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# 60 The Advance Combustion Control in a Hybrid SI/HCCI Engine by Using Ion Current Sensing

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In a future 'hybrid mode' SI/HCCI engine transition between these modes, over the operating map, will play a crucial role. The engine management system must provide a fast and smooth transition between these two modes, hence a new combustion feedback based control system is needed. The aim of this paper is to investigate the use of an ion-current sensor in SI/HCCI engine for direct combustion feedback control. The experimental results obtained, at different speed and loads, show that the estimation of cylinder pressure, through the ion signal, can be performed with high accuracy, and that ion-current has the potential to be a cost effective solution for direct combustion control.

Keywords: HCCI, Transition, Combustion control, Ion Sensing

## 1. INTRODUCTION

The HCCI combustion has the potential to be highly efficient and to produce low NOx, carbon dioxide and particulate matter emissions, but experiences problems with cold start, running at idle and high loads which reduces its power density. A solution to these problems is to operate the engine in a 'hybrid mode', where the engine operates in HCCI mode at low and medium loads while switching to spark ignition (SI) mode at a cold start, idle and higher loads. In order to achieve acceptable drivability a seamless transition between the two modes of combustion must be attained. In addition, HCCI requires considerable control, especially during transient performance, to maintain consistent ignition timing (IT) and rate of heat release (RHR). In order to provide a suitable control method, it is clear that a feedback signal from combustion is required but existing production engine sensors are inadequate for this task. The most straightforward answer would be to use a cylinder pressure sensor, but there are issues of high cost and low long-term reliability with this method, so an ion-current sensor could be used as an alternative [1-3].

The most common way to apply a voltage inside the cylinder is to use two existing electrodes (the spark plug tips) but this approach has a problem of the strength of ion-current signal achieved. This becomes even more exacerbated by the fact that for HCCI combustion, the signal acquired displays only one peak compared to two peaks at SI combustion. Given the relatively low HCCI engine cycle temperature, the ion-current from this type of engine is though to come mainly from chemi-ionization (i.e. from ions in the reacting gas) [4].. Provided these problems can be overcome, ion-current becomes a suitable and computationally inexpensive means of acquiring data from the HCCI combustion process.

The aim of this paper is to investigate the use of an ion-current sensor in SI/HCCI engine for direct combustion feedback control. The experimental results obtained, at different speed and loads, show that the estimation of cylinder pressure, through the ion signal, can be performed with high accuracy, and that ion-current has the potential to be a cost effective solution for direct combustion control.

## 2. EXPERIMENTAL APPARATUS AND SET UP

### 2.1 Engine

The engine employed in this research is a single cylinder, gasoline port-fuelled, 4 stroke research engine based on GM 'Family 1' 1.8 litre architecture. In Fig. 1 a photograph of the engine is shown. The detail description of the engine can be found in [5]. For this investigation the engine compression ratio is set to 10.5, intake air temperature to 20 $^0$C (room temperature), AFR to stoichiometric and naturally aspirated.

The research Lotus AVT™ system is fitted to allow the fully variable valve timing strategy, hence to capture various quantities of residual gas (i.e trapped residual gas-TRG). The detail description of the electrohydraulic fully variable valve train system - Lotus AVT™ can be found in [5].

The engine was connected to a Froude AG30 30kW eddy-current dynamometer. A redline ACAP data acquisition system from DSP Technologies Inc. was used together with Horiba MEXA 7100 DEGR heated line emission analyser. The fuel was port injected and the engine management system was a conventional Lotus V8 controller.

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Three combustion regimes are investigated; SI, HCCI and spark-assisted HCCI -SA HCCI (which occurs in transition regions between SI and HCCI) where a spark is still used to position heat release at correct/desire crank angle. To enable this investigation, the valve strategy involves two separate profiles, one for HCCI and one for SI mode (Fig. 2). During HCCI operation the load is controlled by changing the overlap, hence engine operates WOT. During SI operation an electronic throttle is used to adjust the load. The throttle together with the valve profiles, spark timing and fuelling rate is also responsible for controlling the engine load during transitions from SI to HCCI and back to SI.

