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CLOSED-LOOP CONTROL OF EGR USING ION CURRENTS

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ABSTRACT
Two virtual sensors are proposed that use the spark-plug based ion current sensor for combustion engine control. The first sensor estimates combustion variability for the purpose of controlling exhaust gas recirculation (EGR) and the second sensor estimates the pressure peak position for control of ignition timing. Use of EGR in engines is important because the technique can reduce fuel consumption and NO_x emissions, but recirculating too much can have the adverse effect with e.g. increased fuel consumption and poor driveability of the vehicle. Since EGR also affects the phasing of the combustion (because of the diluted gas mixture with slower combustion) it is also necessary to control ignition timing otherwise efficiency will be lost. The combustion variability sensor is demonstrated in a closed-loop control experiment of EGR on the highway and the pressure peak sensor is shown to handle both normal and an EGR condition.

KEY WORDS
Ion currents; Virtual sensing; Electronic engine control; Exhaust Gas Recirculation; Ignition timing; Combustion variability.

1. Introduction

Exhaust Gas Recirculation (EGR) is today a common technique for reducing NO_x emissions and improving fuel efficiency in combustion engines. Using EGR means that some of the exhaust gas is transported back to the intake side of the engine and mixed with fresh intake air. The dilution of the intake charge results in a slower combustion speed (flame propagation) and lowered combustion temperature. The lowered combustion temperature directly reduces formation of NO_x emissions. In a throttled engine (such as a normal gasoline engine), recirculating gas can also increase the pressure level of the intake manifold. This results in less pumping work needed to draw the intake charge into the cylinder reducing the efficiency losses (and thus improves fuel economy) at partial load operating conditions. However, it is very important to not recirculate too much exhaust gas, as it may significantly deteriorate combustion. This can result in partial burning and misfires (and thus increased HC emissions), reduced driveability of the vehicle and increased fuel consumption. It is therefore desirable to control the amount of recirculated exhaust gas in a closed loop fashion by the use of a sensor that provides information on the combustion state. The required information could be provided by an in-cylinder pressure sensor, but those are currently too expensive for use in production. For a sensor to be considered for production it is important that it is cost-effective and able to operate in real-time. The spark plug can be used to measure a small current (Gillbrand, Johansson & Nytomt 1987) in the cylinder during combustion. In this paper it is shown how the current can be used as a virtual sensor to control combustion variability to a desired value in a closed loop using the EGR valve. Measurements of the current and the corresponding NO_x emissions and fuel consumption are shown for an engine mounted in a dynamometer, as well as a closed loop experiment on the road.

However, in order to gain the full benefits of using exhaust gas recirculation it is important to not only control the recirculation valve, but also to ignite the mixture at the right point in time. If the same spark advance setting for normal operation is used for EGR operation then the pressure peak position will be late (because of the slower combustion) and efficiency will be lost. It is therefore important to also be able to control the pressure peak position in a closed loop without adding an expensive sensor (such as an in-cylinder pressure sensor (Hubbard, Dobson & Powell 1976)). A virtual sensor (based on ion current measurements) for estimating the pressure peak position is therefore also proposed that is shown to work both under normal and EGR operation for data measured while driving on the highway.

2. Ion current measurements

Ion current sensing has been in use by some engine management systems since 1988. The pioneer was SAAB with cam-phase sensing as the first application (Auzins, Johansson & Nytomt September 1995*b*). Development after the initial application was directed towards achieving misfire detection (Lee & Pyko 1995) in all speed and load conditions (due mainly to CARB OBDII regulations). The sensing technique has since then been applied to knock detection (Auzins, Johansson & Nytomt 1995*a*), control of

