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Cycle by Cycle Actuation of Intake Valve Closing in HCCI

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Abstract

Homogeneous Charge Compression Ignition (HCCI) has the potential to improve automobile efficiency in part load operation. However, challenges of limited operating range as well as difficulty in mode switching from spark ignition to HCCI limit the practical use of HCCI technology. One system that shows promise for fast actuation and control of HCCI is fully variable valve timing. A fully variable electromagnetic valve timing system has been installed on a single cylinder research engine. Running in HCCI, the intake valve closing event is switched cycle by cycle between 180 degrees before top dead center (bTDC) to early valve closing during the intake stroke at 230 degrees bTDC in order to modify the effective compression ratio. A return map of the combustion timing for each cycle indicates deterministic ignition timing when cycling between these two operating points. Each operating point at steady state is then compared to the switched case by examining the return map, IMEP and maximum pressure rise rate.

Introduction

The increasing price of fuel and increasingly strict emissions criteria for automobiles has added to the need for more efficient internal combustion engines. One technology that shows promise is Homogenous Charge Compression Ignition (HCCI), where a pre-mixed air fuel mixture is compressed to the point of auto-ignition. This form of combustion does not use a spark plug like a conventional spark ignition (SI) engine, nor does it use the direct injection event for combustion timing like a diesel engine. Combustion timing is thus an interesting control problem for HCCI. A technology that can be used to control combustion timing is fully variable valve actuation (VVA) [1][2]. It has been shown that VVA can reduce emissions [3], vary load, as well as improve power output [4] and efficiency [5]. A camless variable valve actuation system is reported to increase the operating range of HCCI by 200% but also increases manufacturing costs by 40% [6]. When the limit of HCCI operating range is reached, VVA can be used to aid in mode switching between SI and HCCI to ensure a smooth transition torque where there is no misfire or knocking [7].

In a camless system, the four valve timing events are defined as: intake valve opening (IVO), intake valve closing (IVC), exhaust valve (IVO), and exhaust valve closing (EVC) and each can be modified if the system is fully variable. The effect of early intake valve closing was first documented in the 1980s for SI [8]. A reduction in pumping losses of 40% was reported resulting in a 7% reduction in fuel consumption. However, combustion timing in HCCI is more complicated than SI since combustion is dominated by chemical kinetics and factors such as in-cylinder concentrations of reactants and products, equivalence ratio, the intake temperature and the amount the reactants are compressed [9]. Cycle-by-cycle coupling is also documented in HCCI for fast changes in the trapped exhaust gas [10] and for IVC changes[11].

In the next section, the experimental engine setup is briefly described as well as the electromagnetic VVA used to achieve cycle by cycle IVC control. The following section describes the result of the test conducted, where the IVC is switched cycle by cycle from 230° bTDC to 180° bTDC. The ignition timing parameter, θ_{Pmax} [12], is compared against steady state data using a return map to identify deterministic patterns. Finally, indicated mean effective pressure (IMEP) and maximum rate of pressure rise, $ROPR_{max}$, are compared to steady state data in order to evaluate the effect of cycle by cycle actuation on HCCI engine load changes.

Engine Setup

A Mercedes cylinder head and valve actuators [13] is used in this work to provide variable valve timing. This system is a fully electromagnetic variable valve timing (EVVT) system where each valve actuator consists of two electromagnets and two springs pushing in opposite directions [14] [15]. The Mercedes single cylinder head includes a centrally located spark plug, a side port for a in cylinder pressure transducer, and utilizes two valves per cylinder. This cylinder head is mounted on a Ricardo

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Hydra mark III single cylinder engine. Since the valve timing is fully independent of crank angle, the engine has been setup to be free running with a custom made piston with valve reliefs. The valve train used in the experiment allows for full control of the IVO, IVC, EVO, and EVC events; however valve lift is a constant 8 millimeters. A schematic of the engine setup and data acquisitions (DAQ) systems is shown in Figure 1 [16].

