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An indirect in-cylinder pressure measurement technique based on the estimation of the mechanical strength acting on an engine head screw: development and assessment

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Abstract

The increasing application of new concepts for the combustion process in internal combustion engines, e.g. HCCI or RCCI, is mainly aimed at reducing pollutant emissions and fuel consumption. A typical drawback of these technologies is the difficulty of properly controlling the combustion process in the area of medium-high brake mean effective pressure (BMEP), where the thermodynamic conditions inside the cylinder promote a very fast combustion process. To this end, the availability of a fast real-time monitoring of the in-cylinder pressure is then becoming pivotal. This is commonly done by means of piezoelectric dynamic pressure sensors, which are indeed very accurate, but also extremely expensive and characterized by a limited durability due to the harsh working conditions. Moving from this background, the present study describes a new methodology to evaluate the in-cylinder pressure by correlating it with the mechanical stress measured by a strain washer installed on an engine head screw. The strain washer can indeed work in a much more favorable environment with respect to a dynamic pressure sensor flush-mounted on the cylinder head (with aggressive hot gasses and high pressure) with direct benefits for its durability and ease of installation.

To assess the model capabilities, experimental tests have been carried out on a single-cylinder, 4-stroke engine and on a 2-stroke engine at the laboratory of internal combustion engines of the Università degli Studi di Firenze. The results reported in the study show the direct comparison of the in-cylinder pressure, as a function of the crankshaft

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angular position, measured directly with a dynamic pressure sensor and indirectly by means of the strain washer. Sound agreement was found between the two, proving the effectiveness of the proposed methodology.

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Keywords: internal combustion engine; in-cylinder pressure; strain washer; experiments.

Nomenclature

2S	two stroke
4S	four stroke
A/F	air to fuel ratio
BDC	bottom dead center
BMEP	high brake mean effective pressure
CA	crank angle
FTDC	firing top dead center
FS	full scale
HCCI	homogeneous charge compression ignition
LPDI	low-pressure direct injection
MBT	spark timing for the maximum torque
NN	neural network
P_{cyl}	in-cylinder pressure
PFI	port fuel injection
PS	pressure sensor
RBF	radial basis function
RCCI	reactivity controlled compression ignition
SI	spark ignition
SW	strain washer

1. Introduction

The in-cylinder pressure is a key parameter that provides valuable information about the combustion process, allowing one to better handle it by means of advanced control and monitoring systems. Real-time data about the pressure inside the cylinder during the on-board operation of the engine could allow for example a closed-loop control system to optimize the spark timing for the maximum brake torque (MBT), and to regulate air-fuel ratio (A/F) in order to minimize the specific fuel consumption and the pollutant emissions compensating manufacturing variation, aging and variation of fuel properties and/or environmental conditions. To perform the measurement of in-cylinder pressure, a pressure sensor flush-mounted on the cylinder head is generally used. The application of such sensors is indeed common during detailed test bench analyses, but still unusual for large-scale application. Pressure transducers grant good accuracy of the measurement, but present durability issues due to the harshness of the ambient they work in and a cost not suitable for production engine application. To avoid these issues, in recent years many researchers investigated techniques to estimate in-cylinder pressure through indirect measurements [1,2,3], without any physical access to the combustion chamber. In the literature, different methods have been investigated so far. The most exploited solutions are based on the reconstruction of the pressure trace by means of the measurement of engine block vibrations, crankshaft speed fluctuations, acoustic emissions or forces on cylinder head components.

Vibrations on the engine block are measured by means of an accelerometer placed on the cylinder. It gathers information of the pressure rise due to the combustion process, but it is also affected by unwanted vibrations effects sources as piston slap, mechanical unbalances, valves impacts, gear transmissions and other stochastic forces [4]. Filtering or neural networks [5] are needed to reconstruct the pressure signal.

