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An analysis of the in-cylinder pressure resonance excitation in internal combustion engines

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HIGHLIGHTS

- A new mathematical tool is proposed to analyse resonance evolution.
- Resonance excitation is analysed in various combustion modes.
- Experimental results from four combustion modes are analysed.
- The resonance analysis is used to improve the estimation of the trapped mass.

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ABSTRACT

This paper analyses the in-cylinder pressure oscillations in internal combustion engines, which are initiated by combustion and resonate during the expansion stroke. A specific mathematical tool, which takes into account the resonant frequency theory, has been developed to determine the resonance intensity evolution from the in-cylinder pressure signal.

Two engines, a conventional spark-ignited (SI) engin modified to perform homogeneous charge compression ignition (HCCI) combustion, and a conventional compression ignited (CI) engine, were used to analyse the resonance excitation in various combustion modes at different operating conditions.

The new transformation has been used to characterize resonance in various combustion modes and a previous method developed by the authors to estimate the trapped mass was fed by such knowledge to improve its robustness and accuracy.

1. Introduction

In-cylinder pressure oscillations in internal combustion engines are excited by local pressure gradients created by combustion, and resonate in the cylinder combustion chamber during the expansion stroke.

The resonance frequency evolution was firstly characterized by Draper in 1938 by analytically solving the wave equation with cylindrical contour conditions [1]. Draper stated that the frequency of the resonant modes was proportional to the speed of sound. In the last decade, as new tools for time-frequency analysis were being developed, several authors have demonstrated the relation between the speed of sound and the frequency of the resonant modes found by Draper, e.g. Scholl et al. with spectrograms [2], Samimy et al. with the Wigner distribution in [3], or Stanković et al. with the S-method [4]. In engines with bowl, such as compression ignited (CI) engines, the relation between the speed of sound and the resonance frequency may vary from the cylindrical acoustical response, as proved by Torregrosa et al. and Broatch et al. by numerical analysis and experimental results [5,6].

Pressure oscillations caused by resonance are a non-desired consequence of combustion which must be controlled for a safe and efficient operation:

- In spark ignited (SI) engines the main limiting factor at high load is the knock phenomenon, which consists on the autoignition of the end gas, before the flame front reaches all the combustion chamber.The rapid auto-ignition of the end gas heavily excites resonance and its vibration reduces the combustion efficiency and can damage the engine. Xu et al. demonstrate by numerical studies that the convergence of radial and axial modes in knocking conditions are one of the main causes of engine damage [7]. More detailed reviews of knock can be found in [8,9].
- In CI engines, one of the main concerns for the vehicle

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commercialization is its associated engine noise, which is strongly affected by the pressure oscillations caused by combustion. Some authors, such as Torregrosa et al. [10] and Payri et al. [11] have characterized the engine noise by a pressure decomposition between pseudo-motored, combustion and resonance to analyse each effect separately, highlighting the relevance of resonance on the final noise level.
- Regarding new combustion modes, which are based on an homogeneous charge compression ignition (HCCI) to perform a high efficient low temperature combustion with low NOx and PM emissions (a review can be found in [12]), the rapid autoignition of the mixture heavily excites resonance and its intensity control is one of the key issues of its future implementation. Commonly, the ringing intensity index developed by J.A. Eng in [13] is used, and a value under 5 MW/m^2 is recommended.

Most of resonance related studies are oriented to characterize resonance evolution in order to implement combustion strategies for avoiding knocking conditions (in SI) or reducing resonance excitation (in CI and HCCI modes).

The main source of resonance excitation in SI engines, knock, is produced at the end of the normal combustion event when the end gas reaches sufficient energy to auto-ignite. D'Adamo et al. found the highest knock probability area by flame visualization, in a laboratory GDI engine with optical access, at the exhaust side of the combustion chamber. This is consistent with the numerical simulations (RANS) performed, which showed that this region suffers of lean and hot end-gases, promoting knock onset [14]. However, although the autoignition of the end gas could be predicted with physic models, such as Livengood and Wu correlation [15,16] or black box models [17], knock is considered a random phenomenon as unpredicted temperature hot spots or oil deposits may trigger the phenomenon. Pan et al. in [18] analysed the influence of these temperature hot-spots in the knock appearance by performing large eddy simulations (LES) analysis. Several works have been focused on studying the effect of fuel blends in the knock occurrence, such is the case of Wei et al. and Liu et al. with n-butanol gasoline blends [19,20].

