department of Electrical Engineering and Information Science, Ruhr-Universität Bochum, c2001, 0-7803-7041-4/01 IEEE

[4] Samimy B, Rizzoni G, "Time-Frequency Analysis for Improved Detection of Internal Combustion Engine Knock", Center for Automotive Research, The Ohio State University, c1994, 0-7803-2127-8/94 IEEE

[5] S. Femmam, N.K. M'Sirdi, « Comparaison of the performances of spectral parametric estimation, time frequency, time scale, and segmentation with detection of abrupt changes methods in non-destructive evaluation » 3rd IFAC workshop On Line fault detection and supervision in the chemical proc. Indus., Lyon, 15-16 June 98

[6] Zhang F, Ge Y., et al., "A Micro-Processor Based Adaptive Ignition Control System", Beijing Institute of Technology, Beijing, 100081, c1999, 0-7803-5296-3/99 IEEE

[7] Dudek K.P., Sain M. K., "A Control-Oriented Model for Cylinder Pressure in Internal Combustion Engines", IEEE Transactions On Automatic Control, Vol. 34, No 4, c1989, 0018-9286/89/0400-0386 IEEE

[8] S. Femmam, N.K. M'Sirdi, « Application of change detection technique to ultrasound signal processing. Use of spectral parametric estimation, time-frequency and wavelets », 30th IEEE Southeastern symposium on system Theory (SSST), West Virginia University, Morgantown, WV, USA. Vol.1, pp 203-207. March 8-10, 1998.

[9] G. Whipple, "Low residual noise speech enhancement utilizing time-frequency filtering", IEEE Int. Conf. on Acous., Speech and Sig. Proc., 1, 1994, I/1-I/5.