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Knock detection in SI engines by using the Discrete Wavelet Transform of the engine block vibrational signals

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Abstract

In the present work, the Discrete Wavelet Transform (DWT) has been applied on the vibrational signals acquired by an accelerometer placed on the cylinder block of a Spark Ignition (SI) engine, for detecting knock phenomena. In order to collect both vibrational data and in-cylinder pressures, useful for the analysis, a series of experiments on a four cylinder, four stroke Internal Combustion (IC) engine has been carried out. The obtained results show how the presented knock detection algorithm is able to monitor the goodness of the combustion phase in absence of knock phenomena, and otherwise to determine its intensity. This algorithm uses a Multi-Resolution Analysis (MRA) performed on the vibrational signals of the engine block as acquired. The same kind of analysis has been executed by using the traditional index MAPO, which is widely applied on the pressure data, and the results of the two methods have been compared. The comparison, showing how the results are very similar, confirm that the use of the DWT represents a very valid alternative to the traditional knock detection techniques.

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Keywords: Knock, Engine, Wavelet, MRA, MAPO, Vibration analysis

1. Introduction

An Internal Combustion (IC) engine is a thermal plant, thanks to which the chemical energy of the fuel is converted into mechanical energy. With reference to the Spark Ignition (SI) engines, the combustion occurs due to the triggering of a spark between the spark plug electrodes, which gives rise to the propagation of a flame front. In this category of IC engines, the combustion is said to be normal if it is triggered by the spark plug and propagates "gradually" in the entire combustion chamber. The combustion stage strongly affects engine power, fuel

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consumption and noise emissions and, if not controlled, an abnormal combustion like knock may occur. The knock consists of a sudden release of energy in the portion of the mixture not reached by the flame front yet (the so-called end-gas). In an engine which runs in knock conditions, a series of pressure waves caused by the sudden releases of energy are associated, at the end of the combustion phase, with a gradually decreasing amplitude. These pressure waves are repeatedly reflected by the walls of the combustion chamber and the cylinder barrel. These vibrating surfaces, caused a beat outside so-called knocking. These pressure oscillations have a frequency band which ranges approximately in [5-25] kHz but, as it will point out in the following, it may excite the combustion chamber resonant frequencies, [13].

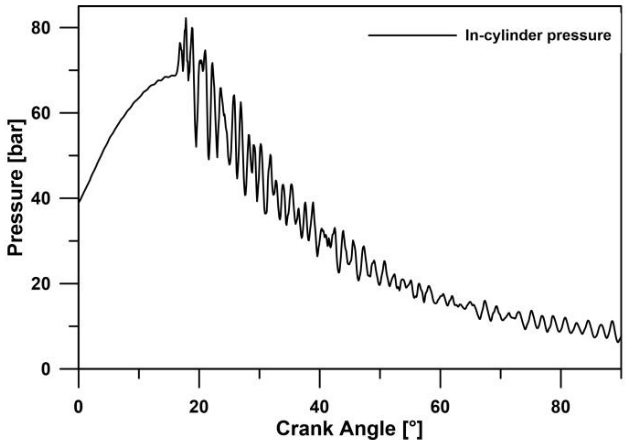


Fig. 1. Knocking cycle.

In Fig. 1, an example of knocking cycle is depicted. Engine knock is probably the most difficult phenomenon to be recognized by the control system and, if left untreated, a series of drawbacks will occur. Firstly, the strong pressure oscillations, caused by the self-ignition of the end-gas, break the film of lubricant placed on the cylinder walls, with consequent increase in the coefficient of heat transmission, then a loss of thermal energy that is removed from the cooling circuit instead of ennobling in work. This leads to an increase of friction during relative motion between piston and cylinder, which causes a dissipation of mechanical energy into thermal energy, with subsequent decrease in the mechanical efficiency. Besides, thanks to the increase of mechanical stresses of the engine in a condition of knock, if prolonged, this can also lead to valve damage, mainly due to increased cylinder temperature, and the fusion of the piston head. The most common used engine parameters for bounding knock phenomena are the compression ratio and the Spark Advance (SA). The lower these parameters, the better avoided are knock conditions. However a low values of the engine compression ratio and SA, strongly reduce the efficiency and the power output of the engine. Therefore, once fixed the compression ratio, a good control system must be able to detect knock phenomena, in order for the engine to work with optimal Spark Advance. Many methods for knock detection have been proposed in current literature. The most useful and valid instrument for identifying the occurrence of detonation during the operation of an SI engine is represented by the knowledge of the in-cylinder pressure. This can be acquired through the use of piezoelectric transducers which, due to their high frequency response (of the order of 1kHz), are able to monitor pressure changes very fast. The cylinder pressure data provide a direct and reliable way to analyze knock. In general cylinder pressure signals are analyzed by an on line system to compute knock indices. The major used indices are called MAPO (Maximum Amplitude of Pressure Oscillations) and IMPO (Integral of Modulus of Pressure Oscillations), [1].

