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Review on Methodologies Used for Knocking Detection and Intensity Evaluation in Internal Combustion Engines

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Abstract: Extracting the knocks characteristics is the key of ignition control in auto-ignition compression engines, especially those severely suffered from abnormal consumption in the engine chamber. Most of the advanced detecting methods of knocking are generally related to the two main variables, including engine cylinder pressure signals and the engine cylinder block vibration signals, commonly measured using piezoelectric accelerometer sensors. Being familiar with different approaches capable of determining the engine knocking occurrence probability as well as providing suitable methods for knock intensity evaluation is significantly helpful to propose a comprehensive predicting model for measuring the level of oscillation pressure waves frequencies originated by the knocks. Following by predicting the knock intensity and extracting the knock feature, optimizing the engine operation in terms of fuel consumption, thermal efficiencies, and lifetime duration would be possible. For this aim, the current paper is addressed with overviewing upon the researches performed in the regard of developing high accurate models and optimized knock detection approaches.
Keywords: auto-ignition, Internal combustion engine, Knocking detection approach, Knock intensity evaluation.

I. INTRODUCTION

Recent developments of the internal combustion engines were mostly addressed on reducing the fuel consumption and providing high torque output. To achieve this goal, the compression ratio has to be increased, which leads to improving the engine's thermal efficiency. Engine manufacturers are obligated to follow the global standard-based approaches to increase the target compression ratio together with aggressive utilization of harsh-conditioned operations [1-3]. Although engine operation in such conditions is preceded by growth in unburned gas pressure and temperature, thermal efficiency improvement of the engine would raise the probability of knocking in the engine [3]. Knock is considered energy released from auto-ignition of the air-fuel mixture in the engine combustion chamber resulting from the local increment of pressure and temperature, which occurs fast in front of a turbulent flame spread, causing irrecoverable damages in the in-cylinder components. The resulted knocks would directly affect the engine output power and heat efficiency as well as the engine lifetime because of limiting the compression ratio and creating intensive pressure waves [1,4,5]. Accordingly, shock waves propagating speed would be severely increased under the end-gas area at the end of the fire until it reaches the speed of sound, leading to higher noises and vibrations of the engine [6,7].

In particular, knocking in spark ignition (SI) engines is known as the most crucial combustion phenomenon resulting from abnormal combustion of fuel and air mixture [1]. On the other hand, future improvements of both natural aspirated and turbocharged SI engines [6,7], as well as developments in dual-fuel compression ignition (CI) engines designs, are largely restricted by the knocking phenomena [8]. Currently, there are numerous demands for designing engines with larger efficiency as close as the allowable knock limit and supplying a higher compression ratio, superior thermal efficiency, and enhanced power output [9]. Difficulties against the knocking occurrence prediction are mainly related to a large number of parameters in terms of fuel properties in addition to the engine geometry and its operational conditions. For knock prediction and its intensity evaluation, there are different methods widely recorded by several researchers, which are going to be shortly reviewed in this paper.

II. FUNDAMENTAL THEORIES OF KNOCKING

It is widely accepted that two general theories could be postulated for describing the origin of engine knocking called as: (1) auto-ignition; and (2) detonation [1,10-13]. According to the first theory, hot spots are generally assumed in the end-gas region, denoting some non-uniform conditions regarding fuel concentration, internal temperature, and pressure in the engine combustion chamber. As a result of fuel-air mixture ignition by the spark plug, the end-gas will be subjected to compression provided from the product combustion expanding and the flame heat radiation. Accordingly, one or more hot spots would spontaneously ignite if the end-gas's local pressure and temperature exceed its auto-ignition point. Finally, the chemical energy release followed by these rapid sequence chemical reactions leads to high velocity of pressure waves in the form of knocking [12,13].

On the other hand, the detonation theory holds on a possibility of accelerating the advancing flame from speed up to the sonic or supersonic velocity. In general conditions, the flame front propagates evenly from the spark plug to the cylinder walls; if the consumption rate of end-gas exceeds the level of normal combustion, intense shock waved as a reflectance from the combustion chamber walls would be generated, which in turn causes pressure oscillation characteristics to knock [1,12].

