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Cylinder charge composition observation based on in-cylinder pressure measurement

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ABSTRACT

Accurate cylinder charge and composition estimation is crucial for proper combustion control, however, current sensors and models show different issues for transient estimation. The work presented in this paper combines a novel technique for trapped mass estimation, which relies on the in-cylinder pressure resonance, with on-board engine sensors by taking into account the intake manifold dynamics with a closed-loop observer. The resonance method provides a measurement of trapped mass with one cycle resolution. This measurement feeds a Kalman filter to improve the transient and steady response of the intake charge and composition estimation. The observer was validated in a four stroke heavy-duty engine, showing fast transient capabilities and an adequate steady-state accuracy.

1. Introduction

The estimation and control of the cylinder charge and its composition is already crucial in conventional combustion modes: the composition in SI engines must be maintained in stoichiometric conditions in order to properly operate the three way catalyst (TWC) [1–3], and the soot-NO_x trade-off in CI engines is highly affected by external gas recirculation (EGR) [4–6]. In addition, an accurate intake composition estimation in engines working with low temperature combustion concepts will be necessary not only for emissions control, but also for combustion stability [7–9]. Such accurate and fast composition estimation is a big challenge for the current set of sensors included in commercial electronic contol units (ECUs). The usual set of sensors includes a combination of air mass flow, pressure, and temperature sensor at the intake and a lambda sensor at the exhaust.

Hot film anemometers, usually installed on-board to measure the air mass flow at the intake [10–12], show a non-linear time response [13–15] that varies in the range of 30–50 ms, and are subjected to severe ageing due to the accumulation of dust on the sensing element, which causes a bias that can reach 20% of the measured value [16–18]. In addition, they are usually placed at the beginning of the intake line, far away from the cylinder port, thus limiting any cycle-to-cycle mass flow determination and being significantly affected by intake system filling dynamics.

The injected fuel mass is estimated on-board through the differences in pressure at the injector and the energizing time, however, common rail systems have cylinder-to-cylinder dispersion due to minor errors in hole diameter, unavoidable owing to manufacturing variation and to the accumulation of deposits [19,20] and the use of multi-injection strategies in common rail systems also increases the uncertainties in the final measurement due to pressure waves in the injection line [21,22]. Universal exhaust oxygen sensors UEGO (λ sensors) [23,24] or new on-board NO_x sensors [25–27] permit a linear resolution of the fuel to air ratio over a wide range. Both sensors are also affected by ageing, e.g. Schilling [28] reported a 5% error at $\lambda < 0.8$ and a 8.8% at $\lambda > 1.7$, when ageing UEGO sensors during 3000 working hours.

The estimation of exhaust Gas Recirculation (EGR) is one of the most challenging aspects. Common on-board flow rate meters cannot be used at the extreme exhaust conditions, namely temperature and particles concentration [29,30], and the EGR on-board estimation is usually performed by subtracting the air mass flow to the overall trapped mass estimated by the speed density method, which relies in the volumetric efficiency estimation and a temperature and pressure measurement at the intake manifold [31,32].

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Traditionally, the volumetric efficiency is calibrated as a function of the engine speed n and intake manifold pressure p_{int} with a 2D table [33]. However, variable valve timing (VVT) strategies for intake charge control increase the degrees of freedom for the volumetric efficiency estimation [34,35], and it cannot be stored as a simple 2D table [36]. Some solutions for modelling the volumetric efficiency can be found in [37–39] by using neural networks, or in [40,41] by using physical-based models for η_v in engines with VVT. Although the time response of speed-density approaches is sufficient, variations in the operating conditions, such as wall heat transfer or fluid friction losses, can lead to significant model errors in transient operation [42,43].

Regarding the EGR estimation in test benches, CO_2 balance is the most commonly used technique [44–46]. Nevertheless, the transient response of this measurement technique highly depends on the gas analyser system response and on the intake and exhaust manifold dynamics, leading to significant errors when transients are considered [47]. Furthermore, several authors have pointed out the relevance of the probe location in high-pressure EGR loops: because of incomplete mixing, high-pressure loops create a notable cylinder-to-cylinder dispersion, which may lead to a bias in the determined EGR rate [48–50].

Some authors suggest using the orifice principle to model the mass flow rate at the EGR valve [51–53]. However, this technique requires a detailed knowledge of the valve flow process, i.e. the instantaneous effective area and the conditions at the inlet and outlet of the valves, which may be not available in on-board applications or might lead to significant errors when the sensor measurements are not representative of the conditions at the surroundings of the valve.