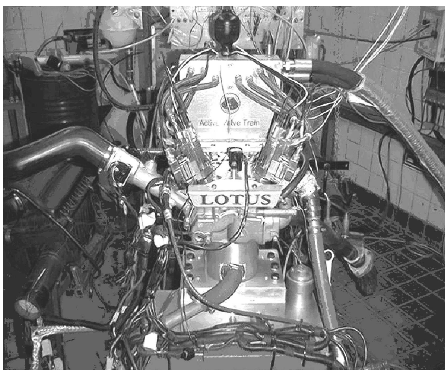


Fig. 1 Single-cylinder research engine with AVT system

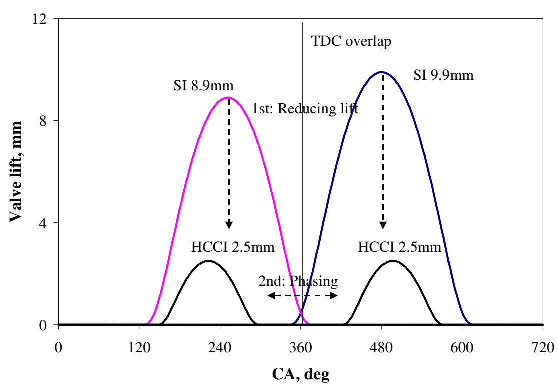


Fig. 2 Valve profiles used for the SI and HCCI combustion

In order to acquire the ion-current signal ionization probe is located in the four-valve cylinder head between one inlet and one exhaust valve as shown in Fig. 3. The probe is electrically isolated from the cylinder head by means of a ceramic sleeve. The diameter of the sensing element is slightly less than 1mm, and the tip protrusion into the combustion chamber was approximately 3.5 mm.

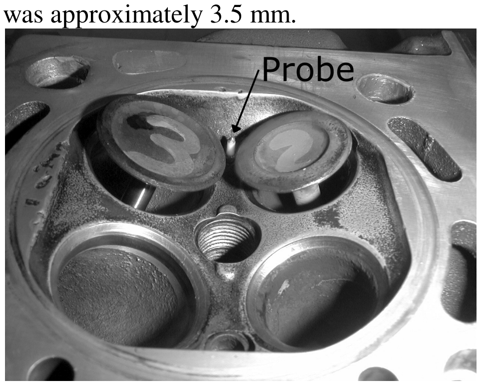


Fig. 3 The location of ionisation probe on the cylinder head

A one-off DC voltage source shown in Fig. 4, is used to power the measuring probe. The DAQ board is fed the output of voltage divider as the ion-current signal, which is inversely proportional to the sensed ion-current (i.e. 5V for zero ion-current and 0V for infinite) to avoid the possibility of damage caused due to excessive voltage. The signal is then inverted during the post-processing phase.

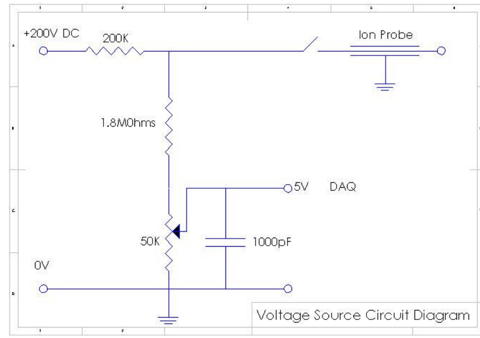


Fig. 4 The voltage source circuit diagram

Issues like fuel additive effects and carbon contamination of the sensor are not examined. However, other studies [6] have shown that fuel additives affect mainly the amplitude and not the shape of the ion signal curve. As such, it was reported that they can be overcome through data normalization. Soot contamination, although not a major problem in gasoline engines, could be resolved through techniques like auto-calibration by measuring the resistance of the ion sensor prior to combustion [7].

## 3. RESULTS AND DISCUSSION

### 3.1. HCCI combustion

The research engine is started in SI mode and when the coolant temperature (and oil sump temperature) reach 90 $^{0}$C the mode transition can be performed. Then the TRG quantity is gradually increased (by increasing the negative valve overlap), hence moving from SI combustion to SA HCCI and then to HCCI as shown in Fig. 5.

