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Linear regression and its use in predicting the link between ionization current and the pressure signal in a hybrid mode engine

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Linear Regression and its Use in Predicting the Link Between Ionization Current and the Pressure Signal in a Hybrid Mode Engine

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ABSTRACT

Homogenous Charge Compression Ignition (HCCI) is an alternative to Spark Ignited (SI) combustion, which can provide part-load efficiencies as high as compression ignition engines and energy densities as high as SI engines, without high levels of NO_x or Particulate Matter (PM). The principle of operation involves reaching the thermal oxidization barrier of a homogeneous air-fuel mixture. This combustion practice is enabled by diluting then compressing the mixture with the Trapped Residual Gases (TRG) to dilute the initial charge thus keeping combustion temperatures down.

Introduction of exhaust gasses in the mixture can be achieved by the use of early exhaust valve closure and late inlet valve opening. The charge is well mixed avoiding particulate emissions, and by using exhaust gasses for load regulation the need for throttled operation is removed allowing the realization of high efficiencies, low pumping losses and a resulting 15 - 20 % improvement in fuel economy. One of the major disadvantages of HCCI is that it can only be used at part load conditions, and so it has been proposed that a 'hybrid mode' engine operation strategy could be used, where the engine uses SI operation at cold start, high load and idle. This demands a closed loop feedback control signal to give a seamless transition between SI (where Start of Combustion (SOC) is dictated by the spark plug) and HCCI (where SOC is unknown).

This paper investigated the use of an ion current sensor to accurately predict the Peak Pressure Position (PPP) and Peak Pressure Magnitude (PPM). This is achieved with the mathematically simple and computationally efficient approach of linear regression. This technique can be used between engine cycles so adjustments can be made to engine strategies to compensate for difficult conditions. The results showed that there is a definite

correlation between the two signals and that the ion current can be used to control the engine during HCCI mode. Finally a good balance between computation time and accuracy was obtained using 20 cycles.

INTRODUCTION

Homogenous Charge Compression Ignition (HCCI) has the potential to reduce NO_x and other emissions down significantly but has various problems; cold start, engine operation at high load and running at idle are just a selection. One of the biggest problems facing the development of HCCI is the location of the combustion event. In order to extend the operating window a hybrid engine is paramount to this situation, operating in Spark Ignition (SI) mode at difficult operating conditions, HCCI mode where possible and a third Controlled AutoIgnition (CAI) mode where a spark is used to position Start of Combustion (SOC), is used during the transition from SI to HCCI and vice versa.

In an SI engine the combustion event is controlled by the ignition of a spark plug but in a HCCI engine there is no such initiator of the combustion process. There are many controlling variables to consider, most notably the chemical kinetics of the combustion process [1]. These kinetic reactions depend on the concentration of reactants and products within the cylinder. A homogeneous mixture of fuel, air and previous cycle exhaust gasses reach the thermal oxidization barrier and are compressed to cause combustion. This charge, as it is diluted, lends to a cooler combustion event which also leads to a reduction in Nitrogen Oxide formation [2, 3]. Auto ignition typically occurs at 800-1100K, but this depends on the fuel type. As this is not an instantaneous reaction, occurring specifically in one place (the fuel ignites simultaneously in several positions within the cylinder) and so a measure or locator of this exact event

is needed. The most obvious feedback signal to use would be a cylinder pressure sensor; development of reliable, low cost and accurate sensors for long term use is ongoing. It has been recently documented [4, 5, 6] that the Ionisation Current (IC), measured within the cylinder has several characteristics which relate to an in cylinder pressure sensor.

The use of an additional spark plug within the combustion chamber, as an engine sensor, has been investigated many times within the last sixty years [7, 8, 9]. In any situation a standard electrode can be used to detect positive ions given in a gas or liquid. In the case of an engine, the flame front created by combustion provides an large number of positive (H_3O^+) ions to be detected by the additional spark plug. Problems occur when using a single spark plug as a sensor due to ringing in the coil after firing and a lack of signal during higher load applications. This can be overcome by using two different sensors in alternative locations within the cylinder. Figure 1 shows the signals for the three different types of combustion under similar load conditions using two different sensors. It should be noted that the location of the two different sensors will effect the phasing and the amplitude of the IC in the case of CAI and HCCI combustion. This may due to stratification in temperature and/or air/fuel ratio, [10][11]. HCCI and CAI cases contain high amount of TRG which have a much higher temperature at the beginning of compression process and the combustion is initiated via fuel auto ignition. When combustion starts, it happens in many places inside the combustion chamber and the IC signal can therefore quickly be picked by the sensor. It is therefore reasonable to conclude that the IC signal advances as auto ignition strength increases. While in the case of SI, the sensor can only pick up the IC signal when flame reaches which clearly takes a bit time. Another interesting phenomenon is that the accumulated signal consists of two phases; an initial peak, where the combustion event starts, and a secondary "hump" where thermal ions are detected. The secondary hump in an SI cycle is generally much more pronounced than in a HCCI or CAI. This is because in an SI cycle, the flame propagates through the sensors. This is not the case for the other two modes as both consist of the charge autoigniting at several different positions within the cylinder.