Between the two theories mentioned above, the available evidences are mostly dealt with the auto-ignition theory for explaining the engine knocking [10].

III. APPROACHES UTILIZED FOR KNOCK DETECTION

Determining the engine knocking needs utilizing a quantifiably indication-based method which are divided into two main classes of direct and indirect approaches. Direct detection techniques are mainly appertained to measuring and analyzing the parameters of in-cylinder combustion in terms of pressure, temperature, and heat transfer. Using the second approach of knock detection, it is necessary to measure and analyze those parameters which are indirectly influenced by knock, such as engine vibration and acoustic emission.

A. Knock Detection with Sensors

Measuring the in-cylinder pressure as a direct approach for knock detection is considered one of the valid and popular methodologies mainly applied using several sensors. Pressure sensors are known as the primarily used equipment for measuring the cylinder pressure oscillations to indicate what will happen during the knock cycle inside the combustion chamber [15-18]. The pressure sensor is directly installed in the combustion chamber of the engine (embedded in a spark plug) to record the signals in a specific time domain. Although the pressure sensors are more accurate, they are expensive and need special software for post-processing the receiving signals. Moreover, since these sensors are directly in contact with hot and high-pressure media inside the combustion chamber, they face limited durability, and their accuracy would be diminished during the time. So, pressures sensors are now replaced by the acceleration type (piezo-electric) sensors which have to be directly mounted on the engine block, cylinder head, or intake manifolds [19-20]. These are known as knocking control systems based on engine vibration measurement in order to generate voltage signals proportional to the acceleration [1]. Despite their simple performance and cost-effectiveness, the accelerometer sensors cannot be as accurate as of the pressure sensors; because it is almost difficult to distinguish between the vibrations induced by resonances in the combustion chamber from those originated by the other combustion events.

In the case of using acceleration-type sensors, there is nonlinear superposition between the characteristic vibration signal and those generated by random excitation such as intake and exhaust valve seat impact, reciprocating intarsia of impact piston, and other working components as well as high-energy background noises. But researchers found some solutions based on processing algorithms and signal transferring techniques, including Fast Fourier Transform [21-22], wavelet analysis [23-26], and empirical mode decomposition [27-30]. However, these methods have their own problems, such as limitation in the time domain, poor adaptive ability, unsuitability for selected wavelet bases (in the case of wavelet analyzing algorithm), and often needs complementary ensemble functional modes (in the case of empirical mode decomposition techniques).

Since the characteristics of the acceleration sensors could be strongly affected by the heat engine (because of having direct contact), some researchers tried to develop another type of sensors in the form of optical sensor [31] and ionization sensor [32]; however, they are not commonly applicable and are just limited as research works.

As a newly introduced sensor type, a complex design of microphone sensor accompanied with accelerometer sensor was developed to be used for knock detection [33-34]. This new technique of knocking detection is based upon pattern recognition using the knock sound identified by employing a microphone sensor and active filter. It is suggested that the regression of the normalized envelope function, as well as the Euclidean distance estimation, be applied to detect the engine knocks. This system uses a microcontroller equipped with a fuzzy logic controller ignition in order to set the proper spark advance according to the operating conditions. It is claimed that the engine performance can be increased up to 15% by using this system [34].

B. Knock Detection Based on the Improved Signal Processing Methods

The basis of knock detection systems is mostly upon the measurement of signal intensity or magnitude using the algorithm-based characterizing methods of the knock intensity oscillations. These methods are classified into different types including [22-29]:

1) Determining maximum amplitude of pressure oscillations;
2) Filtering wavelet transforms upon the dynamic analysis of cylinder pressure (based on the knock intensity threshold value);
3) Analyzing the time and frequency of knocks using Fourier transform on the vibration of the cylinder block;

4) Regression analyzing method applied on parametric models;
5) Analysis of logarithmic knock intensity by using the average energy of the knock signal;
6) Method of differentiated knock intensity in order to analyze the signal level of knock;
7) Pattern recognition after filtering the knock processing signals.

