

Efficient On-Board Pegging Calculation from Piezo-Electric Sensor Signal for Real Time In-Cylinder Pressure Offset Compensation

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ABSTRACT

The introduction of piezo-electric sensor on mass produced engines for in-cylinder pressure measurement represents a near future step in order to improve combustion control. Piezo-electric sensors provide pressure measurements affected by offset error and drift due to thermal sensitivity: a pressure reference is needed for each cycle in order to obtain the actual pressure value (pegging). Three methods for the evaluation of the offset, based on the hypothesis of polytropic compression, have been analyzed in this work: (1) a three-point referencing method, (2) a linear least-square method and (3) a non-linear least-square method. From such a comparison the three-point referencing method appeared the best suited for on-board calculation since it has the lowest computational cost even if it suffers from noise sensitivity. Hence, the accuracy and the efficiency of this method have been improved by means of an original methodology. The proposed method has been applied both to simulated and to experimental signals gathered from a 4-stroke spark-ignited engine. The results are compared to those obtained by using the other two methods showing much better accuracy in all the examined tests. Finally, a computational cost analysis proves the feasibility of the proposed method for efficient on-board pegging calculation with modern engine control units.

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INTRODUCTION

Measurement and analysis of in-cylinder pressure are of major importance in order to optimize engine efficiency and reduce emissions. Indicated mean effective pressure, combustion heat release, volumetric efficiency are just some of the many parameters calculated from indicated cylinder pressure. Online evaluation of such parameters on production cars represents a very valuable solution to improve engine performance. Piezoelectric transducers are the best candidates for measuring online in-cylinder pressure for their impressive thermal stability, high natural frequency, robustness, durability, compactness and large amplitude operating temperature range [1]. These devices generate a signal depending on the pressure variation imposed upon the piezoelectric crystal. Therefore, the measured pressure must be referenced to a known pressure at a point in an engine cycle (pegging).

Piezoelectric sensor for measuring the pressure in the combustion chamber are subject to high temperature variations that cause the so called "thermal drift". Many

technical solutions have been adopted to reduce this error source by limiting the heat transfer to the transducer: special heat shields, coating of the transducer membrane, water cooling and temperature effect compensating design [2-3] even if thermal shock was found to be present. This error can severely influence the calculation of parameters derived from indicated pressure [1]: pressure signal requires to be processed to provide valuable information. Hence, absolute pressure referencing is also used to compensate for inter-cycle and intra-cycle drifts (long term and short term drift respectively).

The aim of this work is to propose a pegging method suitable for on-board calculation having the following features:

- high accuracy in the offset evaluation in order to reduce the errors in the parameters derived from in-cylinder pressure;
- low computational cost in order to allow cycle-by-cycle pressure offset compensation by the engine control unit;

Two of the most used pegging techniques [4] are:

- in-cylinder pressure signal setting at a properly chosen crank angle equal to the pressure value measured by a sensor in the inlet or exhaust manifold.
- modeling the compression stroke with a polytropic transformation.

The first method is often subject to significant errors in a tuned intake system or at high engine rotational speeds even if an average of pressure samples is considered in order to reduce noise sensitivity.

The polytropic method has the advantage of reduced hardware costs and its accuracy is not influenced by inlet or outlet pressure oscillations. In the simplest approach the pressure sampled at two different crank angles during the compression stroke is corrected by means of an offset to achieve a desired mean polytropic index (this is the “two-point referencing” method [5]); the accuracy of this method is strongly affected by pressure signal noise and uncertainty in the polytropic coefficient. In order to avoid the arbitrary assumption of the polytropic coefficient, it is possible to adopt the “three-point referencing” method. Kangyoon [5] proposes a method with variable polytropic coefficient that reduces noise sensitivity by fitting the polytropic curve to a considerable number of sampling points by a linear least-square method. Finally, a non-linear least-square method that evaluate polytropic index and offset by successive iterations is described by Tunestal [6,7].