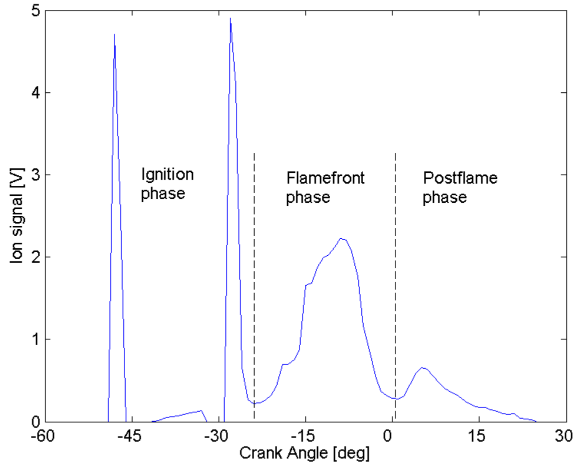

Figure 1. Single cycle ion current measurement with its three characterizing phases; ignition phase, flame-front phase and post-flame phase.

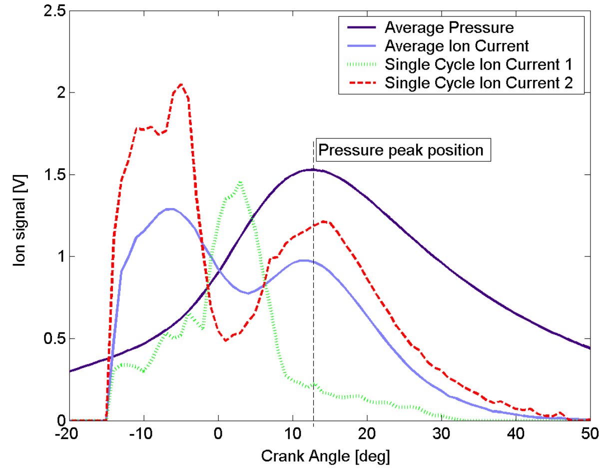

Figure 2. The averaged ion current and in-cylinder pressure signal. Two single cycle measurements of the ion current are also shown to illustrate the diversity of the signal. In the averaged ion current signal a good correlation can be found between the position of the second ion peak and the pressure peak (at least for high load cases).

air-fuel ratio (Wickström, Byttner & Holmberg 2005) and ignition timing (Eriksson & Nielsen 1997). The sensing technique is based on applying a positive low-voltage DC bias to the spark plug after the ignition coil has discharged. This electrical bias is needed in order to attract the ionized species that are created during combustion. An example of an ion current measurement is shown in Fig. 1. The first part in the figure shows the coil charging and ringing which is a disturbance related to the ignition event. It is typically removed as it is believed to not contain much useful information about the combustion. The second part is the flame-front phase which is where the flame propagates and burns through the air-fuel mixture. Chemical ionization is believed to be dominant in this phase and the current has shown to be well correlated with air-fuel ratio (AFR) (Reinmann, Saitzkoff & Mauss 1997) and mass fraction burned (MFB) (Daniels 1998). The third part is the post-flame phase and this is where the temperature has increased to such a degree that thermal ionization dominates the signal. The post-flame ion peak is well-correlated with the location of pressure peak, see Fig. 2. Several algorithms have earlier been proposed which use the position of the post-flame peak to estimate the position of the pressure peak (Eriksson, Nielssen & Nytomt 1996, Holmberg & Hellring 2003, Wickström 2004). The concept of using the ion current to estimate combustion variability has experimentally been investigated earlier for variations in fuel and ignition timing (Andersson & Eriksson 2000) and for EGR and AFR (Byttner, Rögnvaldsson & Wickström 2001). When using EGR, the current becomes smaller and the peak becomes delayed (see Fig. 3). The cyclic variability of the signal shape also increases and it has been shown that the coefficient of variation (COV) of the ion integral is well-correlated to combustion variability. A standard variable that measures the power produced by a combustion cycle is the indicated mean effective pressure (IMEP)