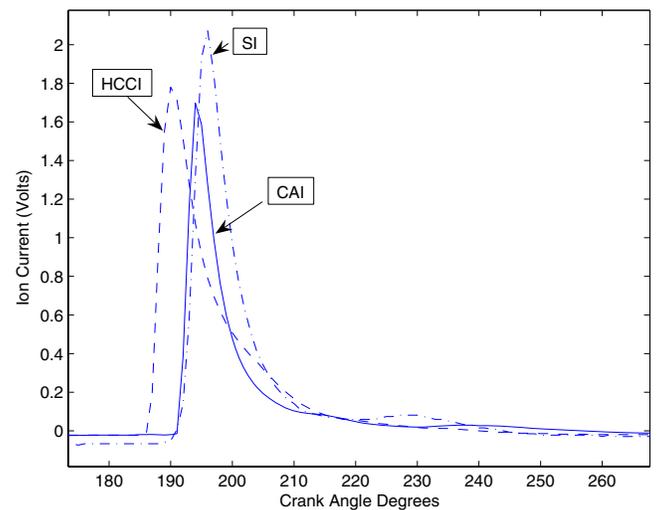


Figure 1 - Typical Ionization Current in a SI, CAI, and a HCCI cycle

Ion-current signals have long been investigated as a combustion diagnostic tool [12, 13, 14]. In SI engines the prevailing conditions during combustion cause ionization of the gases inside the cylinder. This ionization occurs mainly in two phases. The first phase occurs during combustion as fuel reacts with oxygen, and is defined as the chemical phase. The second phase is defined as the thermal phase, and occurs due to compression of burnt gases when fuel further away from the spark plug is burned [7]. By applying a voltage through these gases, a current will be produced since the ionized gasses are conductive, and further information can then be deduced from this ion-current signal [14, 15].

This paper will investigate the potential of using the IC signal as a tool for locating the combustion event. This will be achieved by measuring the accuracy of which the pressure signal can be predicted. Initially an ADALINE neural network was used to analyse the relationship, but this was soon discarded for the simpler tool of linear regression. With this application of linear regression, it is deduced that cycle to cycle prediction of peak pressure magnitude (PPM) and peak pressure position (PPP) could be used to better control the engine, locate the combustion event and give a smooth and steady transition from SI through CAI into HCCI, and vice versa.

EXPERIMENTAL PROCEDURE

The engine employed in this research was a single cylinder, gasoline port fuel injected, 4-stroke research engine based on the GM Family One (architecture series), 1.8litre, see Figure 2. The fuel used to carry out the experimental study was 95RON. A standard 4-cylinder head is mounted on top of a water cooled barrel, with a custom made bottom end. Only the front cylinder of the head is operational. A fully variable valve

timing system named Active Valve Train (AVT); manufactured by Lotus Engineering; was fitted to allow a variable valve timing strategy. Variable quantities of Trapped Residual Gases (TRG) can be captured in this way. For this investigation, the CR was set at 10.5:1. (It is worth noting that intake air temperature was maintained at a room temperature of 20 degrees Celsius) Figure 1. Single-cylinder research engine with AVT system. The engine was connected to a Froude AG30 30kW eddy-current dynamometer.

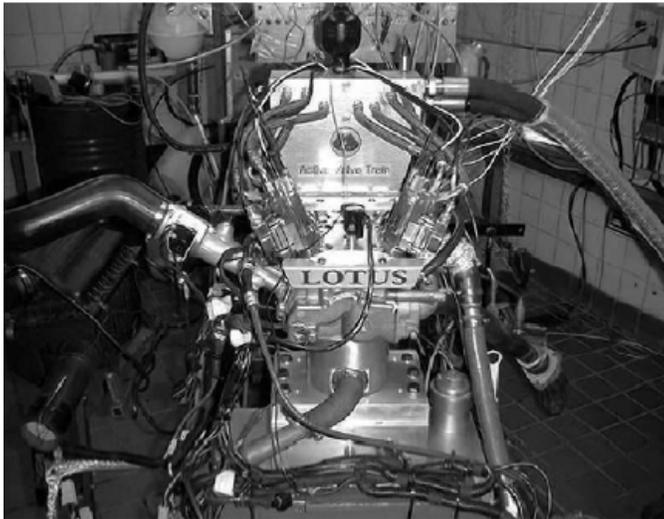


Figure 2 - Single-cylinder research engine with AVT

The data acquisition system used was ACAP manufactured by DSP Technologies, together with a Kistler 6123 piezoelectric pressure transducer and a Horiba MEXA 7100 DEGR emissions analyzer. Port fuel injection was employed, managed by a conventional Lotus V8 engine controller. High speed data were sampled at one degree crank angle intervals. This sample rate is sufficiently high to obtain the salient features of the ion-current signal (as a combustion performance indicator), whilst coarse enough to be realistically used as part of a real time engine control strategy that is compatible with conventional car electronics.