The crankshaft speed fluctuation approach takes advantage from the use a phonic wheel (already available in all modern engines) to measure the acceleration of the crankshaft due the increasing torque connected to the pressure rise. This method also has some limitations, i.e. the need to compensate the incremental error due to the construction tolerance of the phonic wheel [6], the speed variation decrease with the increment of the number of cylinders and with the increase of the rotational speed.

The method based on acoustic emissions consists in a microphone mounted on top of the cylinder block. Similarly to the vibration of the engine block approach, these measurements have the drawback to be affected by a wide range of possible spurious sources as piston slap, valves impacts, gas turbulent flow and many other fluid and mechanical events, which interfere with the pressure source. In addition, data acquisition requires expensive devices for the high frequency content of the signal and data post-processing is not suitable for real time application. The main advantage of the acoustic emissions analysis is that it has a high signal-to-noise ratio in comparison to engine vibration signals.

Detection of the force on cylinder head components is another method to estimate the pressure within the cylinder. The measurement devices can be mounted in various ways [7,8,9], but the most common location is beneath the spark-plug [10]. In this way, the output of the strain washers and the in-cylinder pressure present a linear correlation, but the setup requires the modification of the cylinder head. In this arrangement, sources which differ from pressure do not affect the measurement because their loads are much lower than that caused by the combustion process. For these reasons, the post-processing of the data is quite easy. On the other hand, the main drawback of this setup is that the head of the engine has to be modified to house the strain washer. In addition, the spark ignition could cause electrical noises that can affect the accuracy of the in-cylinder pressure measurement.

In this study, an indirect in-cylinder pressure measurement technique based on the estimation of the mechanical strength acting on an engine head screw is presented. This setup allows avoiding any head modification (only new, longer screws are needed to compensate the strain washer thickness) and making the measurement suitable for large-scale application. Two different data post-processing method have been then tested. The research activity can be summarized into three main steps:

- a piezoelectric strain washer and a piezoelectric dynamic pressure sensor were installed during the first part of the activity on a two-stroke spark ignition single cylinder engine, then on a gasoline single-cylinder, 4-stroke, turbocharged engine for motorsport application;
- an experimental campaign on an engine test rig was carried out at different engine loads and rotational speeds in order to investigate the whole operating range;
- the signal from the strain washer was post-processed to compute the in-cylinder pressure. Two different approaches for the correlation have been used: a neural network during the first activity and a linear correlation for data post process on the 4 stroke engine;
- results show the direct comparison between the pressure sensor flush mounted on the combustion chamber and the strain washer and demonstrate the capability of the proposed methodology.

The tests were performed firstly on the 2-stroke single cylinder engine, which represents a simple case study since it is not affected by the presence of the valve train system. Then, the methodology was tested on a turbocharged 4-stroke single cylinder engine in order to analyze the influence, on the strain washer measurement, of the valve train system and of the turbocharger. Both engines represent a simplified setup since the influence of other cylinders is missing. Nevertheless, this study is the proof of concept of a methodology for the reconstruction of the pressure trace with the potential to be applied in engine mass production thanks to its simplicity and accuracy.

2. Experimental setup

The experimental activity was carried out on a two-stroke spark ignition single cylinder engine with a low-pressure direct injection (LPDI) system [11] and on a gasoline single-cylinder, 4-stroke, turbocharged engine. The main features of the two engines are reported in Table 1. In both cases, the strain washer of circular shape was mounted on one of the engine head screws, which has been chosen as the best compromise for an easy installation. During the engine functioning, the pressure inside the cylinder acts on the piston producing its motion and on the walls of the head that tends to distance from the cylinder. The preload of the screws keeps the two components coupled even while the force, which is transferred to the strain washer, changes. At this point, the strain washer has been chosen by taking into account the following aspects: the measurement range of the sensor should be greater than the sum of the preload and the maximum force acting on a single screw at full load; the preload on the sensor must exceed the 20% FS of the sensor. A crucial aspect to be considered is that it is not easy to predict a priori the intensity of the strength transmitted to a single screw because of the complex geometry of the head and combustion chamber. Once the estimation of the force transmitted to the screw has been made, the authors chose a sensor (Table 2) that, for the present study, fitted the needs of both the tested engines.

