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A direct transform for determining the trapped mass on an internal combustion engine based on the in-cylinder pressure resonance phenomenon

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ABSTRACT

It has lately been demonstrated that the resonance of the in-cylinder pressure may be used for inferring the trapped mass in an internal combustion engine. The resonance frequency changes over time as the expansion stroke takes place, and hence time–frequency analysis techniques may be used for determining the instantaneous frequency. However, time–frequency analysis has different problems when obtaining the spectral content of the signal, e.g. Short-Time Fourier Transform dilutes the frequency spectrum, and the Wigner Distribution creates cross terms that difficult its interpretation. In addition, time–frequency analysis requires a significant computational burden. This paper presents a direct transform, based on the resonance phenomenon, which obtains the trapped mass by convolving the pressure trace with the theoretical resonance behaviour. The method permits avoiding the spectral problems of the time–frequency transformations by obtaining the trapped mass directly without the need of inferring the frequency content.

1. Introduction

In-cylinder pressure has long been used as a powerful tool for engine research and diagnosis [1]. Although for many years restricted to research, the lowering market price of the newest pressure sensors are justifying their frequent implementation [2]. Methods using in-cylinder pressure sensors are of high interest, and many methods are being developed for determining combustion features, e.g. combustion detection [3,4], noise evaluation [5], air mass estimation [6], emissions control [7], heat transfer [8–10].

Most of the algorithms are based on the low frequency pressure trace; however the pressure signal may exhibit significant contents over a broad band of the spectrum, since fast combustion excites the resonance frequencies of the chamber creating pressure oscillations. If excessive, these oscillations can damage the engine, degrade substantially the performance and transmit an excessive high-frequency noise [11,12].

Traditionally, pressure resonance was investigated to detect knock on SI engines [11,13]. Knocking is an abnormal combustion on SI engines characterized by the spontaneous ignition of the end-gas, which causes a high release rate exciting heavily the resonance [11,14,15] and is a limiting factor for SI engines efficiency. Recently, the development of new combustion modes, based on Homogeneous Charge Compression Ignition (HCCI) [16,17], has driven the resonance researches on finding useful indexes to quantify the resonance [18–20]. Although knocking analysis and HCCI resonance

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are based on the same principles, because of the different chamber conditions, the resonance excitation is substantially different: SI knocking resonance is characterized by high excitation of many modes while HCCI resonance is concentrated on the first circumferential mode [21].

Virtually, all the applications and researches on resonance phenomenon are focused on detecting the resonance frequency (knock detection), locating the resonance to filter it (combustion diagnosis) or trying to quantify the resonance (resonance indexes); most of the applications start from Draper's correlation [22] in order to estimate the resonance frequencies as a function of the speed of sound. Draper's correlation has been demonstrated by many authors by using time–frequency analysis at the pressure signal in order to determine the frequency evolution [23–25].

Hickling et al. published in 1983 a method for determining the bulk temperature by measuring the period of the resonance pressure oscillation [23], the trapped mass determination was only mentioned as a possible application. Two main problems appear when trying to use the Draper's correlation for inferring the bulk temperature and hence the trapped mass: the variation of the frequency resonance over time, and the determination of the instantaneous frequency.

The variation of the frequency resonance is rooted on the variation of the cylinder geometry with the crankshaft position: the cylindrical assumption of the Drapers correlation is no longer valid when the engine approaches the Top Dead Center (TDC) and only the combustion chamber is left. This problem was addressed by Guardiola et al. [26], who suggested a method for experimentally characterizing the cylinder resonance.

On the other hand, Drapers correlation requires the determination of the instantaneous resonance frequency. In opposition to Hickling et al. manual method, this must be automated for the real-time implementation of the algorithm. Although Bodisco et al. [27] have discussed the possibility of determining the instantaneous frequency by statistical inference methods, the straight-forward solution is using time–frequency analysis (e.g. the Short Time Fourier Transform (STFT) is used in [26]). However, spectral analysis imposes an elevated computational burden, and does not necessarily calculate the actual instantaneous frequencies: there is no method capable of obtaining the real time–frequency content [28], but the solution depends on the transform used (Wigner, STFT, etc.). The goal of the paper is the development of a direct time-to-mass transformation including the resonance behaviour inside the signal transform.

The paper is organized as follows: the experimental layout, whose data will be used along the paper for demonstration purposes, is presented in Section 2; Section 3 will introduce the basics of determining the trapped mass through the pressure resonance, while Section 4 will be focused on the determination of the instantaneous frequency through some of the most common time–frequency transformations (WD and STFT). This will serve for illustrating the resonance behaviour, and for identifying the main drawbacks associated to each of these transformations. The new direct transformation will be described in Section 5, where it will be compared with the aforementioned spectral transformations, as with the classical sensing methods for trapped mass determination. Finally, last section sums up the contributions of the new transform.

2. Experimental layout and test data

The tests were developed on a single cylinder Reactivity Controlled Compression Ignition (RCCI) engine [29]. The engine was equipped with gasoline port injection and diesel direct injection, allowing multiple diesel injections during the cycle. EGR facilitated the control of the engine over different combustion modes, while electrohydraulic variable valve timing (VVT) permitted controlling the valves to change the mass instantaneously at transient tests. The pressure was measured with a Kistler 6125c sensor and processed by a National Instruments RT-PXI acquisition system, with a resolution of 5 samples/deg. The main characteristics of the engine are summarized in Table 1.

Pressure signal was crank angle based acquired. On one hand, time based acquisition is more precise to estimate frequencies but on the other hand, crank angle based acquisition permits locating the signal during the combustion cycle and this is specially important when using the volume in the calculations (because volume is a function of the crank angle).

Some tests were focused on detecting the instantaneous engine speed during the cycle: the pressure was acquired crank angle based and the time between samples was measured by an onboard clock (80 MHz). The engine speed variation was bounded below 5% on medium load. For simplicity the engine speed was considered constant, consequently time evolution (t) or crank angle evolution (α) will be used indiscriminately along the paper.

Even though all tests were conducted at the same engine speed due to test bench requirements, the only limitation of the method is the Nyquist frequency ($F_s/2 \geq f_{res}$). Then, if the pressure measurement is crank angle based, the frequency

Table 1
Main engine characteristics.

Displaced volume (V_d)	1806 cc
Engine speed (n)	1200 rpm
Bore (D)	123.6 mm
Combustion mode	RCCI-Diesel
Pressure samples/degree (s_n)	5
In-cylinder pressure sensor	Kistler 6125c