Three combustion regimes were investigated; SI, HCCI and CAI (which occurs in transition regions between SI and HCCI) and where a spark is used to position heat release in the correct time window. This region is not the same as HCCI where ignition occurs due to compression. To enable this investigation, the valve strategy involved two separate profiles, one for CAI/HCCI and one for SI operation. The CAI/HCCI profile had a fixed lift of 2.5mm and fixed duration but variable overlap, which was changed from positive to negative in variable step sizes until the misfire limit was reached. For high power SI operation a high lift (8mm), long duration valve profile was used. During HCCI operation the load was controlled by changing the overlap, so the engine manifold was unthrottled. During

SI operation an electronic throttle was used to adjust load. The throttle is also responsible for controlling the engine load during immediate transitions from SI to HCCI and back to SI. In order to acquire the ion-current signal an ionization probe was located in the four-valve cylinder head between one of the inlet and one of the exhaust valves as shown in Figure 3. The probe was electrically isolated from the cylinder head by means of a ceramic sleeve.

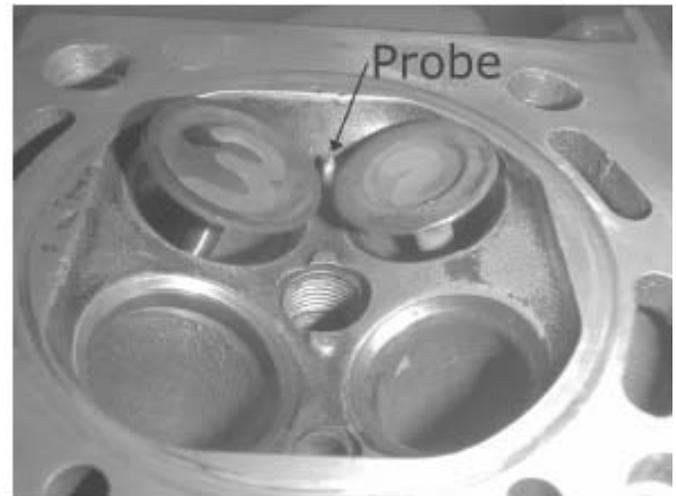


Figure 3 - Photograph of cylinder head showing the location of the ionisation probe

The diameter of the sensing element was slightly less than 1mm, and the tip protrusion into the combustion chamber was approximately 3.5 mm. Since the mass of positive ions, such as H_3O^+ , is approximately 30,000 times larger than that of an electron (negative charge), the light electrons can be accelerated much more easily towards the positive electrode than the heavy ions, when driven by an applied electromagnetic field. The voltage polarity at the gap of sensing spark plugs was therefore selected such that the small area centre electrode was positive, and the rest of the combustion chamber was negative. This coincides conveniently with the original engine polarity where the engine block is negative.

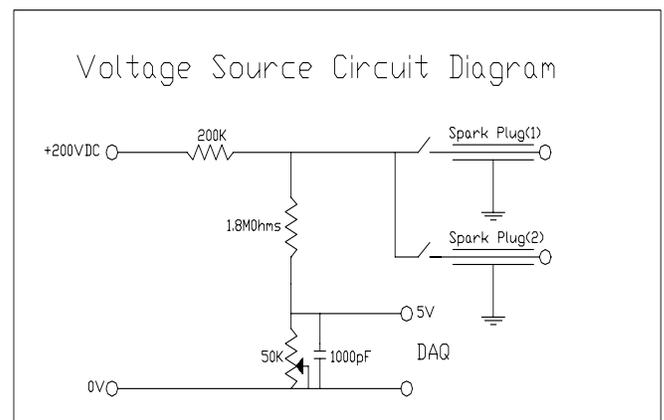


Figure 4 - Circuit Diagram of DC Source

A purpose built DC voltage source, (shown in Figure 4), was used to power the measuring probe. The output of the voltage divider was passed to a Data Acquisition (DAQ) board as the ion-current signal. The voltage divider would produce a voltage that was 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 was inverted during the post processing phase. The DAQ sampling rate was one sample per 2 degCA. Data were acquired using either a single sensing plug or both. When using both sensing plugs, these were connected in parallel, as shown in Figure 4, which essentially results in the addition of the two ion-current signals.

Issues like fuel additive effects and carbon contamination of the sensor were not examined. However, other studies [16] 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 [17].

DATA MANIPULATION

In each experimental run, the ion current signal and the pressure signal was taken. The measurant used from the ion current signal was the crank angle degree at which its maximum occurs. This is illustrated in Figure 5 in a HCCI cycle.

