

Cycle by Cycle Trapped Mass Estimation for Diagnosis and Control

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ABSTRACT

The development of one cycle resolution control strategies and the research at HCCI engines demands an accurate estimation of the trapped mass. In contrast to current methods for determining the mass flow, which are only able to determine averaged values of the flow entering the cylinders, the present paper proposes a methodology based on the in-cylinder pressure resonance. The determination of such frequency allows inferring the cylinder mass with one cycle resolution. In addition, the method permits determining error metrics based on the mass conservation principle. Validation results for a reactivity controlled compression ignition (RCCI) engine equipped with electrohydraulic variable valve timing (VVT) are presented to illustrate the performance of the method.

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INTRODUCTION

Trapped mass estimation is currently achieved by the estimation of different inputs: air mass by flow sensors, fuel mass by injection calculations, and residual gases through different assumptions.

The air measurement can be improved by observers [1,2], Kalman filters [3,4,5], mean value models [6,7], or data-driven methods [8], which improve the estimation of the air mass flow. The injected fuel mass estimation provided by the electronic control unit (ECU), despite its possible deviations [9, 10], has in most cases the required precision. The external exhaust recirculated gases (EGR) are estimated from exhaust and intake CO₂ concentration. However, the internal residual gases cannot be sensed properly and different assumptions are used, e.g. valve flow methods calculate the residual trapped mass by physical valve models [11,12,13], while Δp method relies on polytropic compression [14].

Nevertheless, none of these methods is suitable for estimating accurately the trapped mass on transient operation: On the one hand, flow methods, which make use of averaged values, cannot estimate instantaneously the trapped mass with precision, then leading to important errors during transient operation. On the other hand, the assumption of adiabatic behavior or the use of unknown in-cylinder parameters for the models, such as the temperature of the gases, results in serious errors on the estimated trapped mass [15].

The present paper harnesses the relation between the speed of sound and the resonance frequency to develop a method for

estimating the mass. A method based on the resonance permits obtaining a mass estimation with cycle-to-cycle resolution, just relaying on the pressure signal, a volume calculation and a composition assumption. Even more, it is possible to calculate the cylinder mass variations in poly-cylindrical engines.

Only R. Hickling et al., in the early 80's, tried to use the resonance phenomenon in order to estimate in-cylinder variables, particularly the bulk temperature [16,17]. Herein, unlike the works developed by R. Hickling et al., the authors have made use of time-frequency signal processing [18] for an accurate estimation of the resonance frequency. Moreover, the possibility of obtaining many measures during a cycle permits an error metric based on the mass conservation principle. The method was tested under specific transient tests and compared with current methods on different stationary points, varying the trapped mass and the injection strategy.

The paper is organized as follows. First, the main working principles of the method are explained: the state of the art in the study of the pressure resonance, followed by the singularities of the proposed method. Once the methodology is known, the RCCI engine used to test the method is described. Following, the tests developed are presented and the results obtained are commented: transient steps will evidence the one cycle resolution, while stationary measured points will demonstrate its accuracy. Finally, last section is aimed to highlight the main contributions of the method.

METHODOLOGY

Pressure Resonance

In-cylinder pressure resonance is a well-known phenomenon, extensively studied along the last decades in order to detect knock and reducing noise [19, 20, 21]. Pressure resonance consists on high frequency (few kHz) oscillation caused by pressure waves on the cylinder (figure 1).

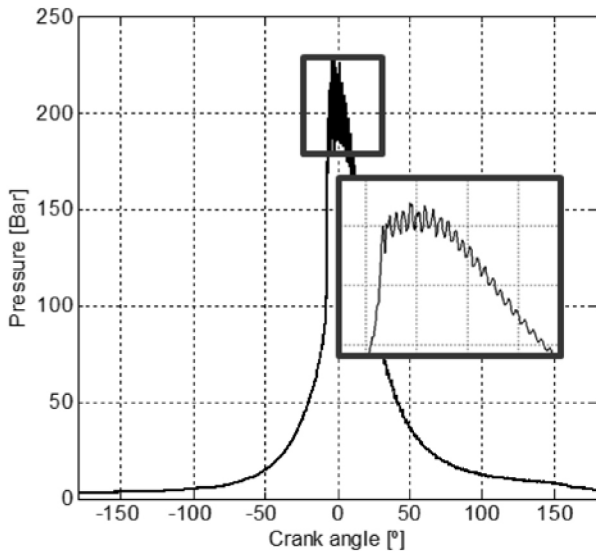


Figure 1. Pressure signal of a cycle with knock

Most of pressure resonance works use the approach stated by Draper [22] to estimate the resonance frequencies by a cylindrical chamber assumption: Draper solved the wave equation with Bessel functions for a cylindrical geometry. He ended up with (1), which relates the resonance frequency ($f_{i,j}$) with the cylinder diameter (D), the speed of sound (a) and a Bessel constant ($B_{i,j}$), tabbed at table 1. The axial modes can be neglected because the frequencies associated to h (height of the combustion chamber) are too high.

