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IFAC-PapersOnLine 49-11 (2016) 461–468

Simultaneous Estimation of Intake and Residual Mass Using In-Cylinder Pressure in an Engine with Negative Valve Overlap

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Abstract:
This work presents a new method for the simultaneous estimation of the intake and residual mass in an engine operating with negative valve overlap. The method exclusively uses the in-cylinder pressure information and no additional measurement is needed. It is based on the determination of the total mass through the pressure resonance in the cylinder and the assumption of a polytropic expansion of the gas during the exhaust stroke for determining the residual gases. The method has been demonstrated on an engine with negative valve overlap operating in SI, SACI and HCCI combustion. The results show that the proposed method can provide good mass estimations in most cycles in HCCI and SACI combustion, and in lightly knocking cycles while operating in SI combustion.

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Keywords: In-cylinder pressure, residual mass, air mass, estimation, negative valve overlap, HCCI, SACI, SI

1. INTRODUCTION

Cylinder charge determination in internal combustion engines is a difficult task, which is usually achieved through the combination of different measurement and modelling techniques for the individual determination of the external flows (air, fuel, recirculated gas) and the residual gases. Most of the standard techniques rely on sensors that are slower than the characteristic engine cycle time, and then cannot provide a proper description in the case of fast transients or significant cycle-to-cycle variability, as is a common situation in low temperature combustion (LTC) modes.

LTC modes, such as homogeneous charge compression ignition (HCCI) and spark assisted compression ignition (SACI) combustion, have shown potential in increasing the thermal efficiency of the conventional spark ignited (SI) engine, while maintaining low or easily treatable engine-out emissions (Zhao et al., 2002; Manofsky et al., 2011). For the practical implementation of these LTC modes, an exhaust gas recompression strategy is often employed using negative valve overlap (NVO), as this strategy provides fast control of the gas charge composition and temperature, which directly impacts combustion phasing (Cairns and Blaxill, 2005; Wheeler et al., 2013). In NVO engines, the exhaust valve closes well before top dead center of the exhaust stroke, as shown in Figure 1, thereby trapping high levels of residual exhaust gas necessary to promote autoignition of the charge in the following cycle. However, the temperature and composition of the charge have to be well controlled to achieve the appropriate top dead center

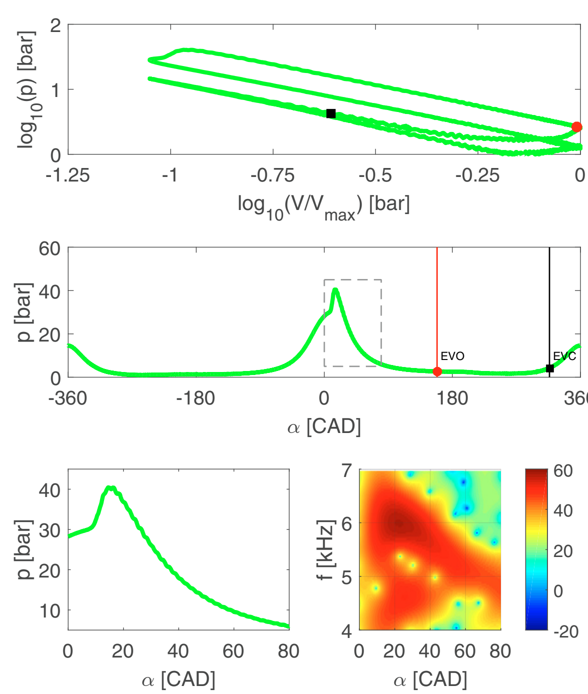

Fig. 1. Unfiltered pressure trace of a given cycle operating with NVO; EVO and EVC have been marked. Left bottom plot is a zoom of the 0 to 80 CAD region showing pressure resonance phenomenon. Right plot is the spectrogram of that section in the region from 4 to 7 kHz; power spectral density is expressed in logarithmic scale (dB/rad/sample).

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10.1016/j.ifacol.2016.08.068

(TDC) conditions for optimal combustion characteristics (Lavoie et al., 2010).

For the case of an HCCI engine with NVO, Hellström et al. (2013) developed a two-state deterministic model able to predict the mean combustion phasing behavior via the evolution of recycled thermal and chemical energy carried from cycle-to-cycle through the trapped residuals. The global characteristics of the cyclic variability at various operating points were also captured in Hellström et al. (2013) by introducing a small random perturbation on top of the predicted mean residual mass. The prediction of the cyclic dispersion patterns led to cycle-to-cycle control of fuel injection for reducing the combustion variability (Hellström et al., 2014). Analysis of various model-based control techniques in Hellström et al. (2014) showed high sensitivity away from the nominal operating conditions, hence an improved calculation of the residual mass could augment the modeled residuals and improve the control robustness.