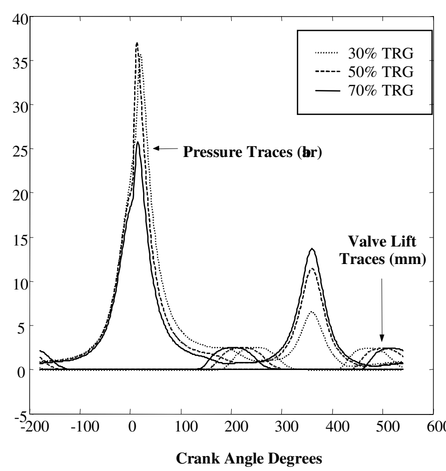


Fig. 5 Typical pressure signals and valve profiles at various TRG levels

The amount of TRG presented is a calculated molar ratio of fresh charge to exhaust gasses using a zero dimensional thermodynamic model and equation (1).

$$\%TRG = \frac{Charge\_Moles}{TRG\_Moles} \times 100 \qquad (1)$$

The entire HCCI and SA-HCCI operating range is investigated varying the speed over a range between 1500rpm to 3500rpm. In the area surrounding this range SI operation is used. The Fig. 6 shows the speed and load, (in terms of IMEP) and the corresponding amount of TRG used for load control, where the NVO is limited by zero TRG and misfire. It can be seen that NVO, the controlling parameter of TRG, cannot be the same in all speeds, hence the achieved IMEP.

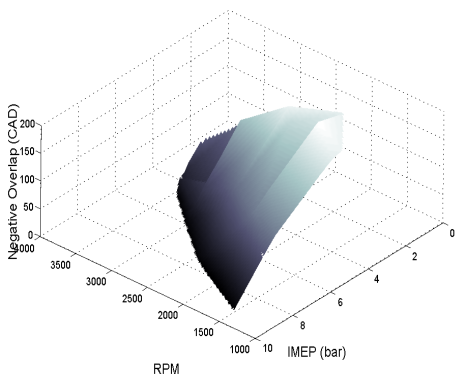


Fig. 6 The HCCI operating range

### 3.2 Ion-current signal interpretation

For controlling the SI/HCCI engine operating in dual mode, four groups of parameters need to be known: misfire and pre-ignition detection (so that operating conditions leading to unstable combustion can be avoided); quantity of TRG, combustion performance parameters (so that the engine performance can be monitored); and finally IT (which is used for engine control outside the HCCI envelope). When engine runs in HCCI mode, these parameters have to be monitored on a cycle-by-cycle basis and the simplest way is the misfire and pre-ignition detection.

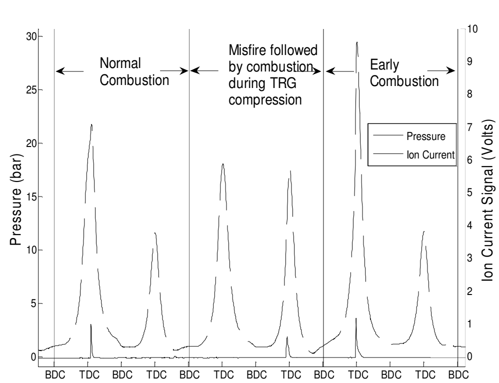


Fig. 7 Cylinder pressure trace and corresponding ion-current signal

In Fig. 7 three consecutive cycles are shown during unstable SA-HCCI operation. In the 1st cycle where the ion-current signal starts after TDC, the peak cylinder pressure (APmax) is within normal levels and position. In the next cycle a misfire happens and no ion-current is present. However, during the following TRG compression the mixture ignites and is manifested by the presence of ion-current signal during that period. In the 3rd cycle, the ion-current signal starts before TDC since an early combustion occurs, hence the elevated in-cylinder pressure and early APmax.

### 3.3 Combustion parameters and ion-current signal

Although important conclusions regarding the combustion process can be drawn by inspection and simple diagnostics can be performed directly through the ion-current signal, more detailed analysis yields greater insight. In order to do this, four basic characteristics of the ion signal curve is extracted and compared to combustion parameters. As shown in Fig. 8, these are the signal start, the signal slope, the ion-current 50% position and the signal peak. It has to be noted here that the signal peak includes two measurements, the signal strength, and the signal peak position (X and Y coordinates).

The ion-current can also be used to determine APmax, or similar combustion parameters like 50% of mass fraction burned (MFB50) and maximum rate of heat release (dQ MAX). Determining any of these is important in any engine, however in a 'hybrid mode' SI/HCCI it is almost essential as combustion change from flame propagation only to spark-assisted auto ignition and finally pure auto ignition. As these modes change, different relationships occur between APmax, MFB50 and dQ MAX, in contrast to SI engines where their correlation is far simpler.