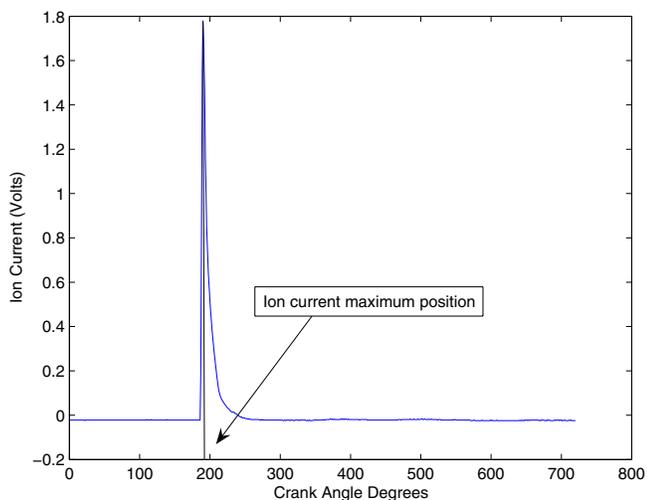


Figure 5 - Ion current measurant used in a HCCI ion current cycle.

The pressure signal measurants which were used, in the initial relationship deduction and prediction are the PPM and PPP of the signal. This can be seen in Figure 6 in a HCCI engine cycle.

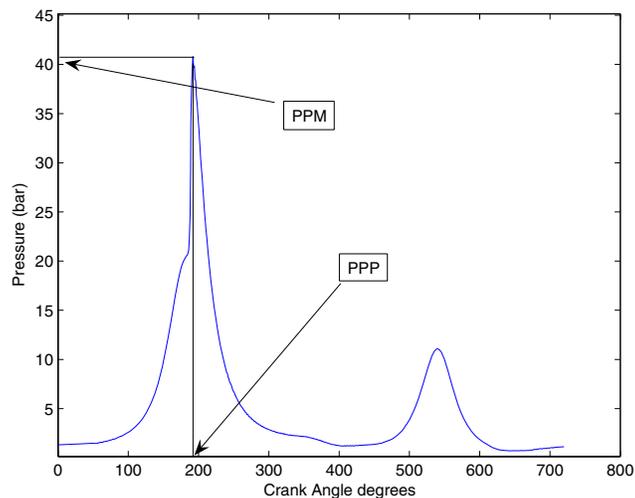


Figure 6 - Pressure measurants used in a HCCI pressure cycle.

The predictions of PPP and PPM were made using the Matlab function Polyfit. This function uses least squares regression to calculate the relationship between two arrays of data points. It calculates the line of best fit by minimizing the sum of the squares of the vertical deviations from each data point to this line. This can be seen in Figure 7. Because the deviations are first squared, then summed, there are no cancellations between positive and negative values. The perfect solution would be when all points are upon the line and this would of course mean that the sum of the square of the residuals would be equal to zero.

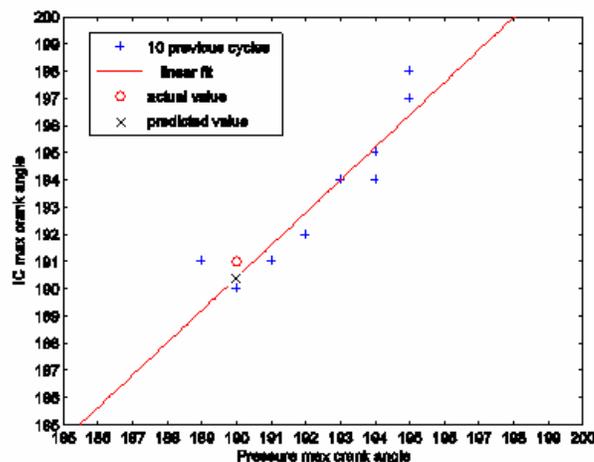


Figure 7 - IC crank angle maximum plotted against PPP with the next predicted maximum and next actual cycle marked. This is done with 10 cycles.

In each experimental run a set number of cycles was specified and this is the amount of data points that were plotted against each other. This value was set at either 5, 10, 20 50 or 100. The relationship between the X and Y variables for the amounts of data was calculated, and then, using the X variable and the linear equation the Y

variable, was predicted for the following cycle. These points were used to prove that the ion current peak location has a definite correlation with the PPM and the PPP.

The simple code was applied to SI, CAI and HCCI data. The model performance was evaluated by the Root Mean Square Error (RMSE). The root means square error is the calculation between the difference of the actual value minus the predicted value. This is then squared and summed over the dataset and square rooted so there are no cancellations between positive and negative values.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (Y_a - Y_p)^2} \quad (1)$$

where the subscript a indicates the actual value and the subscript p the predicted. If the model is perfect the RMSE should be zero, this is because all actual values would be the same as predicted values. This also means the smaller the RMSE, the less the deviation between actual and predicted and therefore the better the performance of the model.