The first represents the maximum peak of pressure oscillations, while the second one is an index of energy intensity which refers to the fluctuations in pressure due to knock. Although these indices are extremely valid, the direct measurement of the pressure cycle implies a series of drawbacks which make its use impossible when the vehicle is marching. Firstly, the installation of the sensor in the combustion chamber constitutes a disturbance of the measurement environment, as alterations of mixture ratio may occur. Besides these sensors are very expensive and, being exposed to high pressures and temperatures, they result little durable. For these, and other reasons, various indirect techniques have been gradually developed, and most of these use vibrational signals detected by accelerometers. These sensors are characterized by the fact that they produce signals with a low signal-to-noise ratio but, at the same time, they are cheap, very little and can be easily placed on the engine block. Moreover, due to their external location, the accelerometers are more durable than the piezoelectric ones. At the current state of art, there are two types of methods for processing vibrational signals: parametric and non-parametric. The first rely on a parametric representation of the signal through a mathematical model by which it is possible to extrapolate the indicators of the knock, e.g. the ARMA model (Auto Regressive Moving Average), [2],[13]. In this model, the engine is represented as the studied system whose output is the signal acquired on the engine block; then, from the model, parameters to be studied are extracted. Whatever change of the operating conditions of engine will cause the change of some ARMA parameter and, therefore, depending on the type of change, the variation will be different. By monitoring these parameters it is possible to establish the occurrence of knock. As regards the non-parametric methods, these rely on representations of the energy associated to the vibrational signal as a function of time and frequency. For example, such methods use transformations such as the discrete Fourier transform, the wavelets[4][5][6][7][8][9] etc.. Fourier based methods monitor the power spectrum of a resonant frequency specific to an engine and when the power spectrum exceeds a threshold value, the knock is judged to occur. However, since resonant vibrations may occur even in normal combustion, due to many factors, a method which compare data about the present combustion and data about several combustions in the past is executed. In this way a detection delay occurs, undermining control strategies specially in acceleration conditions, [12],[14].

In this work a new methodology, which is based on the Discrete Wavelet Transform (DWT) of the cylinder block vibration signals as acquired, has been used. A series of experiments on a SI engine has been carried out. Three different conditions have been tested, at constant speed, with Spark Advance variations in order to produce no-knock/knock cases. During the tests, pressure, vibrational and tachometer signals have been acquired. The latter has been useful to extrapolate the thermodynamic cycles from each set of acquired data. After tuning the presented method a Knock Index (KI) have been defined. A sensitivity analysis has been carried out to establish, by viewing the KI, when knock occurs. The pressure signal was used to calculate the index MAPO, in order to compare the results coming from the two methodologies.

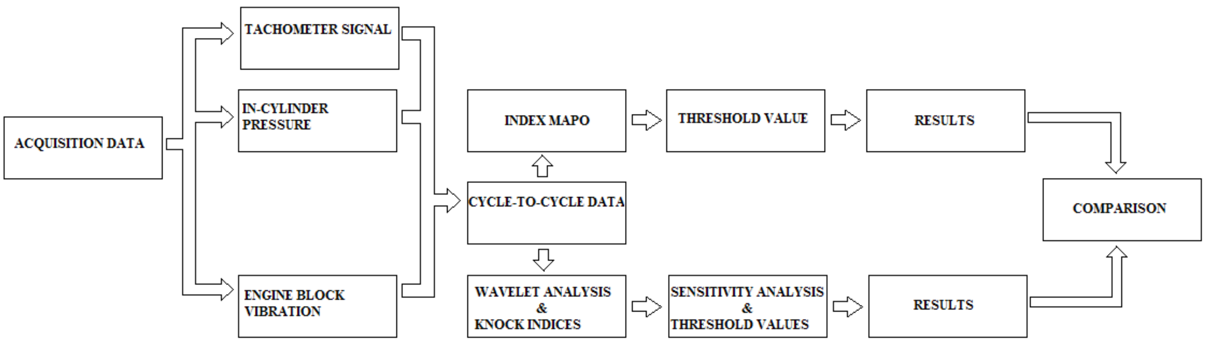


Fig. 2. Schematization of the presented work.

In Fig. 2 a flux diagram of the present work is depicted. From the comparison between the two methods it is clear how the results are almost the same, testifying the goodness of the presented knock detection algorithm. In the following, a brief description about the experimental campaign is given.

Nomenclature

IC engine	Internal Combustion engine
SI engine	Spark Ignition engine
SA	Spark Advance
MAPO	Maximum Amplitude of Pressure Oscillations
IMPO	Integral of Modulus of Pressure Oscillations
ARMA model	Auto Regressive Moving Average model
DWT	Discrete Wavelet Transform
KI	Knock Index
BTDC	Before Top Dead Centre
TFA	Time-Frequency Analysis
STFT	Short Term Fourier Transform
EVC	Exaust Valve Closening
EVO	Exhaust Valve Opening
TDC	Top Dead Centre
KSW	Knock Sensity Window
MRA	Multi-Resolution Analysis

2. Tests program and experimental setup

In order to verify the goodness of implementation of KI index, a set of experimental data has been planned. For this purpose, a four stroke SI engine, four-cylinders, has been chosen. More precisely, several block vibration, pressure and tachometer signals have been acquired at constant speed. Following, the table with the acquisition tests is reported.

Table 1. Tests carried out on the spark ignition engine.

rpm	ST	Cycles number	Pressure sensor	Vibrational sensor	Tachometer sensor
1500	-15	400	✓	✓	✓
1500	-20	400	✓	✓	✓
1500	-25	400	✓	✓	✓

In order to tune the used methodology, the in-cylinder pressure has been used since it is well known that knock is easily distinguishable by in-cylinder pressure oscillations. The data have been acquired over a range of operating conditions with the Spark Advance variations, in order to induce knock. In fact, increasing the SA, the pressure of the end-gas increases, by virtue of the major compression exerted by the piston on the end-gas when the spark is triggered between the spark plug electrodes. The experimental acquisition is, finally, composed by more than 400 thermodynamic cycles for each investigated conditions; clearly, for brevity, only some results will be shown. The engine was running at constant speed of 1500 rpm and Spark Advance has been varied from 15° BTDC to 25° with two steps of 5°, in order to realize knock and no-knock condition.

