

HCCI Engine Cyclic Variation Characterization Using Both Chaotic and Statistical Approach

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1 ABSTRACT

This paper investigates the cyclic variation of ignition timing in an Homogeneous Charge Compression Ignition (HCCI) engine using a range of experimental data collected from a single-cylinder Ricardo engine. Under certain operating conditions, HCCI engines can exhibit large cyclic variations in ignition timing. Cyclic variability ranging from stochastic to deterministic patterns can be observed. This work applies two methods to study patterns of CA50 (Crank angle of 50% fuel burnt) cyclic variation in an HCCI engine.

Nine points ranging from the misfire to knock limit within the HCCI mode are experimentally measured by varying the intake manifold temperature. The return map techniques used in nonlinear dynamics and chaos theory are applied to observe possible deterministic structures inherent in these points.

Probability distribution for cyclic combustion timing is the second approach examined. Experimental data of 338 different points over a wide range of operating conditions are examined to find out the conditions where a normal distribution for CA50 is observed. Three common statistical testing methods are used to verify the hypothesis of having a normal distribution for each data point.

2 INTRODUCTION

HCCI engines are of great interest to researchers because of their advantages which include very low emission levels and higher efficiency compared to Spark Ignition (SI) and Compression Ignition (CI) engines [1]. On the other hand, these engines have some disadvantages. One of their main drawbacks is the control problem due to the lack of any direct control means to trigger combustion [2, 3]. Methods to extend the HCCI operation range is also a focus for researchers [2]. Cycle-by-cycle experimental observations of important engine parameters have shown an inherent non-random structure inside the SI engine [4]. The presence of deterministic structures suggests that techniques for real-time control to stabilize the unstable operating regions of the engine can be implemented [5].

The transition between spark ignition and HCCI combustion which follows a relatively low-dimensional deterministic dynamics has been documented in [5]. There the internal EGR (Exhaust Gas Recirculation) is varied by changing the timing and lift of the intake and exhaust valve. In [6], the connection between past and future combustion events are investigated using experimental nonlinear mapping functions. Their results confirm that the deterministic component of lean combustion variations can be approximated by fitting the data to a low-order nonlinear map. Chaotic behavior in a production internal combustion engine has also been documented in [7]. Different patterns of cyclic variation of combustion patterns have been observed in [8] including normal, periodic and cyclic variations with weak/misfired ignitions.

This paper is organized as following. In the next section, the experimental setup for collecting the data is briefly described. Then, the engine variation and bifurcation plot are used to describe how the general behavior of CA50 varies as intake manifold temperature changes while other variables are held constant. Return maps from chaotic theory are

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used to check the deterministic structure inherent in the data points as intake manifold temperature decreases. Finally, the experimental data is statistically analyzed to examine the normality of probability distributions for a range of measured operating conditions.

3 ENGINE SETUP

A Ricardo Hydra Mark 3 engine fitted with a Rover K-7 head is used [9]. The engine specifications are given in Table 1. This engine represents a typical spark ignition engine, outfitted with a piezo-electric pressure transducer. A schematic of the test cell is shown in Figure 1 where the external EGR is controlled with a valve, and is routed into the intake before the supercharger. The intake air is heated with a temperature controlled 600W electric heater, while the intake pressure is adjusted with an externally driven supercharger.

N-heptane and iso-octane are individually port injected with the fuel scheduling of the two injectors done using a dSpace-MicroAutobox ECU. Real time combustion analysis is done with A&D Baseline CAS. Using this degree based real time processor the cylinder pressure was recorded 3600 times per crank revolution, this was then analyzed for the pertinent combustion metrics, such as IMEP (Indicated Mean Effective Pressure), CA50 and burn duration. All other parameters are logged on a time basis using A&D Baseline DAC. The tests operating conditions are listed in Table 2 and 338 points are analyzed of which 9 are used for the manifold pressure sweep and all are used for the normal distribution analysis.