Table 1. Engine main characteristics

Type	1-Cyl SI naturally aspirated	Gasoline PFI turbocharged
Strokes for cycle	2	4
Number of cylinders	1	1
Displaced volume	293.1	520
Stroke	72	63.4
Bore	72	101.98
Compression ratio	8.2:1	9.02:1

Table 2. Strain washer main features

Sensitivity	123.6 mV/kN
Measurement range	44.48 kN
Uncertainty (non-linearity)	±1% FS (±450 N)
Low frequency response	0.0003 Hz
Upper frequency limit	60 kHz
Minimum preload	8.896 kN
Temperature range	-54 to +121 °C

2.1. Two stroke engine setup

During the experimental activity, the engines were installed at the test bench of the department of industrial engineering at Florence university. Both engines were equipped with a dynamic pressure sensor installed on the engine head in order to measure the in-cylinder pressure curve as the reference signal for the strain washer installed under one of the head screws.

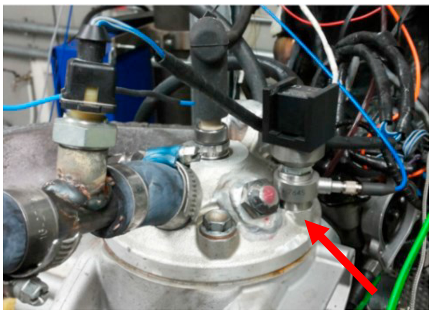

Fig. 1. Strain washer placed on one engine stud, the red arrow indicates the strain washer installation on the head.

At the same time, the instantaneous angular position of the crankshaft has been measured in order to reconstruct the pressure-angular position diagram of the combustion process (Fig. 1).

Since the installation of the strain washer needs a stud longer than those originally present on the engine, all the studs have been replaced with longer ones to guarantee a uniform load distribution. A piezoelectric pressure sensor and an encoder with a resolution of 720 pulses for revolution were adopted. A data acquisition system by National Instrument and a piece of software in LabVIEW purposefully developed for this application were used.

2.2. Four stroke engine setup

In order to avoid machining the head, the load cell was installed under the left head screw on the intake side, which was the only feasible solution on this type of engine (Fig. 2).

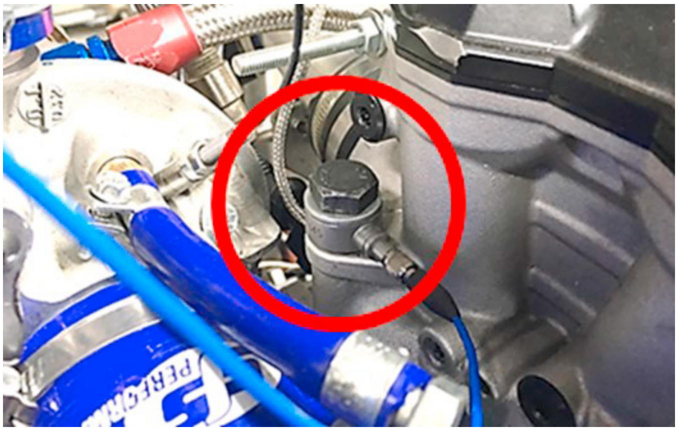

Fig. 2. Strain washer installation on one head screw on the 4S single cylinder engine.

In fact, two head screws were located under the intake and exhaust camshafts, respectively, hampering an easy installation. The last screw available, at the left of the exhaust side, was outside the engine head, but there was no space between the screw and the head surface for the installation of the sensor, so a dedicated machining was needed. For the proper installation of the sensor, a dedicated engine screw (10 mm longer respect to the original one, same as the sensor thickness) was designed and realized. To ensure the same load on each screw, all of them have been lengthened by 10 mm and a spacer of 10 mm was installed between each screw and the head. As for the 2 stroke engine, even in this case the engine was equipped with a dedicated system for the measurement of the in-cylinder pressure.