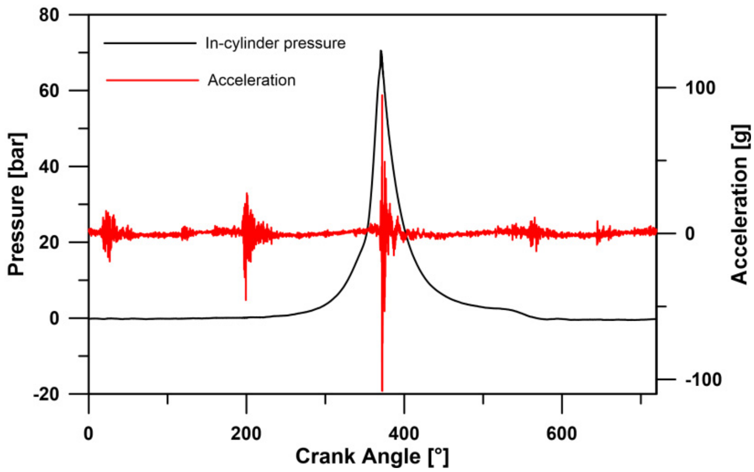


Fig. 3. Example of acquired data.

Fig. 3 shows an example of the acquired data. Due to problems of layout, the accelerometer has been placed on the head of a cylinder which was close to the joint for the tests with the engine to be motored. Therefore the signal coming from the engine block had an another noise component because of the location of the sensor. The engine has been connected to an electrical generator, which monitored the speed of 1500 rpm. As regards the acquisition, this has been carried out using SCADAS III built by LMS Instruments. The tests have been conducted by acquiring simultaneously in-cylinder pressure and vibrational sensor, triggered with tachometer. In all of the experiments, the sampling frequency was fixed equal to 45 kHz. The accelerometer used during the tests is manufactured by PCB Piezotronics, and its serial number is 12337. Subsequent to the execution of the previously mentioned tests, in order to perform the knock detection, and the manipulations of the acquired signals, the software Labview of National Instrument, 2012 version, has been used. In Fig. 4, a schematization of what above is represented.

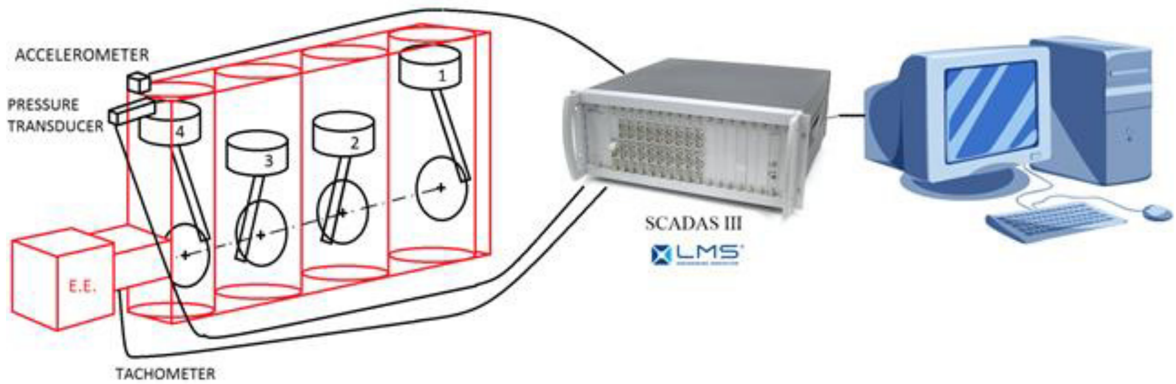


Fig. 4. Schematization of the test's layout.

In the next paragraph a brief summary of theoretical aspects which lie behind the MAPO methods and the Discrete Wavelet Transform is given.

3. Theoretical aspects

3.1. The time-frequency analysis

The Time-Frequency Analysis (TFA) achieves the study of non-stationary signals, in which the spectral components change over the time. The Short Term Fourier Transform (STFT) is one of the mathematical artifice which allows to perform TFA. The main difference between the discrete Fourier transform and the STFT is that the latter divides the signal into pieces small enough to consider these portions as stationary; in order to obtain this, a window function whose length must be equal to the length of the portion of the signal assumed to be stationary is chosen. In this way it is possible to derive the trend in different Δt of the spectral components of the signal. Therefore, the STFT is a function of time and frequency which indicates how the spectral components evolve throughout the duration of the acquired waveform. The Short Term Fourier Transform of a continuous function is defined mathematically as[11]:

$$STFT(\tau,\omega) = \int_{-\infty}^{+\infty} f(t)w(t-\tau)e^{-j\omega t}dt \quad (1)$$

in which usually the window function satisfies the condition:

$$\int_{-\infty}^{+\infty} w(\tau)d\tau = 1 \quad (2)$$

The main advantage in the use of the Short Term Fourier transform lies in the fact that it is extremely quick and simple to compute. Nevertheless, there is an important limitation in the use of the STFT represented by the fact that it is not possible to obtain simultaneously a good time resolution and frequency resolution. The type of used window affects both resolutions, in fact a small window has an excellent temporal resolution, thanks to its compact support, but a poor frequency resolution due to the large bandwidth in the frequency domain. Conversely, a large window has excellent frequency resolution, but poor temporal resolution, although it might violate the stationarity condition of block of the windowed signal. The optimal length of the window depends on the characteristics of the signal to be analyzed. It should be small enough so that the block of the windowed signal is practically stationary in the windowed interval, but, at the same time, it should be large enough so that the Fourier transform of the block provides a good frequency resolution.

In this work, the TFA of the engine block vibrational signals has been used to establish the exact frequency band the knock may affects. In this regard, Figure 5 shows the TFA of the vibrational signal corresponding to a knocking cycle to which the pressure waveform has been superimposed.