Table 1: Configuration of the Ricardo single-cylinder engine

Parameters	Values
Bore \times stroke [mm]	80 \times 88.9
Compression Ratio	10
Displacement [L]	0.447
Valves	4
IVC [aBDC]	55
EVO [aBDC]	-70

Table 2: Engine operating conditions

Parameter	Range
Manifold Pressure [kPa]	88-162
Manifold Temperature [$^{\circ}$ C]	60-161
External EGR [%]	0-30
Fuel Octane Number [PRF]	0,10,20,40
Engine Speed [RPM]	760-1340
Equivalence Ratio [-]	0.29-0.95
Coolant Temperature [$^{\circ}$ C]	25-84
Oil Temperature [$^{\circ}$ C]	48-80
Oil Pressure [psi]	45

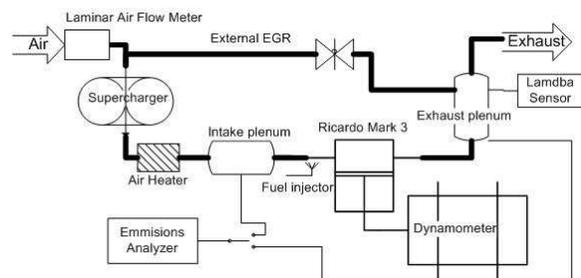


Figure 1: Schematic of the experimental setup

4 TRANSITION ANALYSIS

4.1 Stability Analysis

An intake manifold temperature sweep from the knock limit to the misfire limit in HCCI mode where the intake manifold temperature is varied while keeping all the other parameters constant is performed for nine temperatures. The reason for varying the intake manifold temperature is that HCCI combustion is sensitive to temperature [8]. Measurements at each intake manifold temperature level have 3000 consecutive cycles. To characterize the cyclic HCCI combustion dynamic behavior, several methods are used.

First, the engine stability in terms of Coefficient of Variation (COV) of Indicated Mean Effective Pressure (IMEP) of HCCI combustion is shown in Figure 2 during the transition from misfire to knock limit. COV is defined as

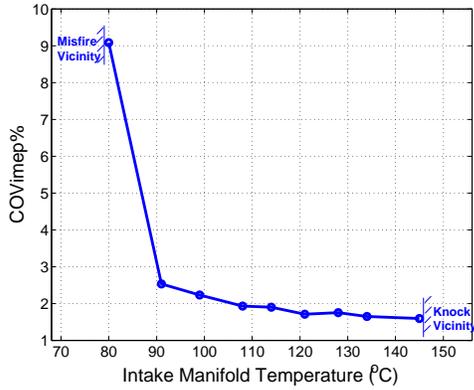


Figure 2: The coefficient of variation (COV) in the IMEP for intake manifold temperature sweep

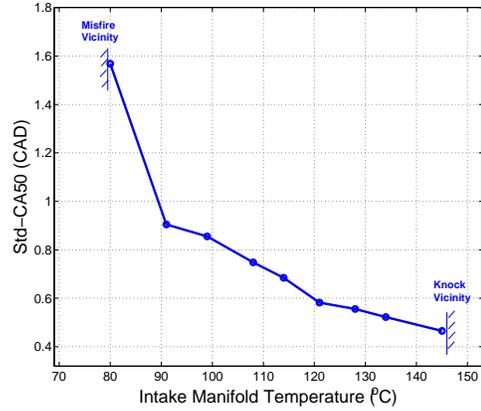


Figure 3: Variation in STD of CA50 cyclic ensemble for intake manifold temperature sweep

Standard Deviation (STD) divided by the mean value. The point in the plot with $T_{man} = 80^{\circ}C$, corresponds to the HCCI operation region near the misfire limit where COV of IMEP is high. As the intake manifold temperature increases, these variations decrease. Near the knock limit region ($T_{man} = 145^{\circ}C$), COV of IMEP reaches to its minimum value which indicates the most stable mode of the combustion.

Since CA50 is a very good indicator of ignition timing in HCCI [10], it is used here as is the cyclic variation of CA50 during HCCI operation. The Standard Deviation of CA50, which is a good measure of how CA50 variation changes, is shown in the Figure 3 for varying intake manifold temperature. Increasing the intake manifold temperature from the misfire limit to the knock limit results in CA50 variation decreasing.

A bifurcation diagram is used to reflect the effect of each parameter on the whole time series [11] and is shown in Figure 4 where the variation of the grey scale seen in the plot is indicative of variation in density of CA50 data points. The concentration of data points around their mean point (darker area), increases near the knock limit. In addition, increasing intake manifold temperature advances CA50.