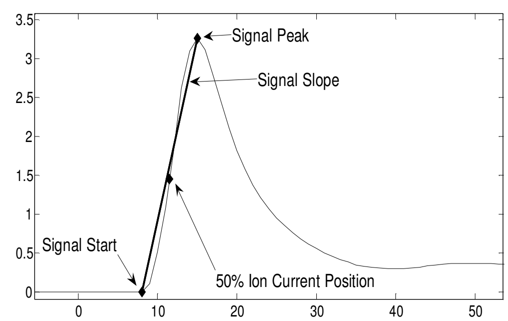


Fig. 8 Signal measurements from ion-current signal

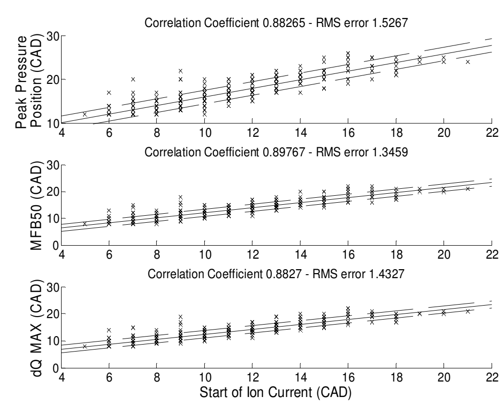


Fig. 9 The start of ion-current vs. combustion characteristics

Three ways of correlating ion-current to combustion parameters are shown. The results presented here are for 3000rpm medium TRG%, but similar results are obtained from all operating conditions. The first method is by correlating the start of the ion-current, shown in Fig. 9. As it can be seen the correlation coefficients are high and almost identical between the three combustion parameters, and the RMS errors are small and well under 2 crank angle degrees ($^{0}$CA).

The second method is to correlate the 50% ion-current signal as suggested by [4] and the third method is to correlate the position of signal peak. In all three methods, a linear correlation is used and the resulting APmax estimation has an RMS error of less than 2 $^{0}$CA. However, the estimation is improved when using the peak ion-current position as the signal is stronger and thus the signal to noise ratio is better. Figs. 10 and 11 show the 50% and peak signal correlations with APmax respectively.

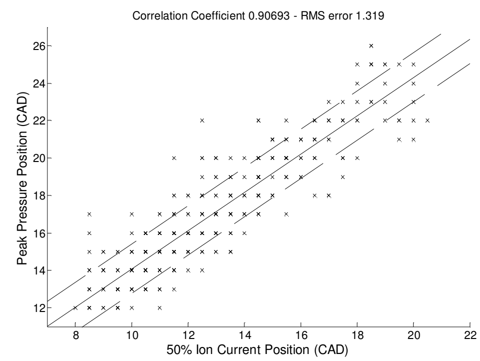


Fig. 10 The position of 50% ion-current vs. APmax

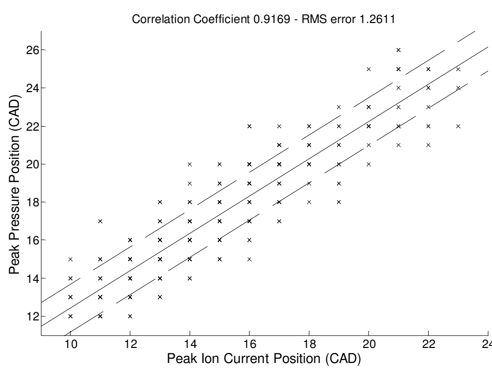


Fig. 11 The peak ion-current position vs. APmax

Although a linear estimation is a simple technique and yields acceptable results, it becomes more difficult to implement when a wider range of engine operation is examined. The Fig. 12 shows the average start of ion-current signal and APmax averaged from 500 cycles across the whole HCCI operating region between 1500 rpm and 3500 rpm and therefore from 0% to maximum TRG amount. The same trends are repeated if 50% ion-current or peak ion-current is plotted instead of start of ion-current.

It is obvious that the estimation accuracy reduces if the same linear equation is used for the whole TRG spectrum, regardless of the correlation parameter employed. This is because combustion mode changes with varying amounts of TRG thus affecting the signal, so the estimation precision could be further increased by correlating more than one ion-current characteristic to APmax, e.g. the ion-current slope. Nevertheless, correlation coefficients remain high, even with the simple linear approach. This indicates that ion-current could, if computational power is an issue, be directly/linearly correlated for combustion analysis purposes. Figs. 13 and 14 show the correlation of APmax to peak ion-current position and highlight the problem that early peak cylinder pressures show on the zero line. This can be overcome by using a different measurement (e.g. MFB50), but for a real time control application, it is quicker and more straightforward to extract signal peaks. Despite these issues, the correlation coefficient is still high, and the RMS error is only increased to 2.64 deg $^{0}$CA.