RESULTS AND DISCUSSION

HCCI

In order to control a gasoline engine operating in HCCI mode, a number of features must be monitored on a cycle by cycle basis. The simplest of these are misfire and pre-ignition detection. In Figure 8, three consecutive cycles are shown during unstable Spark Assisted-CAI (SA-CAI) operation. In the first cycle where the ion-current signal starts after TDC, the peak pressure of combustion is within normal levels and position. In the next cycle a misfire happens and no ion-current is present, (providing a simple way to monitor the engine for this event). However, during the following TRG compression and expansion, the mixture ignites, and is manifested by the presence of ion-current signal during that period [18]. Additional mixing of the charge and TRG during expansion and exhaust stroke (or at least the part of the exhaust stroke that the exhaust valve is open) results in ignition during TRG compression, due to better mixing and increased time history of high pressures and temperatures that break up the fuel. In the third cycle, the ion-current signal starts before TDC since an early combustion, an elevated in cylinder pressure and early peak pressure position (PPP) occurs. After a TRG compression and expansion that experiences heat release, it is usual for early combustion to occur in the next cycle, due to the very high temperature of the TRG gases which result in early ignition of the fresh charge.

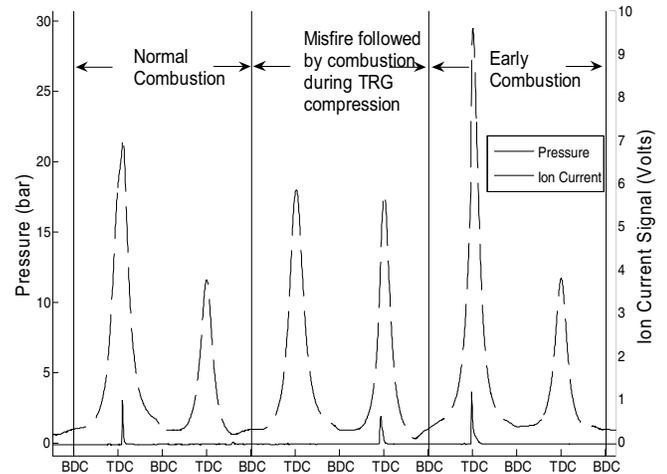


Figure 8 - Cylinder pressure trace and corresponding ion-current signal

Two HCCI runs are considered here, one of the runs consisted of all complete combustion cycles. In this normal combustion, the ion current signal peak occurs in the first pressure maximum of every cycle, Figure 9.

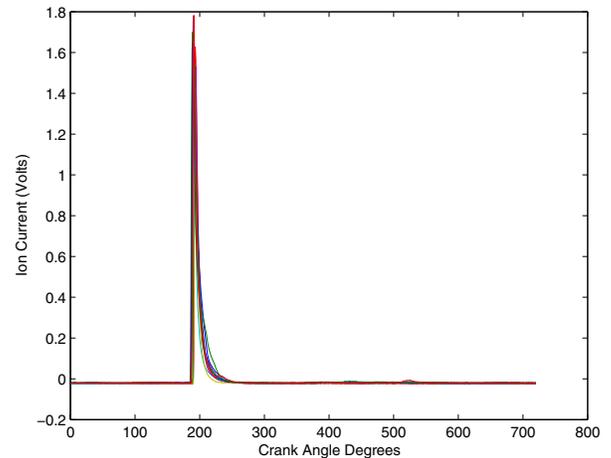


Figure 9 – Ten consecutive successful IC signals plotted against crank angle degrees

In the second run, HCCI combustion was not achieved in every cycle. There were misfires in some cycles, with the result that some of the fuel was recompressed during the exhaust process. This led to late combustion in the second pressure maximum where normally would just be the compression of the trapped gas residuals. This can be seen in the accumulated IC traces plotted in Figure 10.

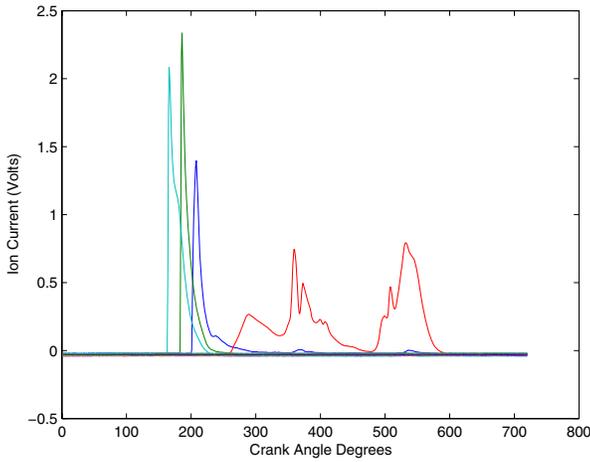


Figure 10 – Ten consecutive unsuccessful IC signals plotted against crank angle degrees

In the successful case, the pressure signal (Figure 11), especially the second maxima, is almost identical in each cycle. Limited cycle to cycle variation is one of the many advantages of HCCI combustion.