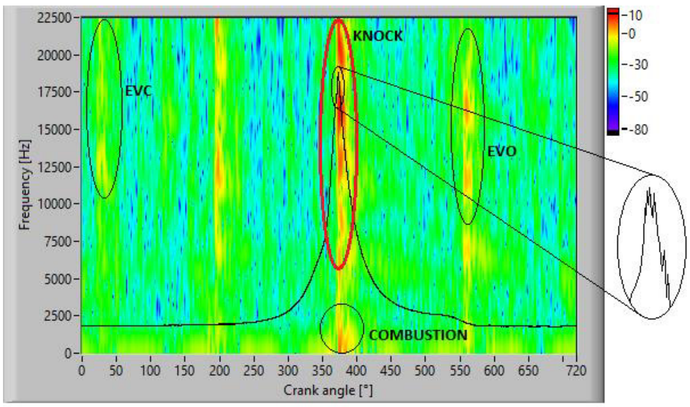


Fig. 5. Time-Frequency Analysis of the engine block vibrational signal belonging to the 100th cycle, acquired with SA equal to 25°BTDC.

As it is possible to note from Fig. 5, the use of the TFA allows to recognize various excitation vibrational sources like EVC, EVO etc.. Besides, it is important to highlight that, for the tested engine, knock may affect the frequency band [6- 22,5] kHz. However, the upper limit is fixed by the sampling rate, because it is known that knock may excite the resonant frequency of the combustion chamber, which may reach very high values [13]. Nevertheless, in this work, that aspect is not taken into account because the sampling rate has been fixed to 45 kHz.

3.2. MAPO based method

As recalled, the best method which achieves to monitor the combustion phase is represented by the knowledge of the in-cylinder pressure. In fact, it allows to simply calculate various index for identifying knock phenomena. The most powerful and used knock index based on the pressure data is the MAPO. It is defined as follows:

$$\mathrm{MAPO} = \max\left(|\hat{p}|_{\vartheta_0}^{\vartheta_0+\varphi}\right) \tag{3}$$

where p̂ is the in-cylinder pressure filtered within a knock-related crank-angle window, starting at ϑ_0, with width equal to φ. The number of samples contained in the above interval is N. Basing on the above definition, MAPO measures the Maximum Amplitude of Pressure Oscillations within the frequency band of interest. For the MAPO calculation, the used flux diagram is reported in Fig. 6.

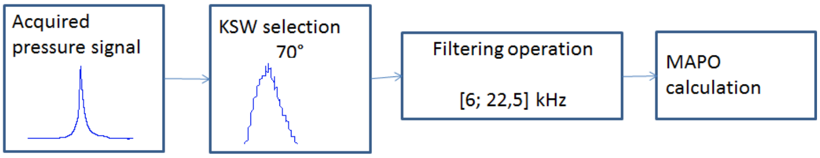


Fig. 6. Schematization of the MAPO calculation algorithm.

In particular, for MAPO calculation, a high-pass filter characterized by a cut-off frequency of 6 kHz is adopted, as suggested by Figure 5. In order to monitor the goodness of the combustion phase in the absence of knock phenomena, it is possible to observe only a particular zone of the thermodynamic cycle, namely that which is over the Top Dead Centre (TDC) after the first revolution of the crankshaft (in the case of 4-stroke engine). Therefore it is appropriate to select a Knock Sensity Window (KSW) of the acquired signals to reduce the amount of data necessary for the post-processing. The choice of KSW is very important in order to obtain reliable results. In literature there are various opinions proposals in this regard[10]. However, having available in this study vibrational signals, with the help of the trigger signal and from the knowledge of the sampling frequency, the pressure waveform is windowed with a 70° crank angle window starting at the SA, in order to analyze only the combustion process, as depicted in Fig. 7.

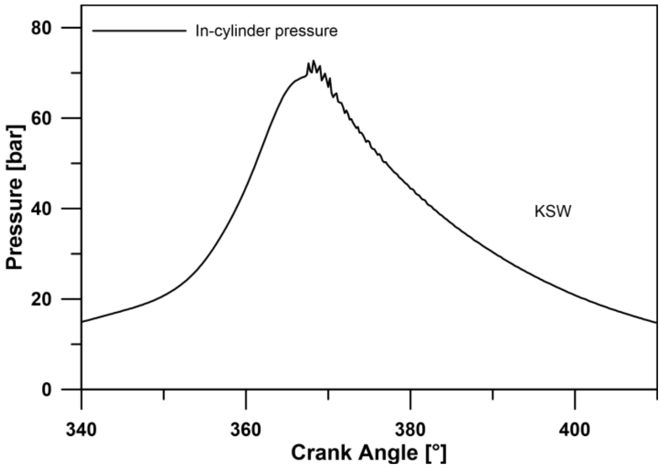


Fig. 7. Knock Sensity Window for the case in which the SA is equal to 25° BTDC.

As regards the results, the overall outcomes, expressed in terms of MAPO index versus the Spark Advance, are shown in Fig. 8 For clarity of the plot, only the first 100 cycles, in each investigated conditions, are shown.

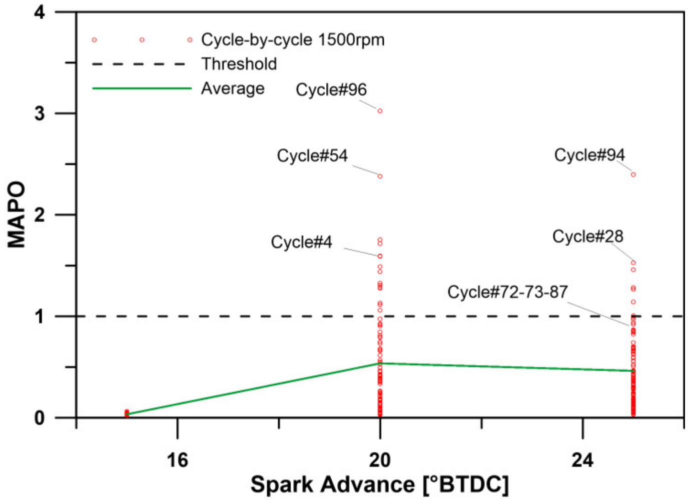


Fig. 8. MAPO values at different SA.

