

Use of Accelerometers for Spark Advance Control of SI Engines

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ABSTRACT

Electronic engine controls based on non-intrusive diagnostics can significantly help in complying with the stricter and stricter regulations on pollutants emissions and fuel consumption. The aim of this paper is the use of a low-cost linear capacitive accelerometer placed on the engine block for non-intrusive diagnosis of combustion process in spark ignition engines. In particular, good correspondences between the engine block vibrations and the combustion pressure signal were obtained. The angular position of pressure peak evaluated by accelerometer data can be used in a closed-loop control system for real time control of spark advance.

INTRODUCTION

In order to comply with the severe future normative on pollutants emissions and fuel consumption, real-time diagnostics for the combustion process monitoring in the internal combustion engines are being widely used. Information on the combustion efficiency may provide a strong tool regarding engine operation and may be profitably used for advanced electronic engine controls. One of the most important parameters for the evaluation of the combustion quality is the in-cylinder pressure. This kind of measure requires an intrusive approach to the cylinder or a special assemblage with the pressure

sensor integrated in the spark-plug. The first montage work could result very hard for the new generation downsized SI engine. The second one is relatively expensive and constrained to the spark-plug lifetime. Moreover, the combustion pressure transducers are expensive and they must resist to a highly hostile environment. For all these reasons, at now the use of diagnostics based on the cylinder pressure analysis is mainly limited to research applications.

Thus non-intrusive diagnostics should be applied because of their several advantages. The sensors can be placed externally the engine without structural modifications. Moreover, the non-intrusive sensors are not requested to resist very high pressures and temperatures; so these sensors can be relatively cheap. Several non-intrusive diagnostics have been developed to control the engine combustion process [1 - 16]. The methodologies based on the accelerometer signal analysis have been commonly used especially for the detection of knock onset and intensity and cylinder-to-cylinder variations [10,11,12].

The strong connection between the characteristics of the combustion process and the so called “vibration signature” of the engine, induced some authors to perform a reconstruction of the cylinder pressure signal by using the information coming from the accelerometer

signal. As signal processing tools were used de-convolution methods, spectrum analysis, cyclostationarity properties and methods based on the neural network models [6, 7, 11, 13, 14]. However, all of these methods cannot be implemented in real time and thus closed loop combustion control cannot be performed.

In this work the correspondence between the combustion pressure signal and the features derived from the engine block vibration signal was evaluated. In particular, the pressure peak angular position was correlated with the accelerometer amplitude data. The final target was a real time and closed-loop control system of the spark advance for the optimization of new generation SI engines.

To this aim, a low-cost low-power linear capacitive accelerometer was mounted on the engine block. The combustion pressure signals were measured by quartz pressure transducers. They were flush-installed in the combustion chamber on the engine head. The tests were carried on two different SI PFI engines fuelled with commercial gasoline: a single-cylinder research engine and a four-cylinder commercial engine.

EXPERIMENTAL EQUIPMENT

All the measurements were carried out by a low-cost low-power linear capacitive accelerometer produced by STMicroelectronics was used. It included a sensing element and an Integrated Circuit interface able to take the information from the sensing element and to provide an analog out signal. The sensor works on a 6 kHz bandwidth. A single-cylinder SI research engine and a four-cylinder SI commercial engine were used in this experiment. The engines were fuelled by EURO4 gasoline.

SINGLE-CYLINDER SI ENGINE

In the first part of this work a single-cylinder ported fuel injection (PFI) spark ignition research engine was used. It was equipped with the cylinder 4V head of a commercial SI turbocharged engine.

Table 1. Single-cylinder SI research engine specifications.

Engine type	Port Fuel Injection
Engine design	1 Cylinder, 4 valves
Displacement	399 cm ³
Bore/Stroke	79 mm / 81.3 mm
Max Torque	20 Nm / 2500 rpm
Max Power	10 kW / 2500 rpm
Compression Ratio	10.0:1
Max Speed	2500 rpm

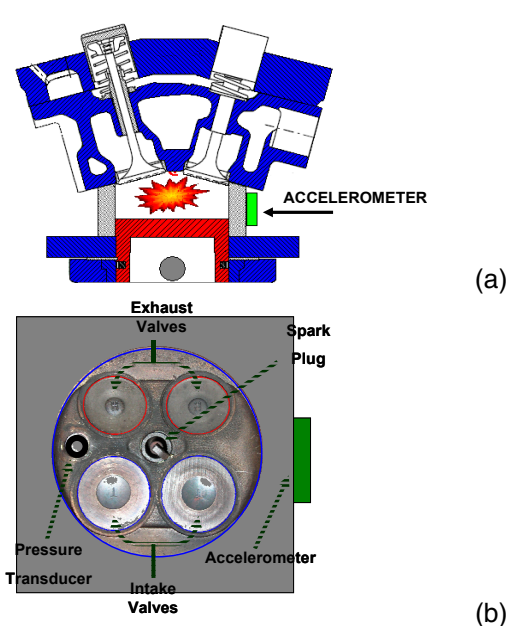


Figure 1. (a) Sketch of the single-cylinder SI research engine with the location of the accelerometer and (b) detail of the combustion chamber.