$$IMEP = \frac{1}{V_d} \int p(\theta) dV(\theta) \tag{1}$$

where V_d is the displaced volume, $p(\theta)$ is the measured in-cylinder pressure and $V(\theta)$ is the volume at crank angle θ. Combustion variability is measured by the coefficient of variation for the indicated mean effective pressure, COV(IMEP), which is defined as

$$COV(IMEP) = \frac{\sigma(IMEP)}{\mu(IMEP)} \tag{2}$$

where σ and μ are the standard deviation and the mean value, respectively, over a number of consecutive combustion cycles. The ion integral (or total mass of the signal) is here computed as a sum over a window of length n

$$M = \sum_{k=1}^{n} I(c_k) \tag{3}$$

where $I(c_k)$ is the measured ion signal at crank angle c_k. Computation of COV(M) is done in the same way as in Eq. 2. Measurements have been made both in a dynamometer and on the road in a SAAB 9000 during normal (steady state) driving. The dynamometer measurements were primarily made in order to quantify fuel economy and NO_x emission improvements. Measuring NO_x online in a vehicle is not practical and it is difficult to quantify the fuel economy improvement on-the-road because of varying external conditions (such as wind and road profile variations).

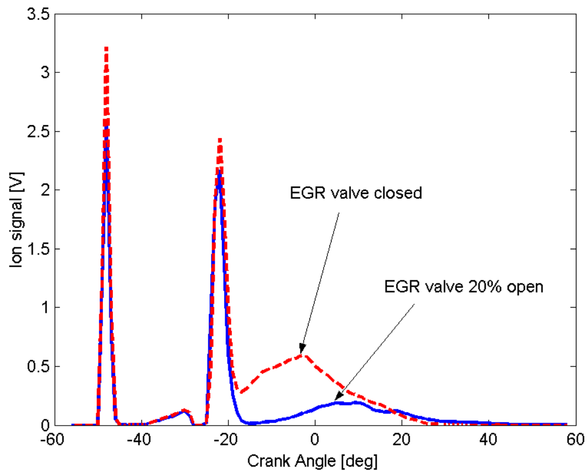

Figure 3. Averaged ion current measurements for a normal and an EGR case. When using EGR, combustion gets slower and temperature decreases resulting in a smaller signal amplitude and delayed peak.

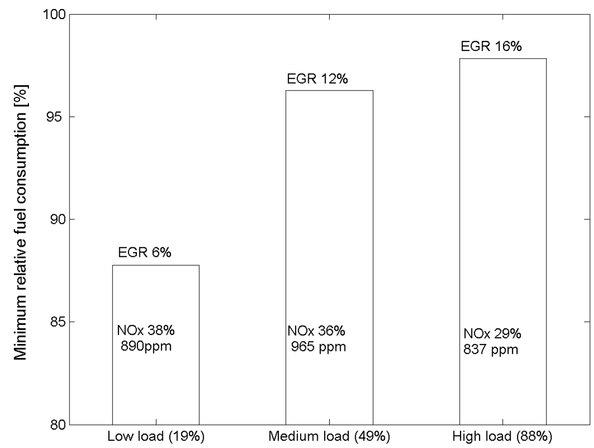

Figure 4. Minimum relative fuel consumption for three different load cases in a dynamometer. The NO_x emission level given in percent is the remaining NO_x compared to the case of not using any EGR.

2.1 Highway measurements

The highway measurements were made in a SAAB9000 with a 4 cylinder 2.3 litre low pressure turbo engine (B234E MY96) where each cylinder had a wide-band λ sensor mounted outside the exhaust ports (for cylinder individual control to stoichiometry). The ion currents were measured on all four cylinders as well as cylinder pressure on the first two cylinders. Cylinder pressure was in these experiments used for closed-loop control of ignition timing. The EGR valve was controlled by a stepper motor that could position the valve in 70 different absolute positions. Since EGR is mostly of interest during steady state driving (since maximum power and driveability is typically desired during transients) an engine speed of 1750 RPM in the fifth gear has been chosen for the experiments. This corresponds to a speed of 90km/h which is a typical cruising speed on the swedish highway. Computing COV(IMEP) on-the-road is however not unproblematic since there does not exist any stationary operating point. For this reason the values of COV(IMEP) are much higher than those measured in a dynamometer (even when using no EGR) since the load (intake manifold air pressure) varies even when driving with a constant engine speed.