More precisely, in order to distinguish no knock/knock cases, the threshold has been fixed equal to 1 bar. In this way, when MAPO index is higher than 1 bar, the knock is judged to occur. The first thing which comes out from Figure 6 is that only in the running condition with SA equal to 15°BTDC no knocking cycles have been found. Such circumstance is to be expected since the greater the Spark Advance, the greater compression of the piston on the end gas during the combustion, and so higher pressure and temperature are reached. Moreover, it is also clear that as the MAPO index increases above the fixed threshold, the knock phenomenon becomes more pronounced as depicted in Fig. 9, in which two of the cycles indicated in Fig. 8 are depicted.

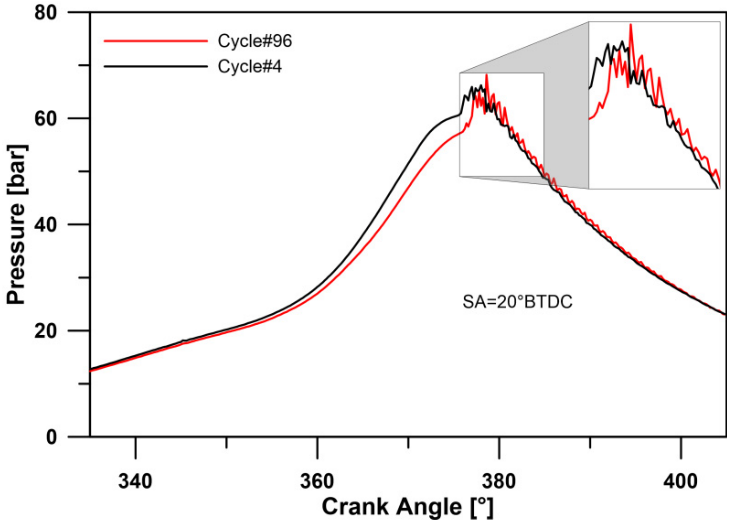


Fig. 9. Pressure waveform of cycle# 4 and 96, both acquired with SA equal to 20°BTDC.

By the observation of Fig. 9, it is clear that as the MAPO increases, the pressure oscillations become more pronounced. In fact, it is evident that cycle 96 is characterized by greater pressure oscillations which last more, as it is expected considering the high value of the MAPO in Fig. 8.

In conclusion of this paragraph, it is clear that MAPO based method allows to correctly recognize strong knock phenomena.

3.3. The Discrete Wavelet Transform and Multi-Resolution Analysis

The Discrete Wavelet Transform is more suitable then the classic Fourier analysis for analyzing both low and high frequency phenomena within a signal [3]. In particular, by using this methodology, a so-called Multi-Resolution Analysis (MRA) is realized. High frequency phenomena are analyzed in fact with high time resolution and poor frequency resolution, while the contrary happens for low frequency events.

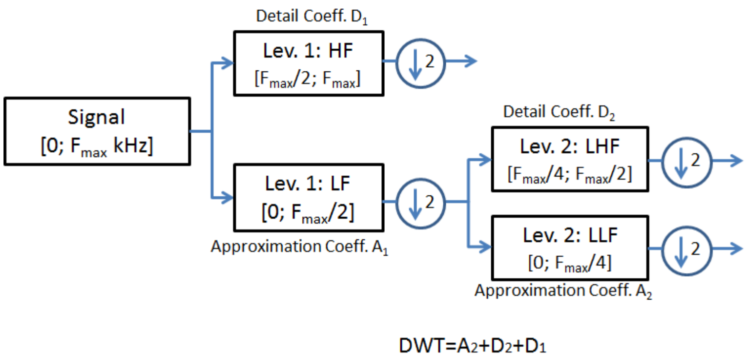


Fig. 10. Schematization of the MRA performed with the Discrete Wavelet Transform at two decomposition levels.

MRA is effected carrying out a decomposition of the original signal. Each decomposition level is constituted by a couple of low- and high-pass filters (LF, HF) as schematized in Fig. 10. Each filter allows to analyze half spectral bandwidth within the input signal (Fmax). The latter, according to the Nyquist's law, is equal to half of the sampling rate. Hence, at the output of each filter, half samples became redundant and can be discarded without loss of information. At each decomposition level, this process halves the time resolution, since only half samples characterizes the entire signal, but doubles the frequency resolution, since the spectral band of the signal is halved. The LF coefficients, regarding low frequencies, only characterize the general structure of the signal, (approximation coefficients, Ai). On the other hand, the HF output includes information on rapidly changing high frequency events (detail coefficients, Di). The Discrete Wavelet Transform of the entire signal is obtained by the concatenation of all the coefficients from the last level of decomposition; the number of coefficients will be equal, thanks to the operation of sub-sampling, to the number of samples of the starting signal. In it, the most important frequency components will result in a high amplitude of the coefficients of the DWT in the region which includes these components. The spectral components, which are not very prominent in the starting signal, will result in a low amplitude of the DWT coefficients and therefore these portions of the DWT can be discarded without loss of information, reducing the computation time; this is what a Multi-Resolution Analysis allows.

In this study, the Discrete Wavelet Transform, through which a MRA of the engine block vibrational signal is executed, has been used for knock detection purposes. The scheme of the presented algorithm is represented in Fig. 11.