An external device controls the intake air pressure in a range of 1000 - 2000 mbar and the temperature in a range of 290 – 340 K. The single-cylinder engine was representative of the new generation downsized boosted engines. Moreover, in absence of boosting it could be used to evaluate the effect of the control on the scooters and motorcycles. Details about the engine are reported in Table 1. Figure 1 reports a schematic diagram of the single cylinder PFI SI engine and a detail of the combustion chamber with the location of the accelerometer and the pressure transducer.

FOUR-CYLINDER SI ENGINE

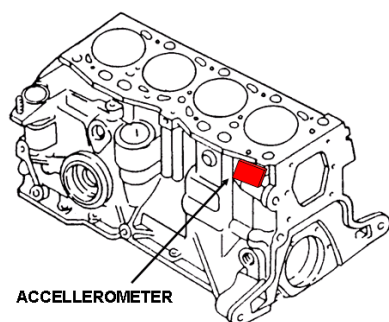
A four-stroke 16 v PFI spark ignition commercial engine, with four in-line cylinders and a multipoint electronic injection system was used in the second part of the work. It was a natural aspirated engine that powered the most diffuse Italian passenger car on 2007.

Table 2. Four-cylinder SI commercial engine specifications.

Engine type	Port Fuel Injection
Engine Design	4 Cylinders, 16 valves
Displacement	1242 cm ³
Bore/Stroke	70.8 mm / 78.9 mm
Max Torque	114 Nm / 4000 rpm
Max Power	59 kW / 5000 rpm
Compression Ratio	10.06:1
Max Speed	6000 rpm



(a)



(b)

Figure 2. (a) Four-cylinder SI commercial engine. (b) Position of the accelerometer on the cylinder basement.

More details about the engine are reported in Table 2. Figure 2(a) reports a picture of the four-cylinder PFI SI engine and Figure 2(b) shows the location of the accelerometer on the engine basement.

For both engines, the piezo-electric pressure transducer was flush installed to avoid either cavity resonance and/or low sensitivity to the pressure oscillations. The transducer entered vertically from the top of the cylinder head and was positioned in the region between the intake and exhaust valve. The in-cylinder pressure and the accelerometer signal were evaluated on an individual cycle basis and averaged on 400 cycles.

A data acquisition and analysis system was used to carry out real-time processing of the cylinder pressure data. It was fitted with 14 bit analogue to digital converter cards. A cylinder pressure charge amplifier equipped with 200 kHz analogue filter was used to convert the transducer charge into signals with a ± 10 V. A high precision Crank Angle Encoder was used for angle-based measurements. Flywheel generated trigger and crank angle degree marker pulses were produced at 0.05 crank angle degree resolution allowing data acquisition at any multiple of 0.05 degrees. In this work the angle resolution was fixed at 0.1° crank angle.

ENGINE OPERATING CONDITIONS

Single-cylinder Engine - The measurements were carried out over the engine speed range 1000-2000 rpm at full load (wide open throttle) for different boosting levels. The equivalence ratio was fixed at $\lambda=1$ as measured by a lambda sensor installed at the engine exhaust. The injection pressure was fixed at 3.5 bar over the boost pressure. Details on engine operating conditions are reported in Table 3.

Table 3. Operating conditions of the single-cylinder engine.

Speed [rpm]	Absolute Intake Air Pressure [mbar]
1000	1000
1000	1400
1000	1600
1500	1000
1500	1400
1500	1600
2000	1000
2000	1400
2000	1600

Four-Cylinder Engine - All the measurements were carried out over the engine speed range 2000-4500 rpm for the air to fuel ratio planned by the engine manufacturer. For each engine speed, the measurements were performed at three different loads 30%, 50%, and wide open throttle, respectively. Details on engine operating conditions are in Table 4.

Table 4. Operating conditions of the four-cylinder engine.