3. Signal processing

The correlation between the strength measured by the strain washer and the in-cylinder pressure has a key role to understand the suitability of the measurement technique.

Originally the authors expected to find a direct correlation between the measured force and in-cylinder pressure. However, the results obtained on the 2S engine showed a low sensitivity to the force measured during a cycle for the entire range of loads and engine speeds tested, while a linear correlation was not found. The reason may be due to an overestimation of the strength transmitted to the stud and so to the choice of an inadequate load cell. For this reason, the authors, in order to find a correlation between the SW signal and the PS signal, have adopted a neural network (NN) on a radial basis function. The second test on a 4-stroke, turbocharged engine overcame this issue. In this case, the presence of only four screws and an engine power higher (which means higher in-cylinder pressure) than the previous one allowed obtaining an improvement of the variation of the strength measured by the sensor and a direct correlation with the pressure inside the cylinder has been found.

Even if the NN approach showed good agreement between the direct and indirect pressure measurements, it is thought to be not suitable for a real-time use on vehicles. On the other hand, the use of a load cell on the 4S engine revealed the existence of a linear correlation with a good accuracy with the measurement and it turned out to be suitable for the monitoring of the engine behavior. In the following sections, only a brief summary of the NN approach will be presented, while the direct correlation will be explained in detail.

3.1. Neural network data processing

The authors identified a feed forward neural network based on a radial basis function (RBF) as the best performing NN in this case. The NN parameters need a calibration process to find the right values for the weight sets in order to provide the correct output. For the training of the RBF, the engine was tested from 3000 to 6000 rpm with step of 500 rpm and varying the engine load from 25% to 100% of the whole throttle opening with step of 25%. During the experimental tests were measured contemporary the in-cylinder pressure with the pressure sensor and the strength on the engine stud with the strain washer. More in detail, 60 couples of pressure/strength values per cycle concentrated around the pressure peak were used as the input/output for training of the NN; it was chosen the area around the pressure peak because in this range the SW is properly stressed [12].

Even if with the NN approach good agreement has been achieved between the in-cylinder pressure directly measured with the PS and the one indirectly estimated with the SW, the high computational time associated to this methodology does not allow this application to be implemented on vehicle; this aspect dissuaded the authors to follow the NN approach during the subsequent studies.

3.2. Direct correlation

At the basis of the proposed approach for the indirect in-cylinder pressure measurement there is the physical correlation between pressure and force. In other words, during the entire cycle, the pressure transfers its energy acting on the combustion chamber surface and producing a force that is elastically transmitted through the cylinder head to the head bolts or studs. This means that one can obtain a direct correlation between the pressure and the force measured, for example, by a strain washer installed on the head. In spite of the neural network strategy, this approach is suitable for on-board engine control systems thanks to the low computational cost in the post-processing of the data.

The strength measurement, based on the average of 100 consecutive cycles, has been here reported at 4000 rpm and full load as an example of the signal obtained by the load cell (Fig. 3).