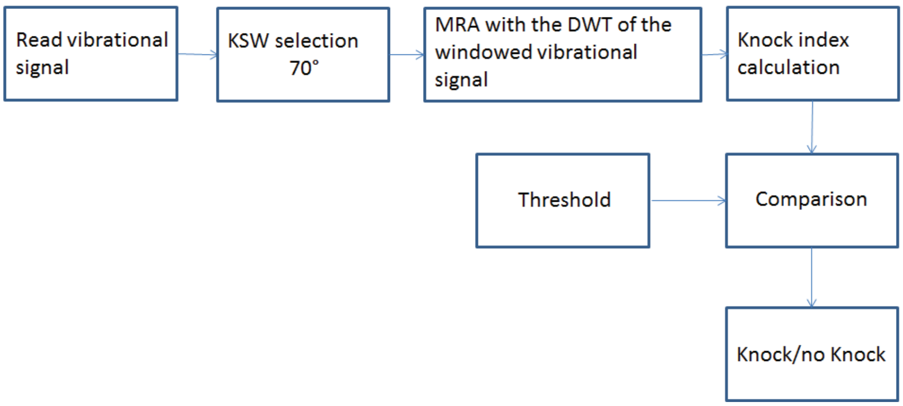


Fig. 11. Schematization of the knock detection algorithm.

Regarding the windowed operation of the signal, the KSW has been chosen similarly to the MAPO case. Therefore, the number of samples contained within the windowed vibrational signal is 350, like the number of DWT coefficients.

As regards the analysis, since the highest frequency which is present within the signal coming from the accelerometer is 22,5 kHz, two levels of decomposition have been chosen, as it is shown in Fig. 12.

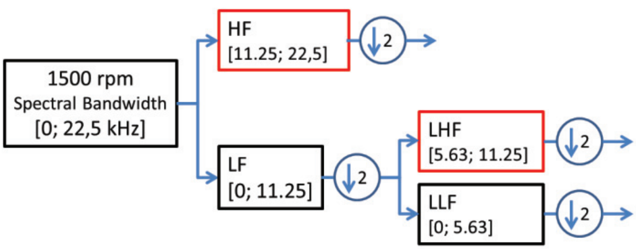


Fig. 12. Decomposition level of the Multi-Resolution Analysis.

Consequently, as it has been proved (see Fig. 5) that the knock phenomenon may interest the frequencies in the approximate range [5; 23] kHz, it is only necessary to monitor the DWT detail coefficients belonging to the first and second level of decomposition. In literature various indices are proposed for the knock[7][9], but since the higher the amplitude of DWT coefficients in a fixed decomposition level, the greater the intensity of the corresponding frequency components within signal, in this work it has been decided to use a parameter defined as follows.

$$KI = \sum_{i=1}^{2} D_{i,max} \quad (4)$$

In particular, the Knock Index is obtained by summing the maximum value of the DWT coefficients D1 and D2.The Threshold level has been fixed equal to 65. In Fig. 13 the results of the knock detection are reported similarly to Fig. 8.

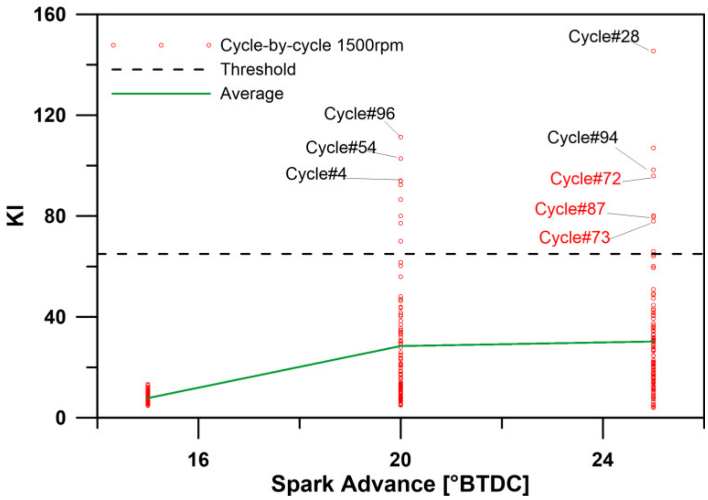


Fig. 13. KI values at different SA.

From the examination of Fig. 13, and comparing it with Fig. 8, it is clear how the results coming from MAPO based method and the Discrete Wavelet Transform are almost the same. In particular for both techniques, no knocking cycles have been found when the SA has been fixed equal to 15°BTDC. Moreover, when the SA is equal to 20° BTDC, the strongest cycles are the same. The main differences regard the third investigated case, when the SA has been fixed to 25° BTDC. In particular, for DWT based method cycle#28 has a strongest knock phenomenon than cycle#94, whilst the contrary happens for MAPO index. Fig. 14 shows the in-cylinder pressure of the two above mentioned cycles.

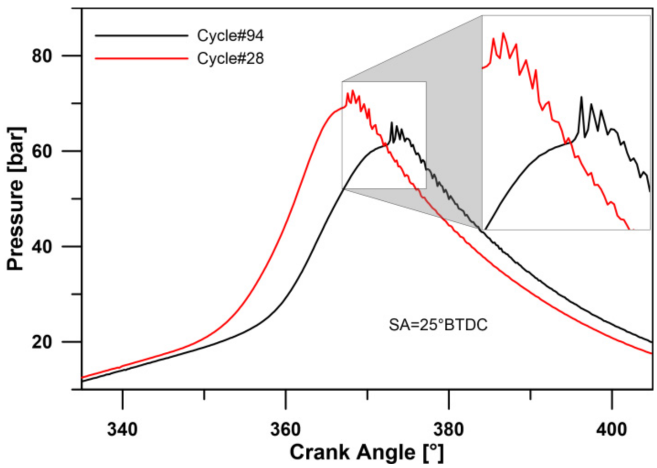


Fig. 14. In cylinder pressure of cycle 28 and 94, both acquired with SA equal to 25°BTDC.