It is reported that the processing techniques might distort the in-cylinder pressure characteristics from the accurate evaluation of the knock intensity [35]. A comprehensive research work [36] was conducted on different techniques of digital signal processing in order to evaluate the in-cylinder pressure in compression ignition engines. According to the findings of the power spectrum, it was illustrated that averaging and smoothing approaches under the applied processing algorithms would eliminate most of the high-frequency elements from the in-cylinder pressure signal.

For solving the above-mentioned problems, various metrics of knock intensity have been provided, which are mostly based on qualifying the knocking intensity from the in-cylinder pressure oscillation [37-38]. Another intensity metric was developed according to the resonant frequency of the in-cylinder pressure. It was found that this method provides high values of signal-to-noise ratio and is able to do data commutating faster than the average-filtered processing techniques [39]. The auto-regressive moving average model was rarely developed as another intensity metric for investigating the knock detection according to the engine block vibration [40]. This technique in which the accelerometer sensors are required has significant perform-ability to differentiate the knock phenomena from other types of combustion events. Another alternative method was based on knock probability estimation using the in-cylinder temperature and exogenous noise as the model inputs [41]. The estimation of trapped mass according to in-cylinder temperature can improve the accurate measurement of air mass flow rate as well as the precision estimation of knock probability. It was revealed that the random knocking nature could be assigned to the temperature irregularity.

Simultaneously with the introduction of the empirical mode decomposition theory [42], researchers were interested in using signal analysis in cooperation with improved decomposition modes [43-44]. In this regard, the knock detection in spark-ignition engines was investigated by using complementary ensemble empirical mode decomposition transform according to the signals from engine cylinder pressure and the engine cylinder block vibration [45]. The results suggested the high ability of the applied method in extracting the knock characteristics of both the cylinder pressure signals and the vibration signals. Using this algorithm and the Hilbert transform would help accurately distinguish between three different states in the combustion chamber in the form of light knock, heavy knock, and normal combustion.

C. Neural Network and Machine Learning Techniques of Knock Detection

Following to development of artificial intelligence and the introduction of computer-aided methods, approaches based on neural networks have been recently applied for improving knock prediction performances. As reported in Ref. [46], the applied neural network model used for reconstructing the in-cylinder pressure is claimed to be a highly accurate estimation method according to the cylinder block vibration and is strongly able to predict the knock pressure information cost-effectively.

New proposed predicting models were developed employing the machine learning algorithm based on in-cylinder pressure under various engine speeds, which are typically introduced as classification models [35]. In these models, it is not required to analyze the knock representative signals using various signal processing techniques; but several knock cycles with significantly various intensities are utilized for training the model algorithm under different operating conditions. The heat release analysis is one of the basic criteria of these models from which an acceptable accuracy level in the knock and normal cycle classification could be yielded. Moreover, the ensemble empirical mode decomposition transform combined with the wavelet packet decomposition were also involved in these models to provide an accuracy exceeding 99% in the knock cycle detection [35].

D. Knock Detection in Dual-Fuel Engines

It was previously stated that knock phenomena in the internal combustion engines might result in irreparable damages. The low-intensity knocks are often difficult to be distinguished from other noises generated inside the engine combustion chamber; this issue is more serious in the case of dual-fuel engines. The knock phenomenon on dual-fuel engines is rarely can be detected from the combustion analysis graph. Meanwhile, it is essential to determine the knock combustion at the specific engine cycle. Such information is very crucial for saving the engine damages heat losses.

In general conditions, a diesel-CNG dual-fuel engine (DDF) functions by providing a CNG fuel portion inside the cylinder which is auto-ignited via a small diesel fuel portion. When the CNG fuel quantity surpasses the limit, the engine knocking would be occurred as a result of abnormal combustion. But it should be noted that knocking in DDF engines varies from common spark and compression ignition engines.

This difference is mainly attributed to the existence of two types of fuel within the combustion chamber having their properties [47-51]. As a result of various reasons like inappropriate frequency response of a pressure transducer, energy release abruption during the combustion cycle, as well as improper combustion timing, the knock phenomena are difficult to be accurately detected on DDF engines [51-52].

