

Knock Detection Based on MAPO Analysis, AR Model and Discrete Wavelet Transform Applied to the In-Cylinder Pressure Data: Results and Comparison

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ABSTRACT

The easiest way to identify knock conditions during the operation of a SI engine is represented by the knowledge of the in-cylinder pressure. Traditional techniques like MAPO (Maximum Amplitude Pressure Oscillation) based method rely on the frequency domain processing of the pressure data. This technique may present uncertainties due to the correct specification of some model parameters, like the band-pass frequency range and the crank angle window of interest. In this paper two innovative techniques for knock detection, which make use of the in-cylinder pressure, are explained in detail, and the results are compared with those coming from the MAPO method. The first procedure is based on the use of statistical analysis by applying an Auto Regressive (AR) technique, while the second technique makes use of the Discrete Wavelet Transform (DWT). The data useful for the analysis have been acquired on a high compression ratio four cylinder, spark ignition engine. Results demonstrate that the analyzed methods give quite similar outcomes but they also highlight that AR and DWT techniques present an higher sensitivity for soft knock detection. Moreover, both AR model and DWT based method may be applied to the engine block vibrational signals, acquired by low-cost accelerometers. Therefore, they can be implemented within modern on-board control units, in order to execute a real time knock detection allowing to realize more sophisticated spark advance control strategies.

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INTRODUCTION

In recent years, economic and environmental issues have forced engine manufacturers to develop high compression ratio, naturally-aspirated or turbocharged engines of reduced displacement (downsized architecture). Increased boost levels and higher compression ratio may however easily induce abnormal combustion phenomena, like knock. This latter phenomenon consists in a sudden release of energy in the portion of the mixture not reached by the flame front yet (i.e. the so called end-gas). The energy release, due to self-ignition of the end-gas, induces the arising of local pressure waves, starting from the ignition zones and propagating throughout the combustion chamber [1, 2, 3]. In-cylinder pressure fluctuations, due to pressure waves reflection on the combustion chamber's walls, typically occur in the frequency band (5;25) kHz.

As known, uncontrolled knock phenomenon can lead to serious engine damages, like valve deformations and/or fusion of the piston head. For this reason, the spark advance must be

precisely set in each operating condition to prevent knock onset. However, a high knock safety margin turns in a high fuel consumption penalty to be paid. That is why it is really important to detect at the test bench the knock-limited spark-advance determining the first occurrence of soft-knock phenomena [4, 5, 6, 7, 8].

At the current state of art, the easiest way to evaluate the presence of abnormal combustions is represented by the measurement and processing of the in-cylinder pressure, acquired by proper transducers [9]. Specifically, the signal processing consists in capturing the high frequency pressure fluctuations by means of a Fast Fourier Transform (FFT) analysis. Firstly, the pressure trace is windowed within a proper Knock Sensitive Window (KSW). Then it is filtered and rectified within a prescribed frequency band. From the filtered signal, it is then easily detectable the Maximum Amplitude of Pressure Oscillations, constituting the MAPO index. Additional indices

can be also defined, referring to the energy contained in the high frequency pressure oscillations (IMPO) or to the maximum pressure gradient (IMPG) [9].

Whichever is the selected index, an important issue is however always related to the choice of a proper threshold level, over which the knock is judged to occur [10]. Although some indices are extremely valid for detecting high-intensity knock, they may fail in recognizing soft-knock phenomena, usually characterized by a lower signal-to-noise ratio.

In addition, for frequency base methods, it is widely recognized that a variable threshold level should be fixed in different engine operating conditions, and particularly at various engine speeds. At high speed, in fact, the magnitude spectrum of the pressure signal increases, determining an increase of the knock index.

In order to solve some of the above discussed limitations, in the present paper it is firstly proposed a normalization of the MAPO index. In this way a unique threshold level can be specified in the whole engine speed range. Moreover, two different mathematical procedures, namely the Discrete Wavelet Transform [11] and the Auto Regressive model [12], are applied and compared to the well-known MAPO procedure.

The wavelet analysis is a more recent procedure characterized by the so-called multi-resolution property. As better explained in the following, DWT allows to observe high and low frequency signal components with different resolutions. A knock index can be then defined by properly selecting some of the above components. Similarly to the MAPO procedure, however, DWT operates in the frequency domain and, for this reason, a normalization of the related knock index is still required.