Speed [rpm]	Load [%Throttle]
2000	30
2000	50
2000	100
3000	30
3000	50
3000	100
4000	30
4000	50
4000	100
4500	30
4500	50
4500	100

CYLINDER PRESSURE PEAK LOCATION FROM ACCELEROMETER SIGNAL

Single-cylinder Engine – This engine was selected to reduce the interferences due to the combustion occurrence and other vibration sources in the different cylinders. Figure 3 reports the typical combustion pressure signals and vibration ones measured on three consecutive engine cycles at the speed of 2000 rpm and the absolute intake pressure of 1000 mbar. A cycle-to-cycle correlation between the angular position of the pressure peak and of the acceleration maximum amplitude was observed. Similar results were detected in the other engine operating conditions. This trend suggested the use of the accelerometer as non-intrusive diagnostic and control tool for the combustion process in the SI engines.

In order to extract information about the combustion pressure from the accelerometer signal, the vibration signal was evaluated by a time-frequency analysis. This processing was due to the several sources of the engine block vibration such as the valve opening and closing, the piston slap, the combustion process and several additive noises. Transient waves generated by these sources overlap each other and the issue is to isolate the contribution of interest.

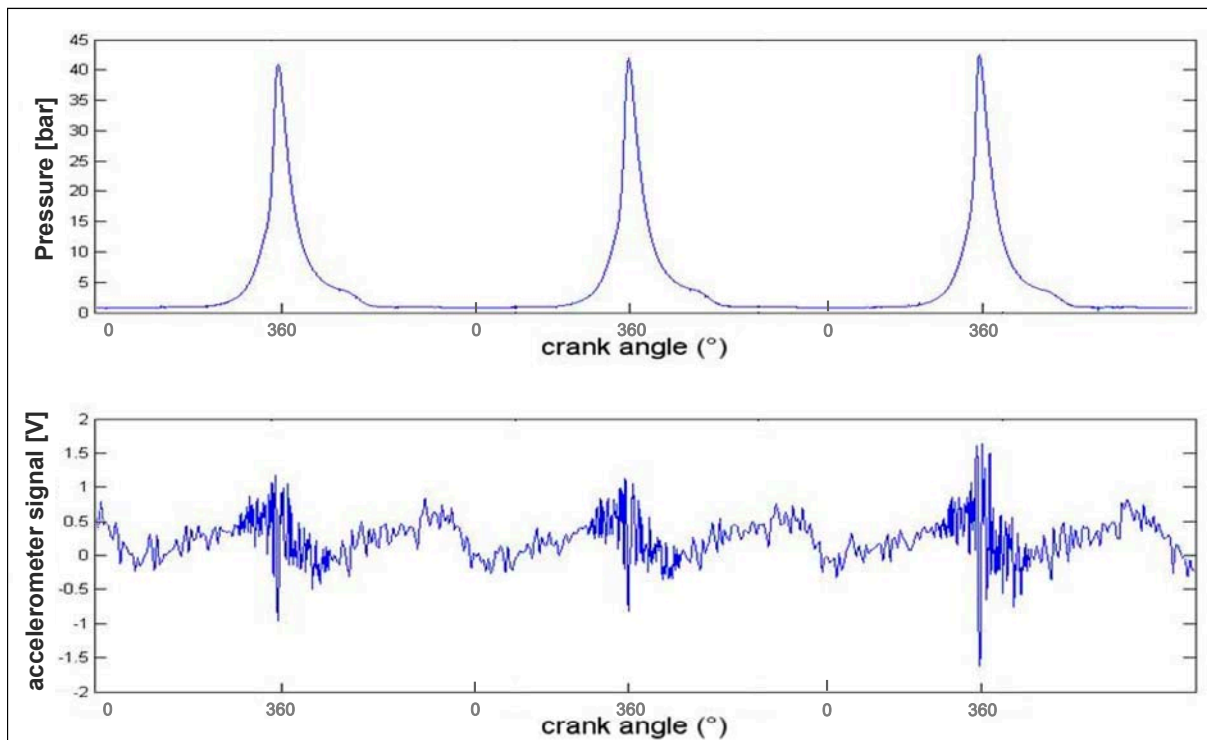


Figure 3. Typical combustion pressure signals (up) and accelerometer ones (down) measured on three consecutive single-cylinder engine cycles at the speed of 2000 rpm and the absolute intake pressure of 1000 mbar.

A time-frequency study of the accelerometer signal for all the selected operating conditions was performed by using the Matlab command called “spectrogram”. This evaluated all the STFTs (Short Time Fourier Transforms) of the same length and then showed the STFTs amplitude as a colorful graph.

Figures 4 and 5 report the time-frequency graph corresponding to the accelerometer signal measured at

the speed of 2000 rpm and the absolute intake pressure of 1000 mbar. To make more understandable the results, the average pressure curve and accelerometer one was superimposed on the graph. The frequencies below 4000 Hz well represented the whole combustion process. Moreover a dominant frequency band was observed in the range 1500-1800 Hz. The high-amplitude frequencies below 100 Hz were due to