Several knock detection methods and the combination thereof (as listed in the previous section) were commonly suggested to be used for knocking detection in DDF engines [53-57]; however, these methods have their own functional limitations in terms of data extraction approaches and knock threshold levels [58-59].

E. *Statistical Approaches in Knock Detection*

The statistical-based approach was rarely introduced for determining the engine knocking (especially useable for DDF engines) by which the knock occurrence could be quantified using the engine block vibration measurements recorded by a single piezoelectric knock sensor [52].

According to this approach, the intensity of knocking sound for each combustion cycle would be represented by using a proposed knocking indexing method. A knock index is a dimensionless unit used to quantify the intensity of knock during each cycle. It is generally calculated by taking the absolute first derivative value integral of the band-pass filtered vibration signal [52-53]. Using this method, it is possible to visually capture the intensity of the knock phenomenon in a subsequent engine cycle [52].

For determining the knock threshold, the statistical three-sigma rule is applied, which can suggest a boundary between the normal engine cycle and the knock engine cycle by using the engine as the model baseline. The knock threshold is considered as a determination of the knock index limit. It could be provided by the baseline engine, which has all of the engine settings are in the original condition. If the compression ratio, as well as the fuel injection timing, are optimally set, the knocking occurrence possibility would be almost inconceivable [52].

The knock detection methods based on a statistical approach would simplify the tracing process through the selection of the engine cycle to obtain a distribution graph of the knock index. Before processing data for further analysis, a specific cycle number is selected according to the knock index, which is closest to the knock threshold. Since it is known that the released energy from the combustion cycle would be yielded in vibration and the knock signal oscillation, the probability of knock occurrence could be hypnotized by comparing the knock signal and the heat release rate. In this case, the maximum amplitude of the knock signal would be observed as the heat release is increased, resulting from the shockwave collision during the flame propagation [52].

It is also claimed that the statistical-based knock detection methods are able to provide a solution for preventing the knock occurrence. After filtering the knock signals, the cause of knocking could be hypothesized as the abruption of energy released. Such evidence is illustrated by a high knock signal amplitude at the mixing-controlled combustion stage. The rapid heat release rate is considered as an indicator of the energy released abruption during the mixing-controlled combustion state, followed by the late combustion occurrence as a result of heat release rate fluctuation [52].

IV. KNOCK INTENSITY EVALUATION

The randomness and complexity of the knock phenomenon cause several challenges to developing accurate and universally applicable criteria for evaluating the knock intensity. Commonly accepted approaches in this regard are generally based on determining the value of knock indices as follows:

A. *Maximum Amplitude of Pressure Oscillation (MAPO)*

Knock intensity evaluation based on MAPO knock index is one of the most employed methods. Using the value of MAPO, it is possible to evaluate the maximum peak of the pressure oscillation due to the knock [60]. According to Eq. (1), MAPO index is based on the high frequency of filtered in-cylinder pressure data:

$$MAPO = max\left(|\hat{p}|_{\theta_0}^{\theta_0+\zeta}\right) \qquad (1)$$

Where, $\hat{p}$, θ_0, and ζ are assigned to the filtered in-cylinder pressure, the crank angle attributed to the calculation window beginning, and the value of the calculation window, respectively.

B. *Integral of Modulus of Pressure Oscillations (IMPO)*

IMPO knock index is related to the energy of high-frequency oscillations and is analyzed based on the filtered in-cylinder pressure [61]. From Eq. (2) the IMPO index as the knock intensity indicator could be calculated:

$$IMPO = \frac{1}{N}\sum_{1}^{N}\int_{\theta_0}^{\theta_0+\zeta} |\hat{p}|\, d\theta \qquad (2)$$

Where, N, is the number of computed cycles. Although the MAPO and IMPO indices seem to be the same in terms of data input characteristics, they are different in determining methodology, as given in the Figure 1.