Recent developments in in-cylinder pressure sensors have lowered the cost of such sensor while the number of application are justifying its commercial application. A new methodology proposes the derivation of the trapped mass through the analysis of the resonant frequency of the in-cylinder pressure oscillations. The method was recently applied to DI and HCCI engines [54–56], and some applications, i.e. NOx and residual gas fraction estimation, have been already explored [57,58].

In this scenario, it may be expected that new engines combine several of the aforementioned sensors, thus processing a variety of information sources for the cylinder charge estimation. In such data-rich environment, advanced techniques may be used for improving the estimation of the air charge and intake composition. Closed-loop observers are a tool for combining information coming from sensors placed at various locations to determine the charge and the composition at the intake. The dynamics at the intake and exhaust process can be represented by an emptying and filling model: these models analyse a control volume with the mass and energy conservation equations, by assuming no wall heat transfer and perfect gas mixture composition [59–61]. This is the case of Leroy et al. [62] where the manifold air mass flow m_{air} is considered as an input, the intake pressure p_{int} is the system state, and unknown parameters can be included in the state equations. Similar examples of Luenberg-like observers can be found in [63,64] for air-charge estimation in SI engines, in [65,52,66] for EGR estimation by using isothermal intake model dynamics and in [51,67,68] by using the transport equations at the intake for the burnt gases concentration.

Kalman filters (KF) are a concrete type of closed-loop observers where the observer gains are continuously adapted to improve the convergence and accuracy of the observer [69,70]. Several examples can be found in literature for automotive applications: in [71], an extended Kalman filter is proposed for air-charge estimation improvements in SI engines, in [72] the complete adiabatic manifold model is used in combination of a throttle model and a first order system modelling the temperature sensor dynamics for predicting the actual in-cylinder air flow, and in [73] an intake manifold model of a CI engine with EGR is used to calculate all the mass flows.

The present work makes use of in-cylinder pressure resonance to feed a Kalman filter with an instantaneous trapped mass measurement, which combined with several sensors, already in use in commercial vehicles, through models of the intake manifold dynamics aims to improve the transient response of the intake charge estimation. The paper is structured as follows: First section presents the experimental facilities employed, the second section is devoted to introduce the main models and algorithms, the third section shows the results obtained, and the last section highlights the contribution of the model and its main capabilities.

2. Experimental facility

Experimental tests were carried out in a heavy-duty engine equipped with port fuel gasoline injection and diesel direct injection. The engine can work with conventional diesel combustion by deactivating the port fuel injection, or using both injections for performing RCCI or PPCI dual fuel combustions. The main characteristics of the engine are collected in Table 1.

A low-pressure EGR loop was used to guarantee a good mixing with a better efficiency. However, a high-pressure EGR loop was also used to ensure sufficient EGR when the exhaust and intake conditions do not allow the LP-EGR to provide the engine with the required residual gases. The in-cylinder pressure was sensed by Kistler 6125C pressure sensors with a resolution of 5 samples/CAD. The exhaust gases where analysed with an Horiba Mexa-ONE-D1-EGR. A complete scheme of the experimental test bench is shown in Fig. 1.

Two type of transient tests were performed to calibrate and validate the models and the observer performance:

- Mass flow variations: The VGT was controlled to modify the intake charge at various engine speed conditions, namely 1000, 1200, 1500 and 1800 rpm. At each engine speed a slow increase of the VGT running from the minimum VGT action (limited by misfire occurrences) to the maximum VGT position (fully closed) was used for calibration and steady validation purposes. Afterwards, fast steps were performed ending at the same initial VGT position to analyse the dynamic response of the mass flows. The EGR valve was closed in order to reduce the number of uncertainties. Fig. 2 shows the evolution of the intake pressure and the engine speed during such tests.
- EGR steps: Four steps were performed at 1200 rpm to analyse the dynamic response of the system. The LP-EGR valve, and the HP-EGR valve, were sharply controlled from the minimum to its maximum value to see its effect at the intake charge and composition. The aforementioned steps (HP-EGR valve, LP-EGR valve) were executed at 25% and 75% load conditions.

Table 1
Main engine characteristics.

Field	Units	Value
Cycle	[–]	4-stroke
Cylinders	[–]	6
Combustion type	[–]	CI-RCCI
Unitary displacement	[cc]	1300
Bore	[mm]	110
Compression ratio	[–]	12.2:1