The AR technique is indeed another alternative procedure frequently utilized [13,14] to analyze a time series. In an autoregressive model, each sample of the signal is reconstructed as a linear combination of a specified number (model order) of previous samples. In an AR model, firstly, the order has to be selected by means of a proper selection criterion, like the Final Prediction Error (FPE) and Akaike Information Criteria (AIC) [14]. Then, the error of the reconstructed signal is utilized to define an additional knock index. Since the AR model operated in the time-domain, a normalization procedure is, in this case, no more required.

In the following, the background theory of each method is recalled, and their pros and cons are highlighted. Data useful for the analyses and comparisons are provided by an experimental campaign carried out on a four-cylinder, four-stroke, SI engine, operating at full load and in its whole engine speed range.

The results demonstrate that both DWT and AR methods exhibit a higher sensitivity than MAPO in detecting soft-knock phenomena in particular. Last but not the least, both DWT and AR procedures can be more easily extended to the processing

of engine block vibrational signals, acquired by low-cost accelerometers. In this way an accurate and economically affordable real-time on-board knock detection is foreseen [15].

EXPERIMENTAL SETUP

Experimental investigations have been conducted on a small four cylinders port fuel injection, four stroke, spark ignition engine mounted on the test bench. The engine was running at full load and variable speed (ranging from 1496 up to 6250 rpm). The spark advance was set for each speed at knock borderline, identified by a standard MAPO procedure. In-cylinder pressure signals were acquired at a base sampling resolution of 0.5 crank angle degrees (CAD), while a higher sampling rate (0.1°) was applied during the combustion process [-30°,90°]. Acquired data are composed of 300 consecutive cycles for each cylinder and operating condition. In the following, for the sake of brevity, the results obtained with reference to cylinder number one are only presented and discussed, since it showed a more pronounced knock tendency as it is possible to appreciate by observing the zoomed box in Figure 1.

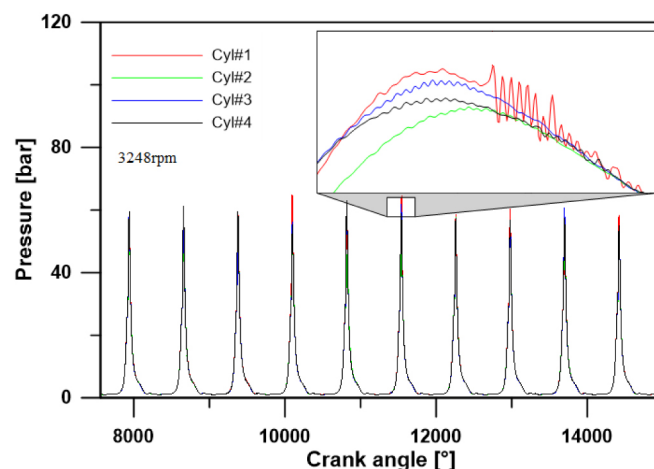


Figure 1. In-cylinder pressure data acquired on the SI engine.

COMBUSTION CHAMBER'S RESONANT FREQUENCIES

As already highlighted, knock essentially consists of sudden self-ignitions of the end-gas. As a consequence, the generated pressure waves may excite the resonant frequencies of the combustion chamber. These latter depend only on the material and geometry of the combustion chamber, and on the speed of sound in the medium. For an ideal cylinder, constituted by acoustically hard flat walls and filled with a homogeneous gas at 2000 K, the expected resonant frequencies are estimated by using the analytical solution of the Draper's equation [5]:

$$f_{r,c} = \frac{a \eta_{r,c}}{\pi B} \quad (1)$$



where f represents resonant frequency, $\eta_{r,c}$ is a non-dimensional number (the integer subscripts r and c denote radial and circumferential mode numbers), a is the Laplacian speed of sound and B represents the cylinder bore. In the previous equation, the axial mode is neglected because knock generally occurs when the piston is just moved beyond the TDC position, and the cylinder axial dimension is negligible. Table 1 lists the $\eta_{r,c}$ values given by Rayleigh [5] while table 2 reports the first vibration modes at the selected combustion temperature.

Table 1. $\eta_{r,c}$ values.

	r=0	r=1
c=0		7,0156
c=1	1,8412	5,3314
c=2	3,0542	6,7061
c=3	4,2012	8,0152
c=4	5,3175	9,2824
c=5	6,4156	10,519

Table 2. Resonant frequencies in KHz of the combustion chamber for each $\eta_{r,c}$ values (first vibration modes).

Resonant frequency [kHz]	f 10	f 20	f 01	f 30	f 40	f 11	f 50	f 51
Theoretical values	7.5	12.4	15.6	17.1	21.7	21.7	26.2	43

It is possible to observe that the resonant frequencies of the engine can achieve high values up to 43 kHz. Nevertheless, in this work, it was found that knock phenomena may excite the combustion chamber's resonant frequencies until 45 kHz.