2.2 Laboratory measurements

The dynamometer data were collected at a single engine speed (1750 RPM) with the same type of engine as was used in the highway experiments. Three different load cases (19%, 49% and 88% of maximum load) and four different EGR rates were measured (slightly different for different loads, but ranging approximately from 0% to 20%). The EGR rate is defined as the percentage of the mixture charge that enters the cylinder as (externally) recirculated gas. The EGR rate is calculated from the difference in CO_2-massflow on the intake and exhaust sides of the engine. Air-fuel ratio was controlled to stoichiometric conditions in feedback by using a wideband λ sensor. Ignition timing was set to a fixed value (the timing that produced the maximum torque for the given operating point).

3. Virtual sensing of combustion variability

Use of EGR implies increased combustion variations; over a certain period of time there can be cycles that produce significantly different IMEP. Earlier papers (Andersson & Eriksson 2000, Byttner et al. 2001) have shown that the variations in the ion integral (computed as COV(M)) is a candidate for estimating combustion variability. We have found that this measure is not useful for the EGR rates that result in the best fuel economy. Figure 4 shows the EGR rates where the best fuel economy was found in the laboratory and the corresponding NO_x emission level for three different load situations. The largest fuel reduction (12%) was found in low load at an EGR rate of 6% and NO_x emissions are here reduced to 38% compared to the case of not using any EGR. In Fig. 5 the COV(M) is shown with the corresponding COV(IMEP) for the low load case. It can be seen here that there is a correlation between COV(M) and COV(IMEP) but that it is not good for low EGR rates. To find the point of minimal fuel consumption it is therefore not appropriate to compute COV(M). It has been found that using the mean value of M is more suitable for low EGR rates (shown in Fig. 6). This is mainly due to that at low EGR rates the (natural cyclic) variation of M is larger than the combustion variation imposed by us-

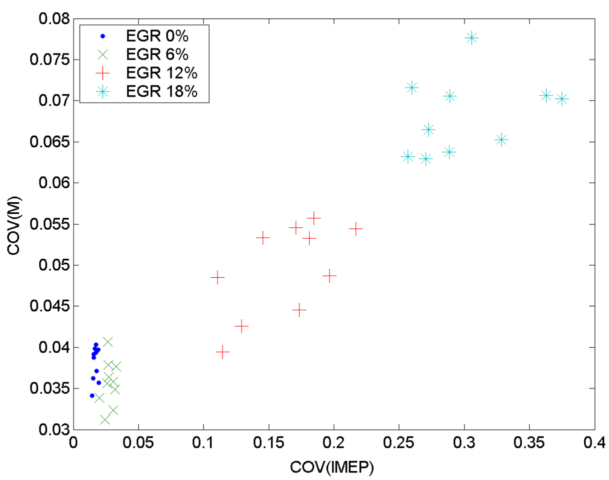

Figure 5. COV(M) vs. COV(IMEP) for the dynamometer measurements. There is a correlation but it is only good for discriminating between the high EGR rates.