$$f_{i,j} = a \sqrt{\frac{B_{i,j}^2}{(\pi D)^2} + \frac{g^2}{(2h)^2}} = \frac{a B_{i,j}}{\pi D} \quad (1)$$

Table 1. First radial modes for a cylindrical chamber

	$B_{i,0}$	$B_{i,1}$
$B_{0,j}$	3.832	7.016
$B_{1,j}$	1.841	5.332
$B_{2,j}$	3	6.75

Draper's equation is normally used to estimate a reference frequency to capture (knock detection) or to eliminate the resonance (combustion diagnosis). To these ends, it is used a pass-band or a low-pass filter with few kHz as margin [21].

Although far from the TDC the cylindrical solution is valid, near the TDC this solution is not precise in common reciprocating engines as consequence of the singular bowl geometries [23].

Figure 2 compares the cylindrical resonance frequencies stated at (1) with the experimental frequencies obtained at a cylinder with bowl: although there is a frequency variation due to temperature, the resonance frequencies change even more. The discrepancies between (1) and the results obtained are presumably caused by the geometry shift between a cylinder dominated geometry (far from the TDC) and a bowl dominated geometry (near the TDC).

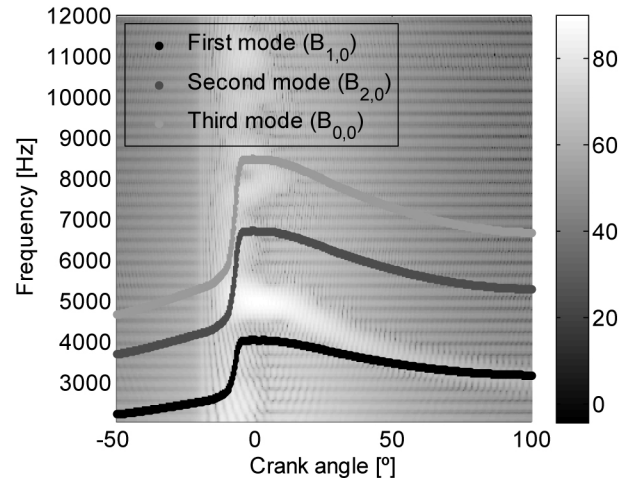


Figure 2. Cylindrical resonance modes over a spectrogram in a cylinder with bowl

A possibility for correcting the bowl, is applying pre-calibrated crank angle varying constants for the bowl (2). In this manner, although a cylindrical solution is being used, the geometry shifting errors are taken into account by specific constants ($B_{i,j}'$). The main drawback of this method is the calibration of constants, because it must be done with previous data when the mass must be precisely known.

$$B_{i,j}' = f(\alpha) = \frac{\pi D f_{i,j}}{a} \quad (2)$$

Resonance Frequencies Identification

Once the relation between the resonance frequencies and the speed of sound is calibrated (2), the opposite process can be done to obtain the speed of sound during a cycle (3). In both processes, the frequency calculation is crucial for the final accuracy of the measurement.

$$a = \frac{\pi D f_{i,j}}{B_{i,j}} \quad (3)$$

The authors have used the discrete Short Time Fourier Transform (STFT) with zero padding to identify the frequency components of the signal: the STFT is based on windowing the pressure signal at different crank angle positions in order to have crank angle resolution while applying zero-padding permits improving the frequency resolution [24].

Figure 3 shows the output obtained by using a *Blackman-Harris* window of 25 degrees. Although the identification of all modes is possible, only the first one appears neatly in all the range.