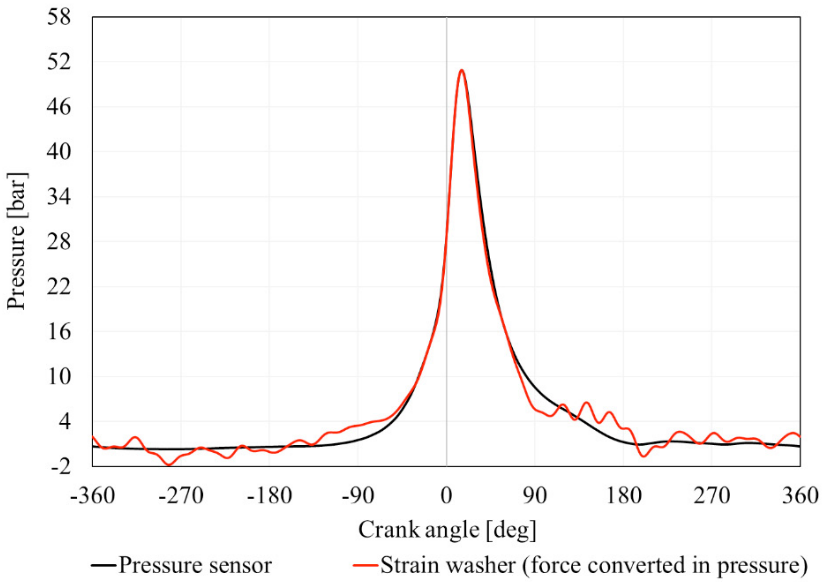

Fig. 3: Strain washer signal vs Pressure sensor signal at 4000 rpm and full load.

Upon examination of Fig. 3, it is possible to notice that during the combustion phase the shape of the curve resembles to the signal detected by the PS. The derivative of the strength signal is similar to the same derivative of the pressure signal. This result proves the existence of a linear correlation between the two sets of data at least in a narrow range of crank angles (± 60 CA deg). On the other hand, during the suction and discharge phase, the data of strength show an unphysical oscillation that leads to a considerable difference with respect to the PS reference signal. The reason of this behavior could be that, during the scavenging phase, measured values decrease below the uncertainty limit of the sensor (450 N). Taking into account the values related to the combustion phase, the linear correlation reported by Eq. 1 was here considered:

$$P_{cyl} = SW/k - q \qquad (1)$$

Before defining the two parameters, it is mandatory to properly set - both for the SW and the PS - the absolute value of strength and pressure, respectively, since both of them are relative sensors. For the PS, a pressure equal to 1 bar [13] is conventionally considered around the BDC with the inlet valve opened. A window of ± 5° CA was then chosen to compute the average of the pressure measured and set to 1 bar to find the right offset of the signal. As a consequence, in the same angular window, it is assumed that the average strength on the stud measured by the SW is equal to 0 N, because it is assumed that the engine block is not stressed. Then, to ensure that the measured data from the SW were outside from the uncertainty range, two angular positions around the firing top dead center (between -5° and +10° CA around FTDC) were considered to calculate the values k and q.

Due to the strong not-stationary nature of SW and PS measurements and to the uncertainty in the definition of the absolute value of both sensors, the values of k and q are theoretically not exactly constant at the different operating conditions. However, their mean values are expected to provide reliable trends for the method. A maximum difference of about 5% between k and q values was estimated during the variation of engine speeds and loads. Average values of k and q have been considered (equal to 27.4 and 125.8, respectively, for the present test case). Once the SW signal has been computed in bar with the linear correlation (1) some main parameters of the cycle as the in-cylinder maximum pressure and its position have been compared with the reference signal (Fig. 4(a) and Fig. 4(b)). Analyzing figure 4(a) can be noticed the correlation between the maximum pressure peak measured with the pressure sensor, x-axis, and the one estimated by the strain washer, y-axis. The analysis is carried out on 100 consecutive cycles both for the PS and the SW. In the graph data are divided in two main groups, low loads (triangular indicators) and medium/high loads (circular indicators). In both cases data are located on the bisector line with minimum dispersion. The less accurate points measured with the strain washer were recorded for the lowest engine load, which causes mechanical stresses on the load cell near to the uncertainty of the sensor. Figure 4(b) shows the position of the pressure peak measured directly and indirectly. Even in this case data are well correlated between the two sensors, where for medium high loads the error is about ±0,5° which is the encoder resolution; slightly worse results are obtained for low loads.