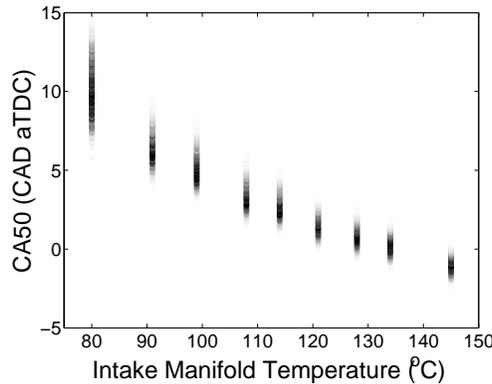


Figure 4: CA50 bifurcation diagram for intake manifold temperature sweep

4.2 Return Maps

The return maps as a chaotic theory technique is often used to determine the inherent deterministic structure of the data [5, 11, 12]. Return maps plot pairs of successive time series values versus each other (here the CA50 value for cycle i versus cycle $i+1$ are plotted in a return map). Using return map plots, each cycle point relates to the next cycle through the general statistical picture of the whole cycles interrelation [12] and these maps provide a qualitative tool to check the deterministic structure inherent in the data points [13]. The analysis of CA50 for a HCCI sweep

from knock limit to misfire limit during HCCI combustion in terms of the CA50 return maps is illustrated in Figure 5 for a range of intake manifold temperatures. The dispersion of these data points over the diagonal line seem to occur

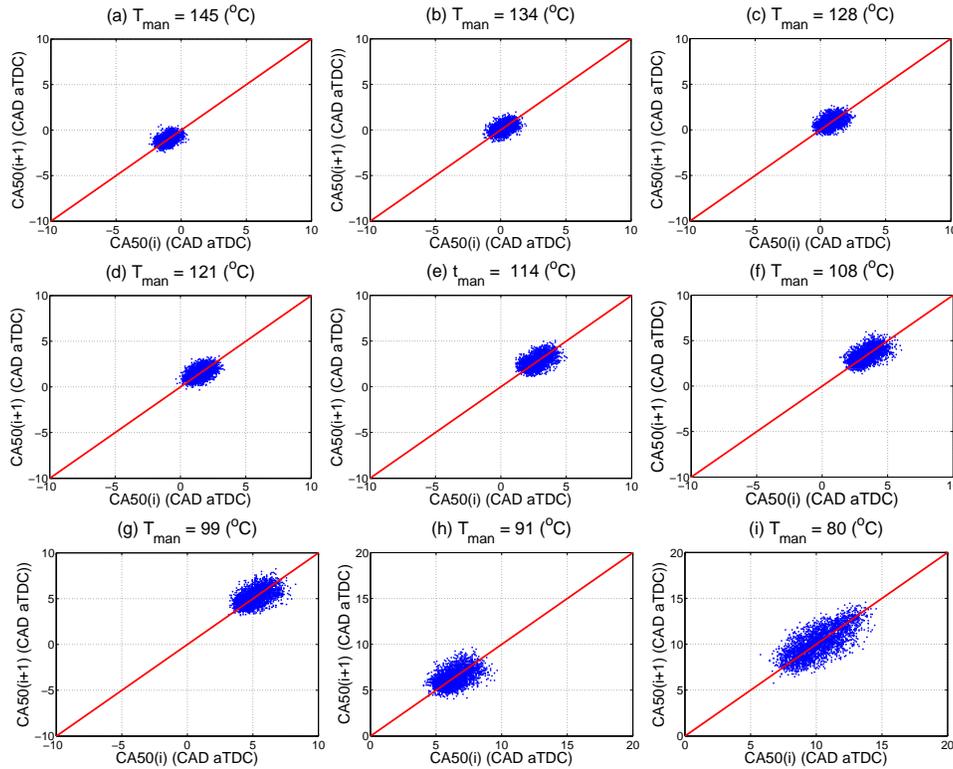


Figure 5: CA50 Return maps for HCCI combustion illustrating the transition from (a) knock limit to (i) misfire limit reducing the intake manifold temperature

because of nonstationary or transient dynamics of the engine near misfire limit, where oscillations between early and late CA50 occur frequently. Return maps result for CA50 near the knock limit show an unstructured cluster of circular data gathered around a fixed point which indicates the HCCI combustion is getting more stable in the vicinity of the knock limit. These data points start to scatter over the diagonal line as they move towards the misfire limit and fixed points becomes destabilized leading to more structured data points. The structured patterns seen in the data can be attributed to the deterministic coupling between consecutive cycles. Overall, the return maps exhibit more asymmetry as they approach to the misfire limit.