A number of residual estimation methods based on in-cylinder pressure information for engines operating with NVO are available in the literature, as summarized and compared by Ortiz-Soto et al. (2012):

- State Equation method, where the exhaust temperature is propagated from the exhaust manifold to the cylinder and the residual mass is calculated through the application of the state equation at the exhaust valve closing (EVC):

$$m_{res} = \frac{p_{EVC} V_{EVC}}{R T_{exh}} \quad (1)$$

- Yun and Mirsky (1974) method, where the gas mixture is assumed to evolve according to a polytropic and the measured intake mass flow is compared with the state equation evaluated at both exhaust valve opening (EVO) and EVC:

$$m_{res} = \frac{(m_a + m_f + m_{egr}) \frac{V_{EVC}}{V_{EVO}} \left(\frac{p_{EVC}}{p_{EVO}}\right)^{\frac{1}{\gamma}}}{1 - \frac{V_{EVC}}{V_{EVO}} \left(\frac{p_{EVC}}{p_{EVO}}\right)^{\frac{1}{\gamma}}} \quad (2)$$

- Fitzgerald method (Fitzgerald et al., 2010), which also uses the measured intake mass flow for solving the mass difference between EVO and EVC, but the in-cylinder temperature evolution during the exhaust stroke is modeled combining the convective heat transfer equation with the assumption of T_{exh} to be representative of the mean temperature inside the cylinder. Woschni correlation (Woschni, 1967) is used for the heat transfer coefficients.

Despite the fact that in-cylinder pressure measurement is fast enough to provide cycle-to-cycle information, in all methods presented above in-cylinder pressure information is combined with another variable to estimate residual mass. Exhaust temperature, T_{exh}, is used as an approximation of in-cylinder temperature during the exhaust process in the State Equation and Fitzgerald methods, and intake mass flow in the Yun and Mirsky and Fitzgerald methods. However, such assumptions present significant drawbacks with the most important being the difficulty to properly represent transient or cycle-to-cycle variability since the method is hampered by the slow response of both exhaust temperature and mass flow sensors. Even if fast sensors are available in a laboratory setting, their time constants for a durable on-board application is not sufficient to provide cycle-to-cycle information, hence the existing method assumptions are not fulfilled.

Residual estimation in an HCCI engine operating with significant cyclic variability has been addressed by several authors. Larimore et al. (2013) developed an online estimator of the residual gas fraction, where blowdown temperature is modeled in order to consider the effect of the residual temperature on the next cycle. In Larimore et al. (2015) a real time implementation of Fitzgerald's method was presented and the effect of errors in the determination of T_{exh} was analyzed, concluding that there is a low sensitivity of the residual mass estimation to errors in T_{exh}. Once again, and as pointed out by the authors, the main limitation of the algorithm is that it requires a transient air mass as an input.

With the aim of overcoming these difficulties, this paper presents a new method which exclusively relies on the in-cylinder pressure signal for simultaneously providing an estimation of the mass flow entering the cylinder and the residual gas mass. The method takes benefit of the excitation of resonant modes in the cylinder by the combustion, which produces pressure oscillations following the combustion as depicted in the lower left plot in Figure 1, for deriving the mix temperature during the expansion stroke and determining the total cylinder mass (Guardiola et al., 2014). This total mass estimate is then combined with the assumption of an adiabatic expansion during the exhaust phase, as in Yun and Mirsky method, for discerning between external and residual mass for the case of NVO engines. Since only pressure information is used and no temperature or flow measurement is needed, the method is expected to have a better time response than the existent methods in the literature.

2. EXPERIMENTAL SETUP

In this study, experiments were performed on a modified 2010 GM LNF Ecotec I4 spark-ignited engine. The engine has been modified to enable multi-mode combustion, including conventional SI, SACI and HCCI combustion. The compression ratio of the engine has been increased from 9.2:1 to 11.25:1, with custom pistons and head machining. The main characteristics of the engine are shown in Table 1.

Number of cylinders	4
Bore (B)	86 mm
Stroke (S)	86 mm
Conrod length (L)	145.5 mm
Compression ratio (cr)	11.25

Table 1. Engine main characteristics.

The engine is equipped with DOHC, dual variable valve timing (VVT) with 50 degrees of crank angle degree phasing authority. A negative valve overlap camshaft set was used in this work with maximum lift of 3.5 mm and 154 crank angle degrees duration, defined at 0 mm opening. A high-pressure cooled EGR system has been added to the engine with associated flow control, which is connected downstream of a 58 mm throttle body. The throttle and

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