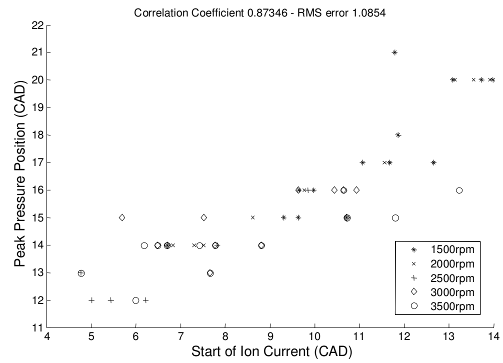


Fig. 12 The start of ion-current signal and APmax at various speeds

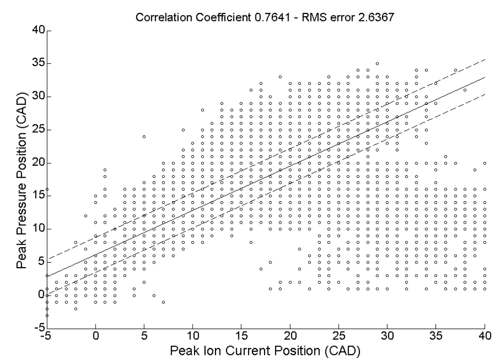


Fig. 13 Cycle to cycle peak ion-current vs. APmax

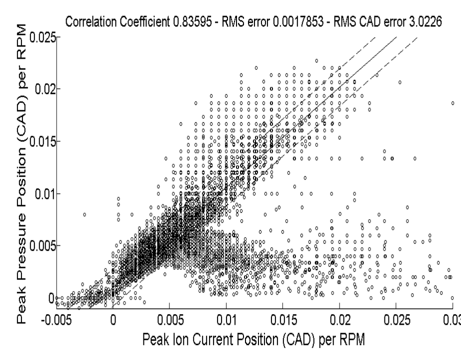


Fig. 14 Cycle to cycle peak ion-current vs. APmax

Transforming the acquired signals on time domain (by dividing them by RPM), provides a better insight into this problem since data from different speeds are better separated. As can be seen in both figures (Figs. 13 and 14), there is a “leg” of data points that breaks off the main diagonal correlation. Although not easily identifiable on the graph, analysis showed that the percentage of data points on this "leg" are relatively small (<5%), so this is not a major source of error.

A possible explanation for this feature might be that the different knocking modes, that result in different acoustic or oscillation modes that may occur in a combustion chamber depend on mixture distribution, which can vary, even under the same operating conditions [8]. These modes can vary between circumferential and radial and also have different shapes, within their domain. More advanced interpretation technique will improve results by taking in account more than one ion-current parameters, i.e. by not looking at peak position of ion-current alone. However, the only way to radically improve accuracy would be to use more than one ion-current sensor. This would give a more complete, and less localized, picture of the combustion process.

From the forgoing discussion, it appears apparent that ion-current lends itself to an easy and cost effective solution to combustion diagnostics during HCCI operation. A simple integration of the signal can reveal misfires, while the position of the start, 50% or maximum of the signal can be used to determine more intricate combustion properties like APmax, MFB50 or dQMAX positions. Its strength or slope can determine dilution levels. Irregular positioning of the signal, like very early or very late in the combustion cycle, can reveal pre-ignition or partial late combustion, and its absence indicated misfire.

## 4. CONCLUSIONS

The experimental study of ion-current sensing in a gasoline HCCI engine equipped with the Lotus AVT system and using a special design ion probe, over different speeds and trapped residual gas amounts, was conducted. The results obtained revealed following:

- The ion signal is sufficiently high during HCCI under all speeds and loads to be monitored/measured
- A detection of misfire, pre-ignition and estimation of TRG% were shown possible with basic mathematical approaches
- The APmax, MFB50 and dQmax were all determined with RMS errors less than 2 deg $^{o}$CA, when a specific engine operating condition was examined. With a derived linear relationship over the whole HCCI operating spectrum, the maximum error rose to 2.64 deg $^{o}$CA, remaining accurate enough for feedback purposes.
- A capability to monitor directly the effect of IT on APmax through ion-current signal monitoring, hence feedback for a closed loop combustion control.

Overall, the ion-current has the potential to be a cost effective and adequately informative feedback signal for both SI and HCCI engine control.

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