Regarding CI combustion, Kyrtatos et al., in [21,22], determined that the resonance excitation in a conventional CI combustion is mainly caused by the first pre-mixed ignition, and not the later diffusive combustion. They made a study based on a single injection strategy by varying the operating conditions, and they shown a relation between the time delay (and hence the amount of fuel burnt in premixed conditions) and the intensity of the pressure oscillations. However, current CI engines, use multiple pilot injections to reduce the in-cylinder pressure oscillations [23]. The main goal of the pilot injection is to increase the temperature of the combustion chamber through a first short combustion in order to lower the autoignition delay of the second main injection, and thus the pre-mixed fuel burned. Zhang et al. analysed experimental data at various operating conditions with a two-injection strategy, concluding that an important part of the resonance energy is due to the first pilot combustion [24], and that the phasing and quantity of the main injection may importantly affect the intensity of the pressure oscillations [25].

Several authors analysed HCCI combustion and the consequent pressure oscillations, such as in [26] through fuel tracer LIF and chemiluminescence imaging, in [27,28] by image-intensified high-speed video camera speed, and in [29] through large eddy simulations (LES). These studies determine that the autoignition of the mixture starts at some given local points characterized by in-cylinder inhomogeneities, which explains the cycle-to-cycle variability of the pressure oscillation intensity. Kirsten, M. et al., in [30], differentiated the pressure oscillation caused by an HCCI combustion, named as ringing, with the autoignition of the end gas at the end of the combustion which is known as knock. Li et al. used thermodynamic models [31] and Bahri et al. neural networks [32]combined with experimental data to analyse the ringing intensity: both concluded that shortest combustion duration (from CA10 to CA50) are associated with higher ringing intensities. Rahnanma et al. suggested using nitrogen for reducing the reactivity of the mixture and hence maintaining ringing intensities under desirable limits [33], while Ahmadi et al. alerted from knock occurrences when adding hydrogen to methane-diesel reactivity controlled compression ignition (RCCI) engines [34].

The authors have recently published a method for deriving the speed of sound by analysing the frequency of the pressure oscillations and obtaining the trapped mass from the ideal gas law [35,36]. A direct transformation was also developed by combining the resonance theory with the Fourier transform. The new transformation avoids the computational burden of time-frequency analysis and directly obtains the optimal trapped mass which characterizes the pressure oscillations [37]. The method does not require any calibration for pent-roof combustion chambers while the acoustical response of piston-in-bowl combustion chambers can be characterized with experimental data or by performing a numerical analysis of the combustion chamber by finite element method (FEM), as demonstrated in [38]. The measurement of trapped mass obtained from resonance has a cycle-to-cycle time response and does not rely in mass flow sensors, which might be used for improving the accuracy and the transient response of some models, such as proposed in [39] for NO_x modelling, in [40] for exhaust temperature estimation, in [41] for residual gases modelling, or in [42] for knock prediction.

This paper analyses in-cylinder pressure data from two engines in order to characterize the resonance excitation at various combustion modes. Current studies of resonance lack from an appropriate tool for analysing the pressure oscillations that resonate along the combustion chamber. Time-frequency analysis, such as Wigner distribution or STFT, is based on identifying constant frequency harmonics during the piston stroke. However, the frequency of resonance evolves during the piston stroke as a function of the combustion chamber properties. The present paper proposes a compact transformation that combines resonance theory with signal analysis for an adequate analysis of the resonance intensity along the piston stroke. The new mathematical tool can be used to design combustion control strategies to reduce the resonance excitation, to detect knock, or to identify the optimal range to analyse the pressure oscillations for a trapped mass estimation.

The paper is organized as follows: next section describes the two engines used and the tests performed. Section three presents the transformation proposed. Section four aims to characterize each combustion mode and its resonance excitation by using some of the tests recorded for illustration purposes. Section five illustrates the potential of such knowledge for trapped mass determination, and finally, Section 6 collects the main conclusions of the work.

2. Experimental setup

2.1. Engine A

A conventional light-duty spark-ignited engine was modified to enable multi-mode combustion, namely SI, CAI, and SACI. The original engine already dispose a double overhead camshaft (DOHC) with a phasing authority of 50 degrees of crank angle degrees in the VVT system of each valve, which was used to perform NVO strategies. Negative valve overlap (NVO) is used to control the internal residual gases for providing sufficient energy for autoignition [43,44] in CAI combustion, while in spark assisted compression ignited (SACI) mode the flame propagation created by the sparks is used to control the autoignition of the end-gas [45,46].

A custom piston and head machining allowed to increase the compression ratio from 9.2 to 11.25. A high pressure cooled EGR system was connected downstream of a 58 mm throttle body. These two elements, the throttle and the EGR, were moved further upstream to ensure a proper mixing. A turbocharger, controlled with a waste-gate