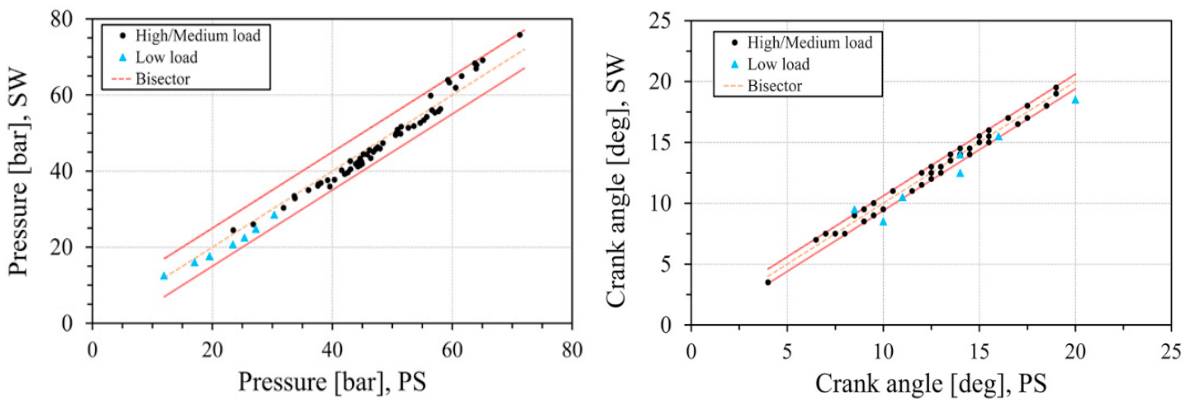

Fig. 4. (a) In-cylinder maximum pressure evaluated by the strain washer and the pressure sensor at different operating conditions in terms of load and regime (from 3000 to 6000 rpm) on the average-cycle. (b) Pressure peak angular position evaluated by the strain washer and the pressure sensor at different operating conditions in terms of load and regime (from 3000 to 6000 rpm) on the average-cycle.

The analysis shown above, demonstrate the potentiality of using the SW as sensor for the indirect measurement of the in-cylinder pressure. A deeper data post process will be surely of interest in order to understand if parameters like MBF50, IMEP and combustion duration can be detected with good accuracy. Moreover, future studies will be focused on the cycle-by-cycle analysis, with the aim of understanding if it is possible to identify anomalous combustion phenomena such as misfire, pre-ignition or arise of knock phenomena.

4. Conclusions

In the study, an indirect in-cylinder pressure measurement technique based on the estimation of the mechanical strength acting on an engine head screw has been developed and assessed. This technique allows avoiding some issues typically encountered in direct measurements as the difficult installation and the low durability of the sensors due to the harsh ambient inside the cylinder. In spite of other indirect measurement methods, the detection of the strength, which propagates from the cylinder surfaces to the engine block and head screws, has no limitations related to engine operating conditions and it presents a simple procedure to post-process data, suitable for a real-time monitoring onboard vehicles. Various tests on a dedicated test bench were performed on two engines to validate the approach: a 2S, single-cylinder, naturally aspirated, spark ignition engine and a 4S, single-cylinder, turbocharged, spark ignition engine. In both cases, the strain washer was placed under one of the studs of the engine head. In the tests on the 2S engine, results showed the potentiality of the use of the strain washer as a sensor for indirect measurement of in-cylinder pressure. However, during the experimental campaign it arises also that the estimation of the force transmitted to the stud is characterized by a considerable variability in the low load area; this issue is due to the low sensibility of the chosen strain washer for this application. The data obtained led to test a 4S engine proving the capability of the measurement technique to gather all the information about the combustion process reproducing the in-cylinder pressure trace with good accuracy in the entire operating range of the engine. A future development of the activity will be to test the method on a multi-cylinder engine to evaluate the effects of other cylinders. In this latter case, the stress transmitted to the engine block from other cylinders could in fact affect the measurement, hopefully enabling the detection of the pressure cycle for each of them with only one sensor, thus reducing the costs and the installation time of the sensor.

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