The “three-point referencing” method appears the best suited for on-board calculation since it has much higher accuracy than the “two-point referencing” method and lower computational cost than the least-square methods reviewed; however it suffers from noise sensitivity [5] and the offset calculation can be affected by a considerable error. The proposed methodology allows either to predict the probability of offset error associated to a noise distribution and to minimize it by a proper calibration of the sampling crank angles of the three referencing points. Noise rejection is further increased by using properly averaged referencing points.

The tuned “three-point referencing” methods with and without averaging are applied both to simulated and to experimental signals gathered from a 4-stroke spark-ignited engine. The results are compared to those obtained by using least-square pegging methods showing high accuracy in all the examined tests. Finally, a computational cost analysis confirms the higher compatibility of the “three-point referencing” method with modern engine control unit performance.

MATHEMATICAL MODEL

The in-cylinder pressure measured by a piezo sensor at a given crank angle can be written as:

$$p' = p + e_t \quad (1)$$

where p is the actual pressure and e_t is the total measurement error. With good approximation, e_t can be considered as the sum of an offset O and a random signal noise e (see Fig. 1):

$$p' = p + O + e \quad (2)$$

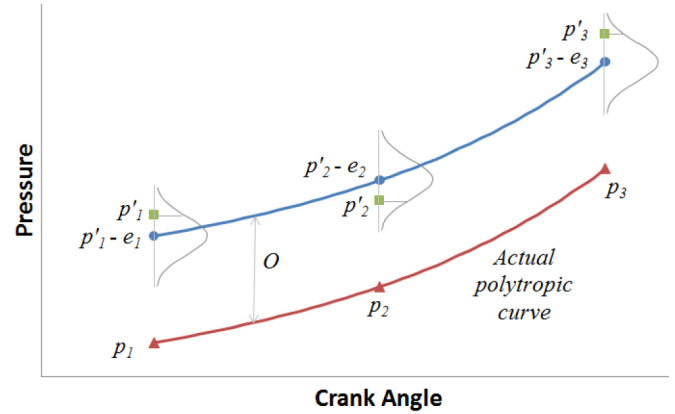


Fig. 1. Qualitative plot of the errors of in-cylinder pressure measurements.

Under the hypothesis of polytropic compression, the actual pressures at any two crank angles are related by:

$$p_1 V_1^m = p_2 V_2^m \quad (3)$$

where m is the polytropic index.

The offset can be expressed as a function of p'_1 and p'_2 by substituting the values of p_1 and p_2 obtained from Eq. (2) in Eq. (3):

$$O = \frac{(p'_1 - e_1) \left(\frac{V_1}{V_2}\right)^m - (p'_2 - e_2)}{\left(\frac{V_1}{V_2}\right)^m - 1} \quad (4)$$

In the “two-point referencing” method, under the hypothesis of negligible signal noise, assuming m from the experience, the value of the offset O can be evaluated. Instead in order to estimate also the polytropic coefficient a third point is needed. Hence O can be expressed in Eq. (4) as a function of the pressures measured at the first and the third points. Since the offset is independent of the measurement points used in Eq. (4), the right hand side of Eq. (4) calculated with the measuring points 1 and 2 is equal to the corresponding calculated by means of the points 1 and 3. Hence we can write an implicit equation with m unknown:

$$\begin{aligned}
& (p'_2 - e_2 - p'_1 + e_1) \left(\frac{V_1}{V_3} \right)^m + \\
& (p'_1 - e_1 - p'_3 + e_3) \left(\frac{V_1}{V_2} \right)^m + \\
& (p'_3 - e_3 - p'_2 + e_2) = 0
\end{aligned} \quad (5)$$

One could observe that Eq. (5) is independent from the offset and, therefore, if the signal noise was negligible, the polytropic index m could be calculated by solving numerically Eq. (5), but in the practical use signal noise cannot be neglected; hence the offset estimated neglecting the signal noise O' is affected by an error:

$$e_{off} = O' - O \quad (6)$$

where

$$O' = \frac{p'_1 \left(\frac{V_1}{V_2} \right)^{m'} - p'_2}{\left(\frac{V_1}{V_2} \right)^{m'} - 1} \quad (7)$$

and m' is the polytropic index that can be calculated by Eq. (5) neglecting the signal noise.