As it is possible to observe from Fig. 14, the pressure oscillations of cycle 28 are more pronounced and durable than those corresponding to cycle 94. This kind of error is due to the way in which the MAPO is calculated. In fact, the higher amplitude of the pressure oscillation, the higher the MAPO. However it is possible that the knock causes only one high pressure oscillation and then the MAPO will be high, whilst the index KI will be not high. Conversely, if in the pressure waveform there are many little oscillations the MAPO will be not high, while the index KI will be relatively high. The MAPO definition, may cause another knock detection error represented by the possibility of failing in soft knocking cycle detection. In fact, by comparing Fig. 8 and Fig. 13, it is clear that MAPO method is not able to detect cycle 72,73 and 87 (SA=25° BTDC). This three cycle are indicated in red in Fig. 13, and the corresponding three pressure waveform are shown in Fig. 15.

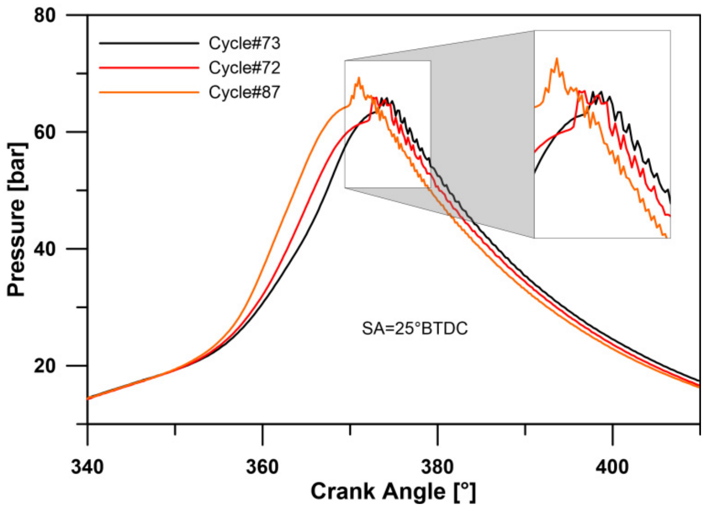


Fig. 15. Pressure waveforms of the three cycles which are indicated in red within Fig. 11.

Once again, this kind of error is due to the way in which the MAPO index is calculated. Indeed, the Maximum Pressure Oscillation of the in-cylinder pressure, has only a local meaning and cannot represent the intensity of the overall knock phenomenon.

From what above, it has been demonstrated that the use of the Discrete Wavelet Transform may be a very powerful tool for knock detection purposes, mainly due to the higher sensitivity and the fact that the DWT is applied to the engine block vibrational signals which are easily collectable on the engine block. In the next paragraph a more deep comparison with the results coming from the two presented techniques will be given.

4. Comparison with the index MAPO

As previous highlighted, the easiest way to detect knock is represented by the use of in-cylinder pressure which allows to monitor, for example, the index MAPO. However, this method has a series of drawbacks, e.g. it is impossible to perform when the engine is marching because it would be necessary to locate the pressure transducer within the combustion chamber. Therefore, in this study a knock detection has been carried out using the vibrations of the cylinder block. Indeed, this is a more cheap way to monitor the progress of the combustion phase, because of the lower cost of the accelerometers and their more durability. In order to verify the goodness of the presented algorithm, the knock detection has been carried out on the same data coming from the SI engine, using the index MAPO, which is commonly used for executing knock detection having available the in-cylinder pressure. In Fig. 16, the results of the knock detection carried out with the two techniques are reported as percentage of knocking cycles, in each tested condition.

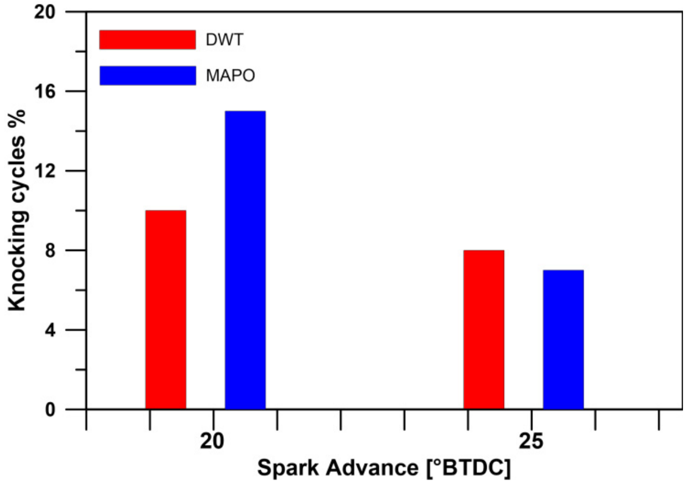
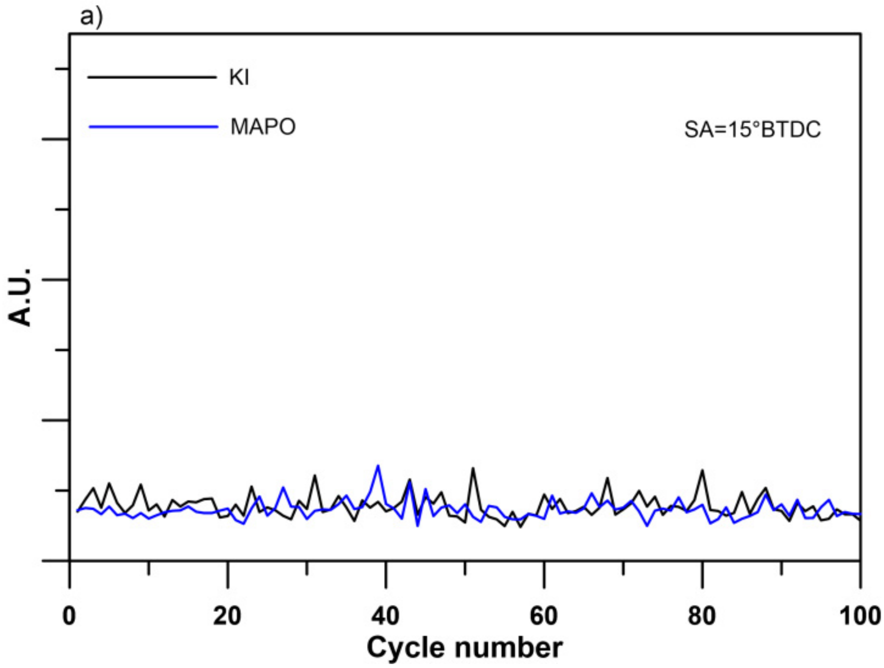
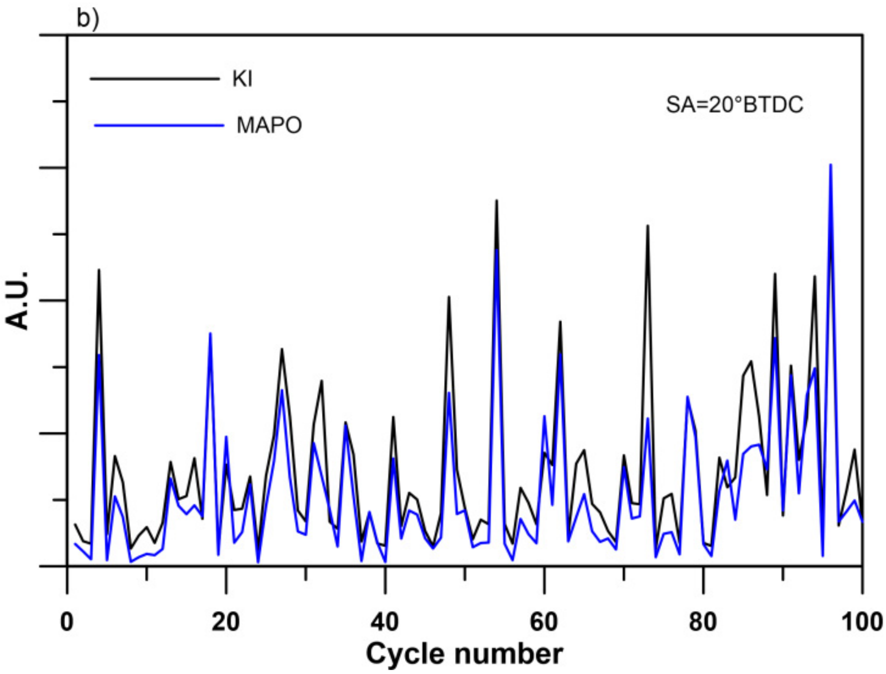