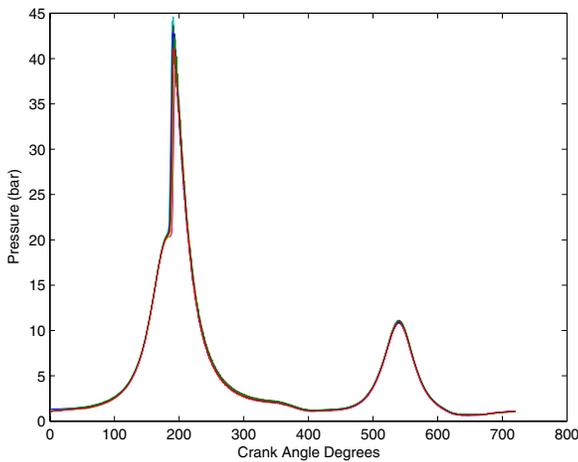


Figure 11 – Ten consecutive successful Pressure signals plotted against crank angle degrees

Figure 12 shows the progression from Figure 11, where the hot gasses within the cylinder and during the next intake compression process, combustion and the first pressure maximum occur much earlier, and in some cycles is only slightly larger than the second maximum.

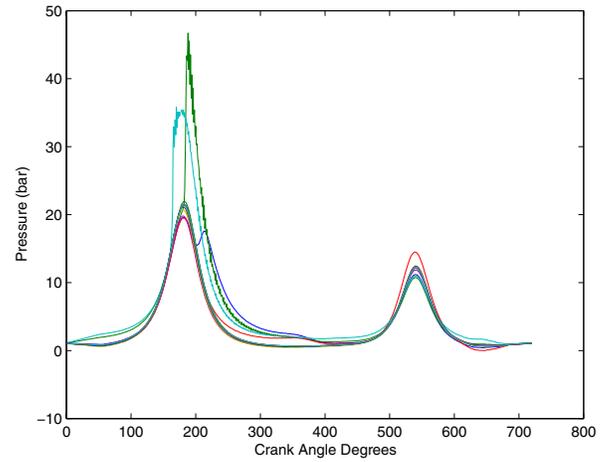


Figure 12 – Ten consecutive unsuccessful pressure signals plotted against crank angle degrees

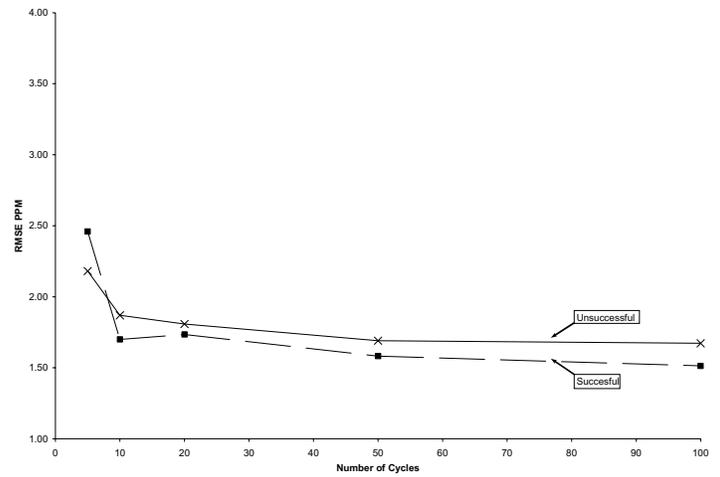


Figure 13 - HCCI operation, RMSE in PPM plotted against Number of cycles at 4.76 bar IMEP and 2250 rpm

The predicted location of the PPM provides reasonable accuracy in both unsuccessful and successful for HCCI (Figure 13). Consequently the predicted location of the PPP is nowhere near as accurate in the unsuccessful as for the successful HCCI (Figure 14). With an RMSE difference of ~2. This could be due to the varying position of the combustion within these cycles. It is also partly because in a misfired cycle the ion-current signal is absent. The program therefore takes the maximum signal to be zero, effectively reducing the number of cycles that the program can use and hence also reducing accuracy. Another reason for the poor correlation during very early or late cycles, could be due to the cycles are neither “very early” nor “very late”, it's the number of cycles used in each prediction.

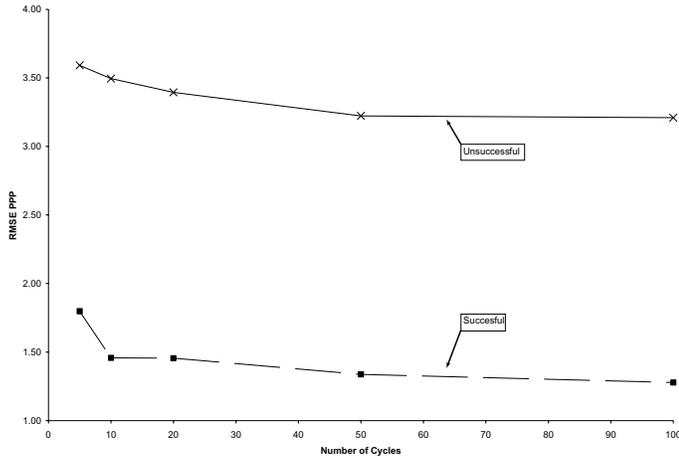


Figure 14 - HCCI operation, RMSE in PPP plotted against Number of cycles at 4.76 bar IMEP and 2250 rpm

CAI

It is clearly an advantage to use more cycles to reduce the error in prediction this can be seen in both PPM (Figure 15) and PPP (Figure 16). Although this is clearly the case, there is no significant gain in using more than 20 cycles as, after this value the error only decreases slightly and this little gain is meaningless compared to the computational disadvantage, (to run linear regression). This occurs in all CAI results, independent of engine IMEP or speed.