Substituting Eq.(2) in Eq. (7), by simple algebraic manipulations, it can be shown that:

$$e_{off} = \frac{(p_1 + e_1) \left(\frac{V_1}{V_2} \right)^{m'} - (p_2 + e_2)}{\left(\frac{V_1}{V_2} \right)^{m'} - 1} \quad (8)$$

meaning that e_{off} is independent of the actual offset.

The measurement noise e can be assumed to have a Gaussian distribution [5,6]. In order to proceed with a numerical analysis of the offset errors as a function of the signal noise level, a discrete probability distribution of the random errors is needed (see Fig. 2).

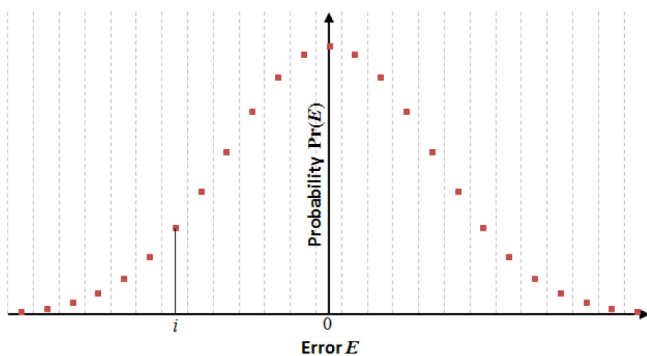


Fig. 2. Discrete probability function of the random errors.

The considered range is $-10\sigma < e < 10\sigma$ since $\Pr(|e| > 10\sigma) = 2.6 \cdot 10^{-11}$

Then the discretization procedure has been carried out according to:

$$Pr(E_i) = Pr(e \in I_i) = \int_{I_i} f(e) de \quad (9)$$

Hence, assigned a polytropic transformation affected by noise with a known probability density function, it is possible to evaluate the probability $\Pr(|e_{off}| > A)$ that the absolute value of the offset error is higher than a value A of interest. The theoretical analysis is carried out on a known polytropic transformation. Then signal noise is added to the ideal polytropic process. The probability $\Pr(|e_{off}| > A)$ is calculated as the sum of the probability of all the combinations of the error E_i at the three referencing points considered (intersection of the three events) that satisfy the condition $|e_{off}| > A$; under the hypothesis of stochastically independent noise errors at the three referencing points, the probability of a combination of errors is the product of the individual probability of such errors:

$$Pr(E_1 \cap E_2 \cap E_3) = Pr(E_1) \cdot Pr(E_2) \cdot Pr(E_3) \quad (10)$$

The proposed methodology quantifies the influence of a noise error probability function on the offset error; therefore it allows:

1. to tune the three referencing points of the pegging method in order to minimize the offset error due to noise.
2. to estimate the probability of the errors in the calculation of the in-cylinder pressure derived parameters associated to the offset error.

AVERAGING FOR NOISE SENSITIVITY REJECTION

Noise sensitivity of the “three-point referencing” method calibrated by means of the methodology above can be further reduced by averaging each pressure p' sampled at a referencing point crank angle with pressure values measured at adjacent crank angles [5]. Signal noise can be considered stochastically independent of the crank angle, that is the covariance is null. Hence the signal noise corresponding to the pressure averaged over N values follows a Gaussian probability distribution with standard deviation equal to

$$\sigma \left(\frac{\sum_{j=1}^N e_j}{N} \right) = \sqrt{\frac{\sum_{j=1}^N \sigma^2(e_j)}{N}} = \frac{\sigma(e_j)}{\sqrt{N}} \quad (11)$$

Therefore, the standard deviation of the probability density function of signal noise corresponding to the averaged referencing points is reduced with respect to the original standard deviation.

It is recommended to perform averages by using an equal number of points before and after the referencing crank angle. However the averaging technique introduces an error due to the non-linearity of pressure as a function of crank angle. This error source can be made negligible by using pressure values sampled at consecutive crank angles and limiting the number of points used for the average.