5 NORMAL DISTRIBUTION ANALYSIS

The second method for analyzing the cycle to cycle combustion timing is using statistical methods. The population of consecutive ignitions at a constant operating point can be used to form a probability distribution for cycle to cycle combustion timing. Normal distribution is the most common probability distribution used to characterize experimental data [14]. Experimental data at 338 different points including the 9 points analyzed previously are analyzed to determine which conditions have a normal distribution for CA50. Two common testing methods for normal distributions are used. The first method is the Lilliefors test that evaluates the input data and returns the result of the hypothesis test for the goodness of fit to the normal distribution [15]. The second method is the Kolmogorov-Smirnov test that compares the values in the data with a standard normal distribution and checks the hypothesis that the data has a standard normal distribution [16, 17]. These two methods are applied on the CA50 data sets from 338 points. Points that successfully pass these two tests are then visually evaluated with normal probability plot. The normal probability plot is a graphical tool to assess whether or not a data set follows a pattern of a normal distribution [14]. Data from the experimental points are plotted against a theoretical normal distribution and if data is normally distributed, it forms

an approximate straight line. The level of departures from normality is judged by how far the points vary from the straight line. Figure 6 shows a normal probability plot for a sample experimental point that exhibits a normal distribu-

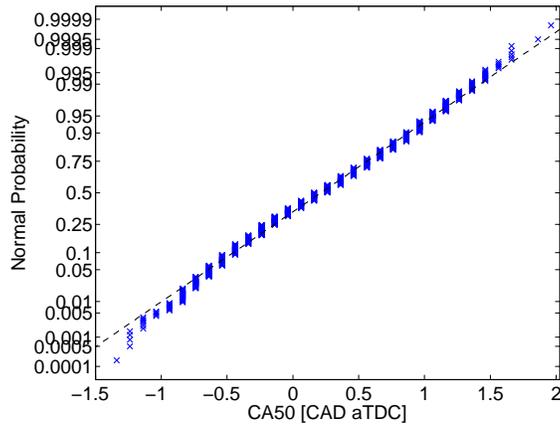


Figure 6: Sample normal probability plot for the test point (h) in Figure 5.

tion. CA50 data sets for all experimental points were processed using the procedure mentioned above and 19 points out of 338 points are judged to have a normal distribution. The range of ignition timing parameters for cases with normal distribution are compared with those of the whole data set in Table 3.

Table 3: Comparing the range of ignition timing parameters for cases with normal distributions with those from the whole 338 HCCI experiments

Parameter	SOC	CA50	BD	STD _{CA50}
Whole Exp. Data	-4.6 → 21.9	1.8 → 24.9	2.4 → 13.1	0.4 → 4.4
Normal distribution cases	0.8 → 7.7	4.5 → 11.5	2.5 → 4.3	0.5 → 1.4

Table 3 shows that normal distribution of CA50 is more likely to occur in HCCI ignitions occurring for a window immediately after TDC ($0.8 \leq \text{SOC} \leq 7.7$ CAD aTDC). In those conditions, cyclic variations of CA50 is typically low ($0.4 \leq \text{STD}_{\text{CA50}} \leq 1.4$ CAD) and the burn duration is short ($2.5 \leq \text{BD} \leq 4.3$ CAD). A large deviation from the straight line is observed in normal probability plots of the operating points which have mean CA50 occurring after 15 CAD aTDC. Furthermore, all the 19 test points are for fully warmed up conditions and none of the points which have low coolant temperature show a normal distribution for CA50. No direct preference for normal distribution was seen in operating conditions in terms of octane number, engine speed, equivalence ratio and intake conditions. However, a combination of these conditions determine the location of SOC.

6 CONCLUSIONS

Experimental characterization of cyclic variation of HCCI combustion using both chaotic and statistical methods has been performed.

Using bifurcation diagrams and return maps more structure is observed as the engine operating condition is changed from the knock limit to the misfire limit by using 9 different intake manifold temperatures. This structure is indicative of a coupling between successive CA50 (engine cycle timing) which has the expected sequence of late and early combustion near the misfire limit.

A wide range of engine operating conditions (338 points) are analyzed using normal distribution variation statistical tests. As expected, stable HCCI combustion with combustion timing near TDC is more likely to have normal distributions since the combustion timing of successive cycles is independent.

7 ACKNOWLEDGMENT

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