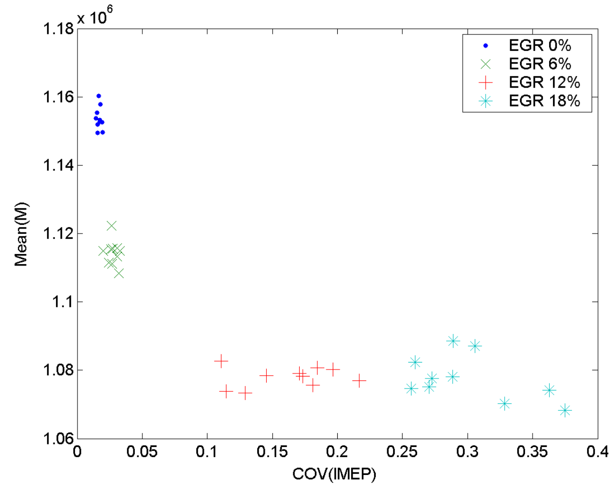

Figure 6. Mean(M) vs. COV(IMEP) for different EGR rates in a dynamometer. Using the mean value alone is much better than the COV value for discriminating in the low EGR rate range (compare with Fig. 5).

ing EGR. At the same time the mean of M is conversely related to COV(IMEP) resulting in low discrimination for high EGR rates (since at high EGR rates there is very little ionization which results in a low signal to noise ratio). Focusing on the low load case, the area of interest for reducing fuel consumption is for EGR rates up to 6%. The relation between the mean value of M and COV(IMEP), for brevity denoted v, is here roughly linear. A simple linear model with parameters d_1 and d_2 can then be fitted which estimates combustion variability as

$$\hat{v} = d_1 \cdot M + d_2 \quad (4)$$

where M is defied in Eq. 3.

3.1 Control of EGR

For the purpose of closed loop control the estimate of combustion variability is used as input to an integrating controller

$$u(t) = u(t-1) + \frac{1}{T_i}(v_{des}(t) - \hat{v}(t)) \quad (5)$$

where $u(t)$ is the EGR valve position at combustion cycle t, T_i is the integrating factor and v_{des} the desired COV(IMEP).

4. Virtual sensing of pressure peak position

Many ion signal based estimator schemes for pressure peak position have been proposed (see survey in (Holmberg & Hellring 2003)), but none has considered the EGR case. In presence of EGR, the ion current signal is weakened significantly. This fact can be explored such that EGR level is quantified by ion signal strength. A simple measure can be taken as the summation of the ion signal samples over a chosen window. In order to estimate the pressure peak position (θ_p), given a certain EGR level, another feature of the ion signal should then be chosen which is measuring signal shape but is independent of signal strength. Considering each sample of the ion signal as a point mass

$$m_k = I(c_k) \quad (6)$$

where $m = [m_1, \ldots, m_n]^T \in \Re^n$ and the corresponding crank angles are defined in a vector $c = [c_1, \ldots, c_n]^T$ where

$$c_k = \theta_w + k - 1, \qquad k = 1, \ldots, n \quad (7)$$

and θ_w is the starting angle of the window. As a measure of shape of the signal, the *center of mass* is chosen

$$c_M = c^T m / M \quad (8)$$

which is the balancing point of the window of point masses. The pressure peak position θ_p is chosen to be estimated from c_M, assuming a linear relationship for a given EGR level.

$$\hat{\theta}_p = a \cdot c_M + b \quad (9)$$

The parameters a and b are changing with EGR level, measured by M. Suppose good model approximations have been achieved for two EGR levels with mean M denoted M_1 and M_2. The resulting linear model parameters are a_1, b_1 and a_2, b_2, respectively. Linear interpolation between these cases gives

$$\begin{aligned} a(M) &= \tfrac{a_2 - a_1}{M_2 - M_1}(M - M_1) + a_1 \\ b(M) &= \tfrac{b_2 - b_1}{M_2 - M_1}(M - M_1) + b_1 \end{aligned} \quad (10)$$

Thus, the pressure peak position is estimated from two features of the ion signal, the center of mass (for shape information) and the mass (for size and EGR information). For