In order to remark such circumstance, a useful way to observe the frequency range of a predetermined time event is represented by the Time-Frequency Analysis (TFA) of the pressure signal. In fact, it allows to extrapolate the spectral components of a signal in time scales smaller than the duration of the waveform, making possible a time localization of the spectral components [18].

In Figure 2 the TFA of a knocking cycle is reported.

Figure 2 clearly demonstrates that knock event is depicted in the frequency range up to about 45 kHz. Obviously, this result has to be taken into account for successive signal post processing by using the well known MAPO index and the more accurately wavelet based methods for frequency filtering operations.

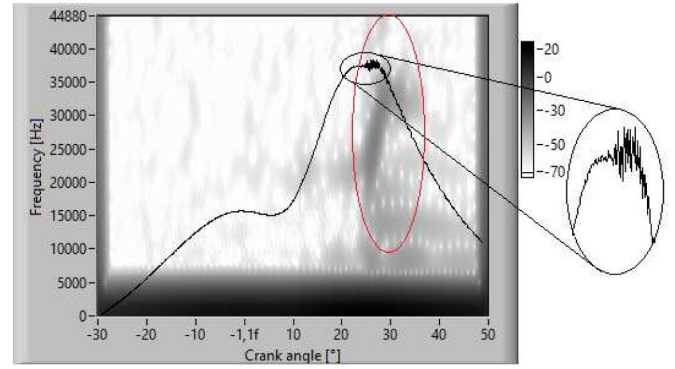


Figure 2. TFA of the 6th cycle at 1496 rpm condition.

Hence, a digital band-pass filter, with cut-off frequencies equal to 6 and 45 kHz, has been used in order to allow the detection of the main knock-related spectral components: the lower cutoff frequency has been set at a quite low level to obtain a negligible signal attenuation at 6 kHz, while the upper cut-off level has been chosen because of the contribution of high-frequency modes found by analytical formulation.

MATHEMATICAL IMPLEMENTATION PROCEDURES

MAPO Based Method

Among all the knock detection methods based on direct measurement and study of inside cylinder parameters (direct methods), commonly used in the literature are those which allow to define the knock indexes MAPO and IMPO [9]. These indices are calculated by processing the in-cylinder pressure signals in the frequency domain through a band-pass filter and they are so defined:

Maximum Amplitude of Pressure Oscillations - MAPO

$$MAPO = \max(|\hat{p}|_{\vartheta_0+\varphi}^{\vartheta_0+\varphi}) \quad (2)$$

Integral of Modulus of Pressure Oscillations - IMPO

$$IMPO = \frac{1}{N} \sum_{i=1}^N \int_{\vartheta_0}^{\vartheta_0+\varphi} |\hat{p}| d\vartheta \quad (3)$$

In the two definitions above, N is the number of samples contained in the window of calculation, ϑ_0 is the crank angle corresponding to the beginning of the window of calculation, φ is the width of window of calculation, $\hat{p}$ is the filtered in-cylinder pressure.

According to equation 2, MAPO is defined as the maximum of the filtered pressure signal absolute value, calculated within a crank angle window including the combustion and therefore is related to the peak of the pressure oscillations due to engine knock; IMPO is the integral of the filtered pressure signal.

absolute value also calculated in a proper crank angle window including the combustion and represents the energy contained in the high frequency oscillations of the cylinder pressure signal.

Starting from these two knock indices, a more general knock indicator namely DKI (Dimensionless Knock Indicator) can be introduced:

$$DKI = \frac{IMPO}{MAPO \cdot \varphi} \quad (4)$$

DKI represents the ratio between two values that can be interpreted as two surfaces. In particular, IMPO is the surface under the pressure signal whereas the quantity $MAPO \cdot \varphi$ is the surface of the computational window. Specifically DKI represents an “image” of the knock intensity, which is calculated taking into account the “noise” before the auto-ignition. It is known that DKI value decreases with the increase of knock intensity whatever are the engine geometrical characteristics and settings [9].

In the present work the above defined indexes have been calculated for all the 300 consecutive in-cylinder pressure cycles for each cylinder and at each investigated engine speed condition, by using the commercial software Matlab. However, as previously stated, more attention has been focused only on cylinder 1 that has been identified as the most detonating cylinder. Firstly, the pressure signal related to each in-cylinder cycle, calculated in a window including the combustion phenomenon $[-30^\circ, 90^\circ]$, has been filtered using a high-pass filter characterized by a cut-off frequency of 6 kHz. Then the filtered signal has been properly processed to obtain the value of MAPO and IMPO indices.