TEST BED DESCRIPTION

The examined engine is a gasoline spark-ignited single cylinder research engine. Main features of this engine are summarized in [Table 1](#). The intake system consists of an intake tube with a boss for the idle speed control valve, a throttle body with potentiometer and an air filter assembly. A piezo-resistive sensor is mounted close to the intake port to measure manifold absolute pressure (MAP) for engine control unit. The piezo-resistive sensor is positioned in a capacity to smooth the considerable pressure oscillations in the intake manifold to obtain a properly averaged pressure measurement for the engine ECU. The engine is equipped with a piezo electric sensor for detecting pressure in the combustion chamber. The piezo-electric signal is highly affected by measurement noise since the engine has a single cylinder. The in-cylinder pressure sampling rate is 1 crank angle degree. The engine speed is measured by an encoder. The engine is supplied with a single point port injection with a fuel pressure regulator rated to 3 bar.

The engine test rig includes an eddy current brake/driving dynamometer; such a system allows the control of two parameters among engine speed, equivalent ratio and torque. The fuel mass flow is measured by a gravimetric cell.

Table 1. Main features of the engine.

Engine	Gasoline - Spark ignited
Number of cylinders	1
Valves per cylinder	4
Stroke x bore	86 [mm] x 86 [mm]
Con-Rod lenght	143 [mm]
Compression ratio	10.5
Maximum power	25 [kW] at 6000 [RPM]
Injection system	Port injection – single injector

MODEL VALIDATION

CALIBRATION METHODOLOGY APPLICATION

The “three-point referencing” method has been tuned by means of the proposed methodology considering simulated compression strokes of the examined engine. The geometry data reported in [Table 1](#) have been used to determine the volume as a function of crank angle. Two polytropic processes with indexes $m=1.3$ and $m=1.4$ have been examined. The pressure at intake valve closure has been set to $p_{IVC}=1$ bar. Measurement noise can be assumed to have a Gaussian distribution with mean equal to zero and standard deviation $\sigma=0.1$ bar [6].

The first referencing point has been sampled at $\theta_I=90^\circ$ BTDC, that is 36° after intake valve closure; this gap reduces the noise due to valve closure. The third referencing point has been tuned to maximize the difference among referencing point pressures in order to reduce the influence of the signal noise on the solution of [Eq. \(5\)](#); such a point has been set to 20° BTDC, when the spark ignition has not yet occurred, since the combustion process cannot be approximated by a polytropic transformation.

Four critical offset values A have been considered to tune the “three-point referencing” method: $A=0.1$ bar, $A=0.2$ bar, $A=0.5$ bar and $A=1$ bar. The dimension of the discretization intervals of the probability density function has been properly reduced to obtain a discretization independent solution.

The results of the analysis are reported in [Fig. 3](#). The offset error probability is reduced by changing from $m=1.3$ to $m=1.4$; the minimum probability to obtain an absolute offset error higher than 1 bar is about ten times lower for $m=1.4$ with respect to $m=1.3$. The minimum of ($e_{off} > A$) occurs approximately at $\theta_2=324^\circ$ ATDC.

Noise error rejection can be further improved by measurement averaging. In this work each referencing point has been averaged over five pressure values. From [Eq. \(11\)](#) it follows that the standard deviation of the probability density function of the averaged noise reduces from 0.1 bar to 0.0447 bar. The statistical analysis of the offset error, calculated in the case of a polytropic compression with $m=1.3$ and $p_{IVC}=1$ bar, shows a strong noise sensitivity reduction (see [Fig. 4](#)) with respect to the case without averaging. In [Fig. 5](#) the offset error probability is reported as a function of the number of points used for the averages; the calculations have been carried out under the following conditions: $m=1.3$, $p_{IVC}=1$ bar, signal noise $\sigma=0.1$ bar, $\theta_I=270^\circ$ CA, $\theta_2=324^\circ$ CA, $\theta_3=340^\circ$ CA.

Under the hypothesis of polytropic compression and noise zero, the actual pressure and the corresponding averaged pressure at a given crank angle are different due to the non-linearity of pressure as a function of crank angle (see [Fig. 6](#)). Therefore the averaging technique introduces a systematic error in the calculation of polytropic index and offset. If a