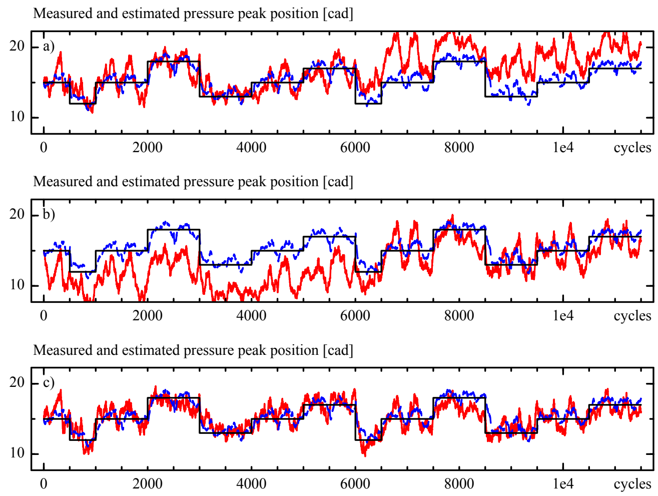

Figure 7. Measured pressure peak position (dashed) θ_p and estimated (solid) $\hat{\theta}_p = a \cdot c_M + b$. The first 6000 cycles are without EGR and the rest are with EGR. **a)** Tuned for no EGR: $a = a_1$ and $b = b_1$. **b)** Tuned for EGR: $a = a_2$ and $b = b_2$. **c)** Tuned for both cases: $a = a(M)$ and $b = b(M)$ as in (10).

a given EGR level, the model is linear in c_M, but the parameters are adjusted appropriately when EGR is changed, measured by M.

5. Results

5.1 Pressure peak position estimation

The ion signal samples are chosen with a start (θ_w) of -4 crank angle degrees (CAD) to 5 CAD in increments of 1 CAD. The ion signal window thus includes 10 ion signal samples around the top dead center from one cylinder. The rather short window that is chosen makes not only calculation complexity small but actually appears to give good performance over a wide range of setpoints, see Fig. 7. A larger window makes a smaller, resulting in less noisy estimates, but also degrades performance for estimating slowly varying trends. Experiments with different θ_p setpoints (12-18 CAD) were made. Each experiment includes 500 combustion cycles and was performed on the highway, in gear 5 and with speed controlled to 90 km/h. A certain EGR valve position (10 steps opened relative the closed position) was chosen in half of the experiments.

The linear models for the cases with and without EGR, respectively, are estimated to $M_1 = 10.5$, $M_2 = 6.5$ and $a_1 = 8.5$, $b_1 = 13.5$, $a_2 = 8.9, b_2 = 8.9$. In Fig. 7, low pass filtered (to show trends more clearly) θ_p and estimates $\hat{\theta}_p$ are shown. The first 6000 cycles are combustions without EGR and the rest of the cycles with one fixed EGR valve position. To show the influence of the interpolation between the models tuned for both no-EGR and EGR, the resulting estimates for each tuning are first shown. In Fig. 7a the estimates are shown when the tuning is made for the case without EGR. The first 6000 samples are without EGR and shows good performance while the last 6000 samples with EGR are estimated with a considerable bias due the the much weaker ion current during EGR. In Fig. 7b the estimates are shown when the tuning is made for the EGR case in stead, resulting in good performance during EGR but worse in the beginning without EGR. The linear combination of the two cases are shown in Fig. 7c and the estimates track well the measured pressure peak position for both cases.

5.2 Closed-loop control of EGR on the highway

Since EGR rate cannot easily be measured on-the-road, the point of minimum fuel consumption had to be found by trial and error. This was done by setting the EGR valve at different positions and measuring fuel consumption by recording the fuel injection timing that was commanded by the fuel controllers to each cylinder. At the engine speed (1750 RPM) and load case of the vehicle (approximately 30% of maximum load) the fixed valve position that resulted in minimum fuel consumption (about 5% reduction) was found to be 10 steps from the position where the valve is closed. The model shown in Eq. 4 was fitted to data from two clusters consisting of 1000 combustion cycles each, one where the EGR valve was closed and the other where the valve was opened 10 steps. The ion sum M was calculated according to Eq. 3 with $n = 51$ and the starting crank angle (θ_w) was chosen as