As an example, in Figure 3 the graphs that describe the indexes calculation adopted procedure for one condition are shown, in particular for the cycle 77 of the cylinder 1 at 5747 rpm. In these conditions the graphs show the presence of a heavy knock phenomenon.

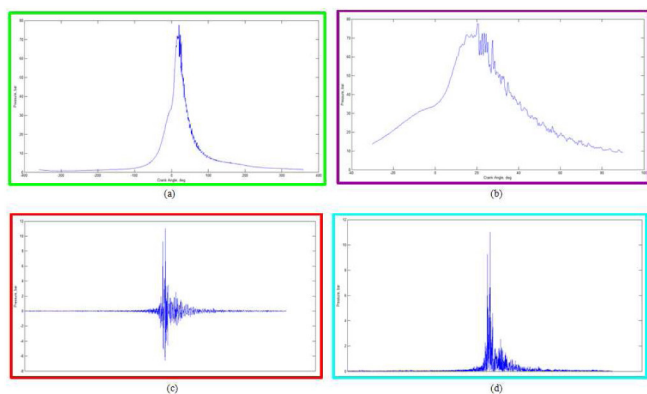


Figure 3. Flowchart to calculate the knock indexes for one of the analyzed cases. (a) Signal Input. (b) Windowing. (c) Filtering. (d) Absolute value.

The obtained results (not shown for brevity) have demonstrated higher sensitivity of MAPO index in respect of the other above mentioned indices. In fact, IMPO does not allow to distinguish between heavy and soft knocking cycles whereas DKI provides partial information. For this reason, MAPO based method has been chosen in order to develop the comparison with the other implemented mathematical procedures, discussed in the following paragraphs. The overall outcomes, in terms of MAPO versus engine speeds, are shown in Figure 4.

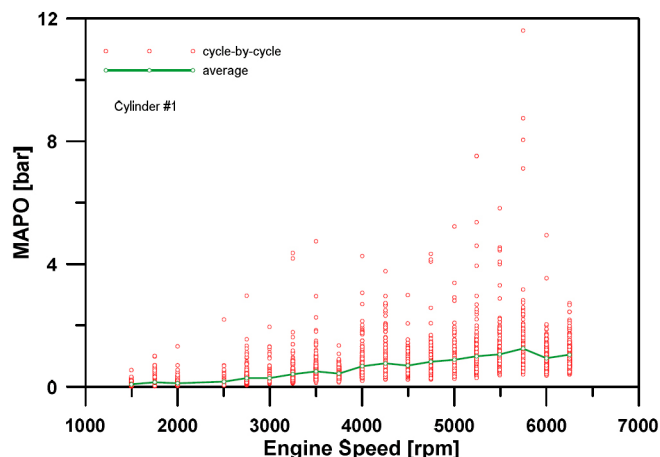


Figure 4. MAPO values at different investigated engine speeds.

In Figure 4, it is possible to note a progressive increment of the index values as speed increases. Such circumstance does not allow to define a constant threshold level. A more clear explanation of this circumstance is related to FFT spectrum of the pressure signal. When the engine speed grows up, the magnitude spectrum of the pressure signal is shifted towards higher frequencies. This is highlighted in Figure 5, which shows the amplitude spectrum of two pressure waveforms corresponding to two knocking cycles at different values of engine rpm.

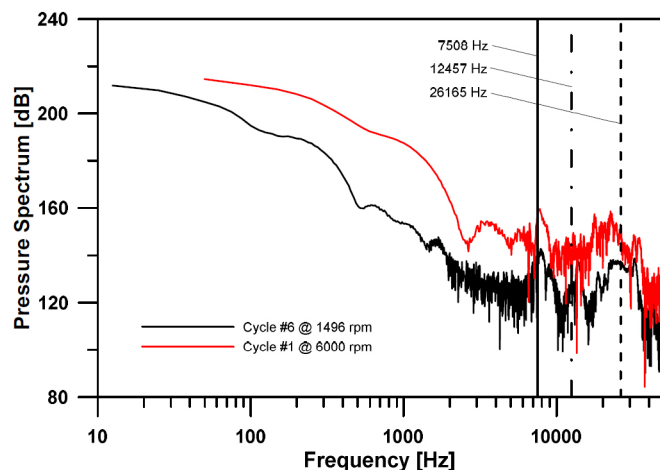


Figure 5. Comparison between the amplitude spectrum of cycles for two different engine speed conditions.