Fig. 16. Percentages of knocking cycles calculated with the two presented procedures.

As it is possible to appreciate by the examination of Fig. 16, the percentages coming from the two methodologies are very close. This testify the goodness of the presented DWT based algorithm. A direct comparison among the two calculated indices is reported in Fig. 17 (a), (b) and (c), for the first 100 engine cycle and at three different Spark Advances.


a)
KI
MAPO
SA=15°BTDC
A.U.
0
20
40
60
80
100
Cycle number


b)
KI
MAPO
SA=20°BTDC
A.U.
0
20
40
60
80
100
Cycle number

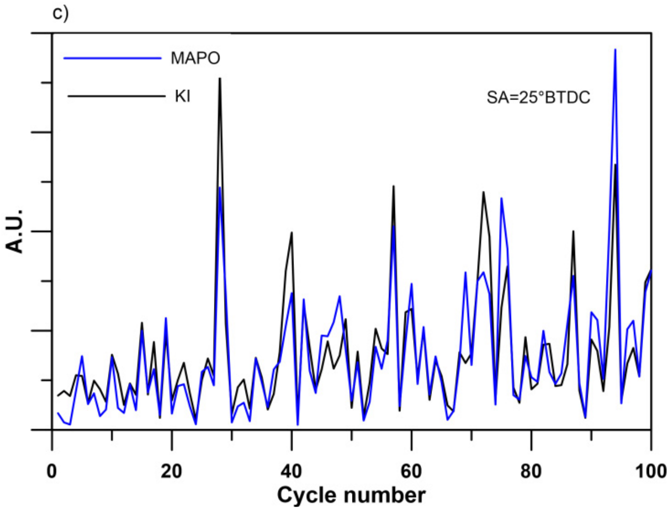


Fig. 17. Trend of the two knock indexes as function of the cycle number at three SA conditions.

From the previous figures, it is possible to appreciate a very good agreement between the two used. From figure 17, it is possible to point out that, both MAPO and DWT based methods, are able to detect the same knocking cycles. Obviously, has already discussed in the previous paragraph, the index MAPO can fail in recognizing soft events. On the other hand, by the observation of Fig. 17 b) and c), a higher sensitivity of the index KI is also confirmed. Such evidence, in spite of the fact that the calculation of the index KI requires a more robust mathematical implementation, makes the possible future implementation of the DWT procedure within control units a very powerful tool for on-board knock control strategies.

5. Conclusions and future developments

In this work a knock detection has been successfully performed on a four stroke SI engine, multi-cylinders, by using the cylinder block vibrations coming from an accelerometer placed on the engine head. This has been achieved by using the Discrete Wavelet Transform, which have proved to be the most appreciate among non-parametric methods, and allows to observe both high and low frequency phenomena simultaneously. The data useful to validate the analysis have been collected by monitoring three different running conditions, at constant speed with Spark Advance variations. By executing a Multi-Resolution Analysis with two decomposition levels on the vibrational signal as acquired, a Knock Index have been found. It has demonstrated, that the higher the amplitude of this index, the more intensity of knock phenomena. To strengthen that, a comparison between this method and the traditional, widely used, index MAPO have been made. From the confrontation, it is clear that the two methods give almost the same results.

Future developments could regard the possibility of the implementation procedure in run-up condition.

Indeed, in order to demonstrate the capability of the implementation for the knock detection, it is necessary that the algorithm is executed in an extremely short time interval, to allow the execution of corrective strategies.

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