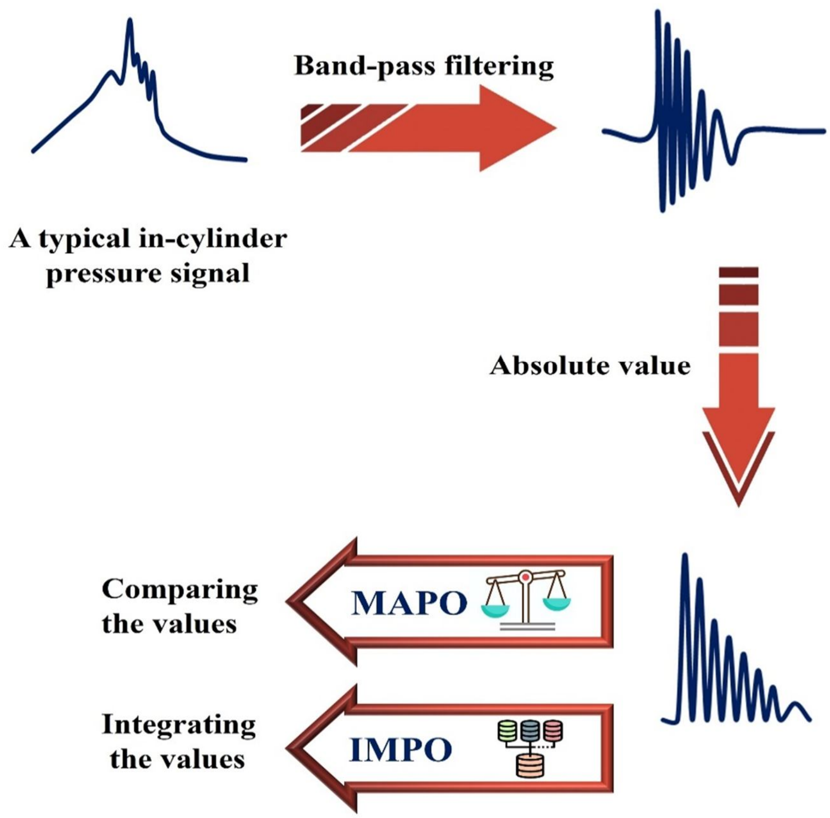

Fig. 1: MAPO and IMPO indices determination from in-cylinder pressure signal

C. Integral of Modulus of Pressure Gradient (IMPG)

Knock index in the form of IMPG is calculated according to Eq. (3) in which the gradient of filtered in-cylinder pressure is involved in the calculation [62].

$$IMPG = \frac{1}{N}\sum_{1}^{N}\int_{\theta_0}^{\theta_0+\zeta} \left|\frac{d\hat{p}}{d\theta}\right| d\theta \qquad (3)$$

D. Rate of Heat Release (ROHR)

Knocking combustion, in general, has a negative effect on the engine efficiency because of increasing the heat losses during the combustion cycle; this, in turn, leads to heat release decrement. So, in order to knock evaluate, the parameter heat release in the engine cylinder is also applicable in the form of POHR [7], which is calculated from Eq. (4):

$$ROHR = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} \qquad (4)$$

In the equation presented above, θ, p, V, and γ are attributed to the crank angle, in-cylinder pressure, cylinder volume, specific heat ratio in the form of $\left(\frac{c_p}{c_v}\right)$, respectively. Notably, ROHR displays the energy release rate from the combustion process minus the wall heat transfer and the heat flow losses [63].

E. Net Cumulative Heat Release (CHR_{NET})

Knock index evaluation based of CHR_{NET} is determined from integrating the Eq. (4) with respect to the crank angle as following:

$$CHR_{NET} = \int_{\theta_s}^{\theta_e} ROHR\ d\theta \qquad (5)$$

Where, θ_e and θ_s are the starting and the ending angles of combustion, respectively. Values of CHR_{NET} for the knocking combustion cycles are significantly lower as compared with those calculated for the non-knocking cycles. This result is mainly attributed to the high level of heat losses during the knocking phenomenon that occurs while the engine operates improperly. The advantage of using CHR_{NET}-based approach for evaluating the knocking intensity corresponds to the parameter of the strong relation with the knock intensity and its independency on the pressure sensor position [63].