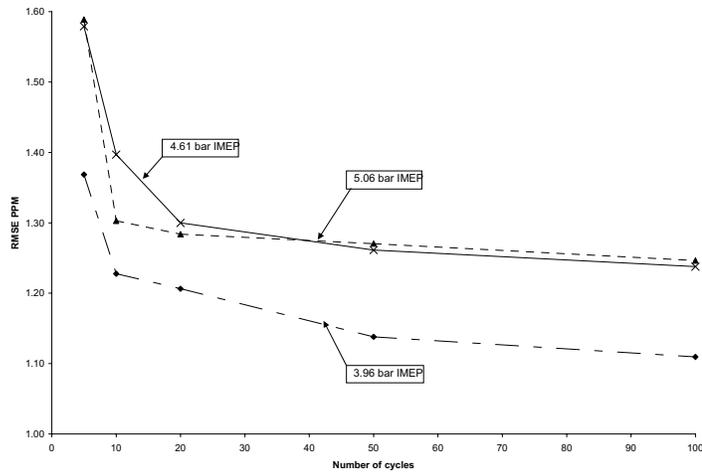


Figure 15 - CAI, RMSE in PPM plotted against Number of cycles used at 2250 rpm at three different IMEPs(3.96, 4.61 and 5.06 bar).

It can also be seen that in both Figures (15 and 16) that there is no pattern in how much error there is. The error is also less in the prediction of the PPP than the PPM. This is because although the range of PPM is much smaller than the range of PPP, there is much less variation in the actual value that occurs.

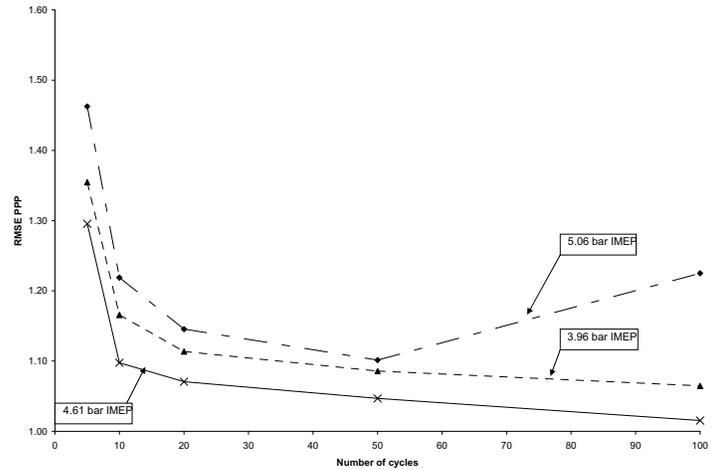


Figure 16 - CAI, RMSE in PPP plotted against Number of cycles used at 2250 rpm at three different IMEPs(3.96, 4.61 and 5.06 bar).

Figure 17 shows that in most cases, as IMEP increases at the same engine speed, the error increases too. This has been illustrated by an exponential fitting through the data. This fitting has been applied to show that although the RMSE fluctuates, the general error increases more with higher IMEP.

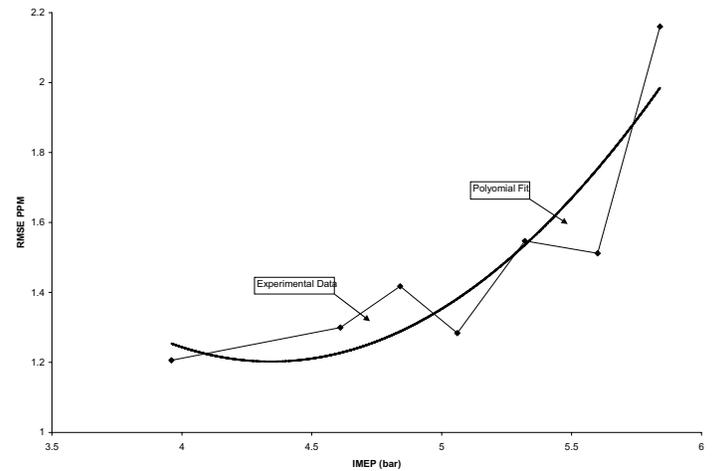


Figure 17 - CAI, RMSE in PPM plotted against different IMEPs all at 2000rpm.

In Figure 18 an exponential fitting has again been applied which fits the data. This increase in error in the higher IMEP ranges could be because of signal degradation making it harder for the program to be as accurate. Again the error in the PPP Figure 18 is smaller than the PPM (Figure 17).