$$\theta_w = \theta_{ign} + 20 \tag{11}$$

where θ_{ign} is the ignition crank angle. This resulted in the model parameters $d_1 = -0.73$ and $d_2 = 21.02$. The integrating factor in the controller was chosen as $T_i = 1$. An experiment showing the performance of the estimator and controller is shown in Fig. 8 consisting of a step in the desired COV(IMEP) from the normal operating variations of about 7% to a 9% level. The controller is activated at cycle 400 to stabilize COV(IMEP) at a desired value since it is unnecessary to have the controller active when no EGR is wanted (desired value of 7% is drawn in the figure for the first 400 cycles because it is a typical long-term average value seen at this operating point). The reference COV(IMEP) values are here calculated from the in-cylinder pressure signal using 75 combustion cycles (non-overlapping blocks). Valve position (from the controller) is only updated once every 20 combustion cycles to not overstrain the stepper motor. Since the estimate ($\hat{v}$) is noisy (and because fast cycle-to-cycle updating of the valve is not needed) it is averaged over 20 cycles before it enters the controller.

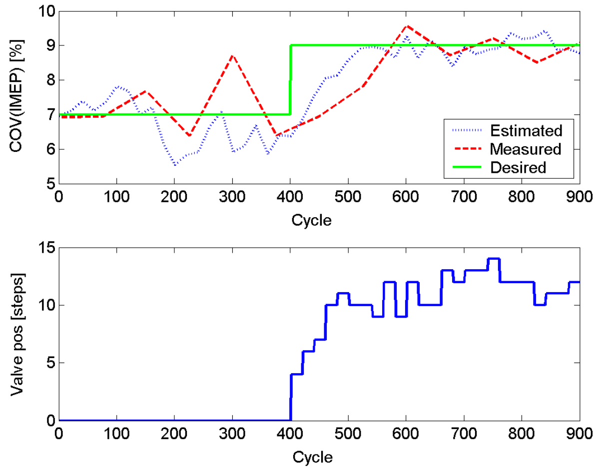

Figure 8. Step response for closed loop control of combustion variability (COV(IMEP)) on the road. The EGR valve (and hence also the controller) is updated every 20 combustion cycles and the reference (measured) value of COV(IMEP) is calculated over 75 cycles. The estimated value of COV(IMEP) has also been lowpass filtered to show the trend.

6. Conclusion

Two virtual sensors are proposed that estimate combustion variability and the pressure peak position by using ion current measurements at the spark plug of a combustion engine. The potential fuel and NO_x reduction is quantified in dynamometer experiments where the best fuel economy improvement (12%) was found at low load. Reaching the point of minimum fuel consumption is not suitable with the previously proposed method of computing the coefficient of variation of the sum of the ion current. Instead, at low EGR rates it is found that the mean value is more suitable. A model based on the sum of the current is therefore proposed for estimating combustion variability. Closed-loop control of EGR based on the variability estimate is demonstrated in a highway driving experiment where a desired (acceptable) level of combustion variability is reached. In order to not rely on having an actual pressure sensor to control ignition timing, a virtual pressure peak position sensor is also proposed that works under both normal and an EGR condition. The proposed virtual sensors are designed for a specific engine operating point but can be extended to a wider range by interpolating between models designed for other engine speed and load cases.

Acknowledgements

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Nomenclature

AFR	Air-fuel ratio
CAD	Crank angle degrees
COV	Coefficient of variation
EGR	Exhaust gas recirculation
IMEP	Indicated mean effective pressure
MAP	Manifold air pressure
MFB	Mass fraction burned
RPM	Revolutions per minute
θ_{ign}	Ignition crank angle
θ_p	Pressure peak position

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