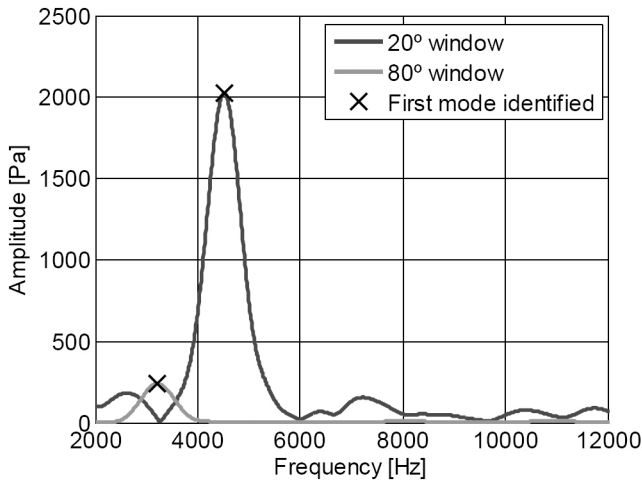


Figure 3. Resonance frequency identification at 20° and 80° (1200 rpm, 50% load, one diesel injection RCCI combustion).

In order to have an appropriate resonance identification, the excitation must be sufficient. Several resonance quantification works [24, 25] relate the resonance amplitude to the pressure gradient. Consequently, although this method can have problems when used with conventional combustions, it is fully adequate for new combustion modes engines which are nowadays investigated and need combustion diagnosis tools [26].

Problem Formulation

The determination of the trapped mass can be solved through the following equations:

$$a = \frac{\pi D f_{i,j}}{B_{i,j}} \quad (4)$$

$$a^2 = \gamma RT \quad (5)$$

$$pV = mRT \quad (6)$$

$$R = f(Y_x) \quad (7)$$

$$C_v = \frac{R}{\gamma - 1} = f(Y_x, T) \quad (8)$$

Actually, the mass variation due to composition (Y_x) is bounded below 3.5% (appendix 1). Accordingly, a rough estimation of a constant composition (by assuming 50% of burnt products) is expected to have errors associated that are lower than 1%. To cope with lower errors, the composition can be inferred by using polynomial expression for R and γ and assuming complete combustion:

1. The dependency of R and γ with the temperature and the composition (Z and δ) can be calculated as in [27]. M. Lapuerta et al. divided the gas in 3 species (fuel, air and burnt gases). They considered the temperature effect over R negligible and obtained polynomial correlations with temperature for estimating C_{vp} , C_{va} and C_{vb} .

$$R = R_f Y_f + R_a Y_a + R_b Y_b \quad (9)$$

$$C_v = C_{vf}(T)Y_f + C_{va}(T)Y_a + C_{vb}(T)Y_b \quad (10)$$

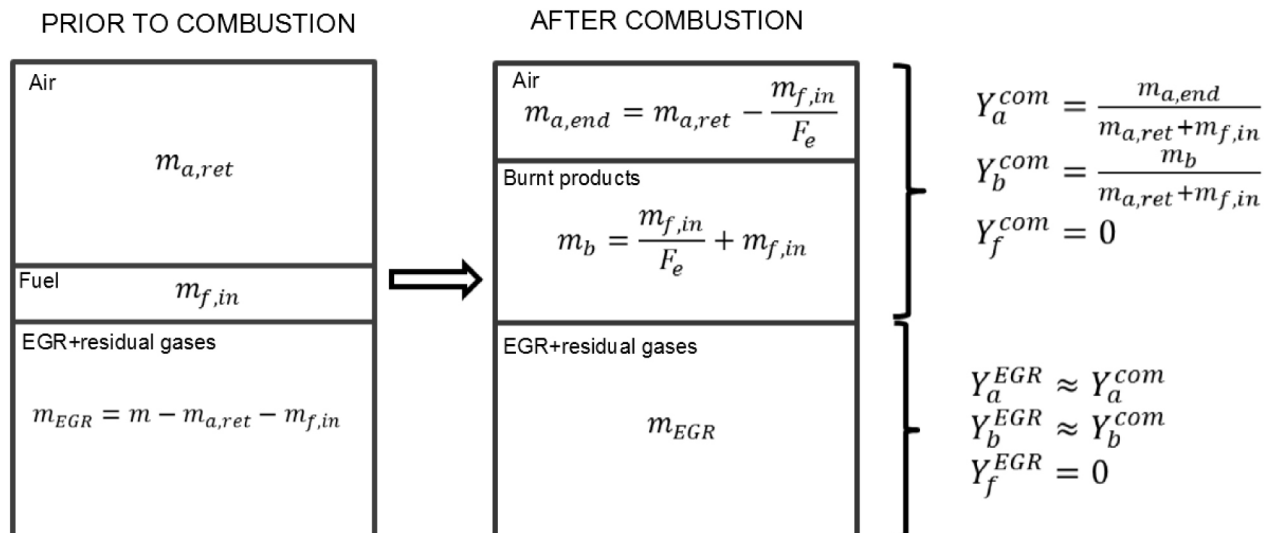


Figure 4. Scheme of combustion assuming complete combustion