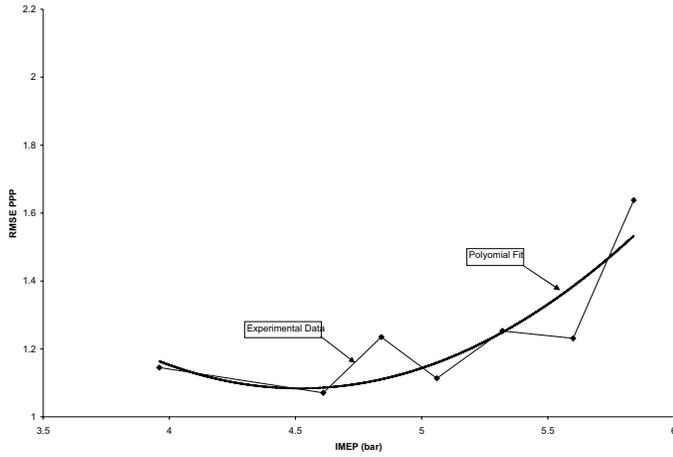


Figure 18 - CAI, RMSE in PPP plotted against different IMEPs all at 2000rpm.

An exponential fit has been applied to Figure 19 and it can be seen that the optimum engine speed range would be between 2000 and 2600rpm when the engine is being run with an IMEP of ~4 bar. This is in agreement with in the PPP results shown in Figure 20. The error is much larger in the PPP prediction, this is a tell tale sign that in some of the datasets analysed that there is again fluctuations in the ion current data.

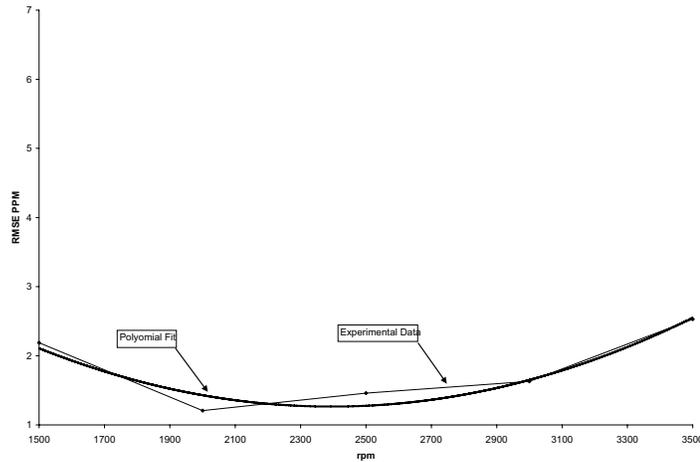


Figure 19 - CAI, RMSE in PPM plotted against engine speed, with all points taken at ~4 bar IMEP

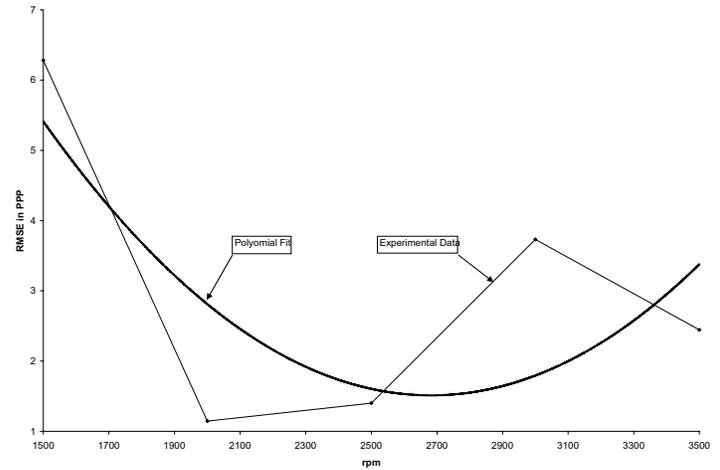


Figure 20 - CAI, RMSE in PPP plotted against engine speed, with all points taken at ~4 bar IMEP.

CONCLUSION

It has been shown in this paper that ion current can predict two of the most important features of an engine cycle, PPP and PPM. Using linear regression this can be done with varying levels of accuracy, depending on how many engine cycles are taken into account. It was deduced that 20 cycles is an optimum amount to use in this prediction process.

The Matlab function Polyfit employed in this research used the relationship between the variables to predict the following cycles. The linear relationship between the ion current peak position and the PPP and the inversely linear relationship between the ion current peak pressure position and the PPM were used.

Two HCCI runs were considered where one with all completed combustion cycles, the other containing misfires and incomplete cycles. It was found that although the PPM was well predicted in both cases, the PPP was not. This was largely because of the varying position of the combustion within these cycles and the misfire signals giving a PPP of zero.

In the CAI runs the error in the prediction of the PPM is always slightly higher than the error in the PPP. This is because there is although the range of PPM is much smaller than the range of PPP, there is much less variation in the actual value that occurs.

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