F. Maximum Correlated Kurtosis Deconvolution (MCKD)

To solve the problem of light knock detection, several researchers have been focused on using signal recessing methods based on the MCKD index, from with the engine knock feature could be extracted, and the knock intensity could be accurately evaluated from the engine block vibration signal [64]. Using this index, the mechanism and morphological details of different signal components could be expressed more accurately and efficiently. The correlation kurtosis in this method is a key parameter for evaluating the knock intensity [65]. Kurtosis is a numerical statistic parameter which can represent the distribution characteristics of shockwave variables and is particularly sensitive to the impact component of the signal. Because of the pressure wave distribution as a result of improper combustion cycle in the engine chamber and knocking phenomenon, such indicator could be applicable for correlating the periodic characteristics on the basis of knock in order to better highlight the continuous impact components [64-65]. The kurtosis index is generally described as following:

$$CK_M(T) = \frac{\sum_{n=1}^{N}(\prod_{m=0}^{M} y_{n-mT})^2}{(\sum_{n=1}^{N} {y_n}^2)^{M+1}} \qquad (6)$$

Where, T is the period, and M is the shift number.

According to the MCKD-based theory, the engine knock feature extraction process includes as [64]:

1) Collected data samples are learned to an indicator, reflecting the original signal features;
2) The target signal is then encoded in order to solve the indicator coefficient;
3) The reconstructed signal is finally processed by MCKD filtering until the correlation kurtosis of the filtered signal could be calculated.
4) The knock intensity is lastly evaluated according to the MCKD index.

The higher the correlation kurtosis, the stronger the knock intensity. Accordingly to the knock index, three kinds of engine operation states could be successfully distinguished as (a) the normal combustion condition, (b) the light knock condition, and (c) the strong knock condition [64].

G. Dimensionless Knock Indicator (DKI)

Detecting the start of knocking as well as evaluating the knock intensity are especially facilitated by using the DKI index [66]. The value of DKI is calculated from the ratio between the IMPO and the MAPO indices as follows

$$DKI = \frac{IMPO}{MAPO.\zeta} \qquad (7)$$

Where, ζ is assigned to the computational window width.

The lower value of DKI represents the greater knock intensity. DKI corresponds to two surfaces, including IMPO and ζ; the former is the surface under the pressure signal and MAPO product, while the latter is the computational window surface. Therefore, DKI demonstrates the “weight” of IMPO in the window of computation [66]. This evaluation method is mainly developed for scientific purposes and has not been applied in practical applications.

V. SUMMARY AND CONCLUSIONS

The importance of the knocking phenomenon and its negative effects on the operational efficiencies of ignition compression engines attracts numerous attention toward documenting the research findings in terms of optimal combustion mechanisms and knock detection and intensity evaluation. Accordingly, demands for designing highly efficient engines have significantly grown in recent years due to the development of automobile manufacturing industries as well as requirements for reducing fuel consumption. The possible solution in this regard is to develop the engines operating under the allowable knocking limit.

Several systematic methodologies and algorithm-based approaches have been proposed to analyze the in-cylinder pressure of the cycled combustion during the engine operation. The higher accuracy of the proposed methods is mainly emphasized by every researcher who was involved in providing a high-quality combustion analysis. This review paper summarizes the current developments in knocking detection approaches based on the auto-ignition theories in accordance with direct and indirect methods and the combination thereof.

The knock detection and intensity evaluation approaches used for industrial applications are mainly developed by employing vibration sensors that are directly attached to an engine; this is because of the high cost and intricacy of those methods based on in-cylinder pressure measurements. Knock intensity evaluation is generally performed using several knock indices, among which the MAPO and the IMPO indices are likely the most employed ones. They are beneficial for quantifying the intensity of knocks based on a high-frequency analysis of filtered cylinder pressure data. As a newly introduced method in this regard, the MCKD index is applicable for extracting the knock features, especially for the light knocking phenomenon, by applying the kurtosis index.

The complexity of the combustion cycle and the random knocking in the consecutive engine cycle makes it difficult to detect knocks from the combustion analysis graphs and the visual data. When this knowledge gap is closed, an opportunity of knock prevention on the engines (single- and multi-fuel) could be easily achieved. Once the knocking prediction and intensity evaluation method is sufficiently validated, it can be implemented for real-time knocking detection in the engine management system.

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