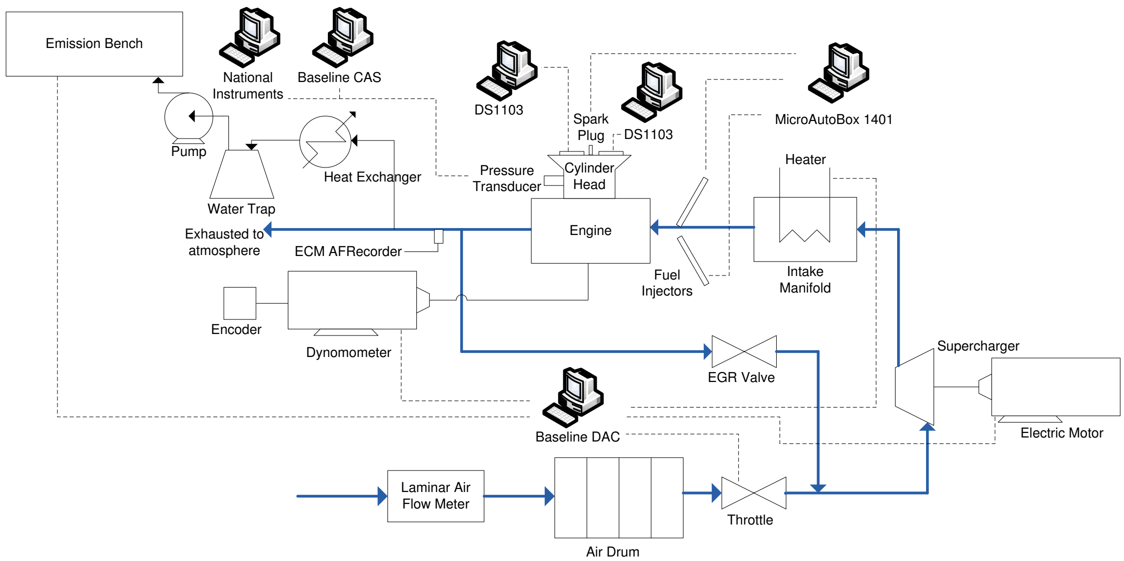

Figure 1: Schematic for the Ricardo single cylinder engine and corresponding Computer systems

The in cylinder pressure signal is recorded by a Kistler 6061B on a 0.1 crank angle degree (CAD) basis from a BEI optical encoder by an MTS Power-train Baseline CAS system. The pressure signal is also recorded by a National Instruments PCIe-6341 DAQ system at 0.1 CAD for 300 cycles. Each intake and exhaust valve is operated by a dSPACE DS1103 Power PC (PPC) target controller which records data, including the pressure trace, for 5 seconds at 50kHz. Other engine operating parameters are measured at 10Hz with an MTS Power train Baseline DAC and averaged over each operating point. Intake manifold air temperature, oil temperature, and coolant temperature are measured with K-type thermocouples. Equivalence ratio is measured with an ECM AFRecorder 1200 wideband oxygen sensor. The injected fuel energy and octane number is recorded on a dSPACE MicroAutoBox 1401 controller. A summary of the engine parameters and operating conditions can be found in Table 1 with the default valve timing at engine start-up. The angles of valve timing in this paper are in reference to TDC of combustion in all cases. The uncertainty indicated in the operating conditions listed in Table 1 is the maximum deviation from the average.

Parameters	Values
Bore $\times$ stroke [mm]	97 $\times$ 88.9
Compression Ratio	13.9
Displacement [L]	0.653
Valves	2
Valve lift [mm]	8
Fueling	Port injection
IVO [bTDC]	300
IVC [bTDC]	180
EVO [bTDC]	-180
EVC [bTDC]	-300

Operating Condition	Values
Engine speed [rpm]	823 ± 12
Intake Temperature [deg C]	95.9 ± 1
Intake Pressure [kPa]	88.0 ± 9.0
Equivalence Ratio	0.42 ± 0.04
External EGR [%]	0
Throttle [%]	50
Oil temperature [deg C]	51.6 ± 2.5
Coolant temperature [deg C]	40.1 ± 0.5

Table 1: Engine configuration and operating conditions for the Ricardo single-cylinder engine

Cycle by Cycle Switch of IVC

To change the engine load cycle-by-cycle, the IVC is switched back and forth from 180 degrees to 230 degrees bTDC on consecutive cycles. 32 cycles are recorded with the DS1103 controllers while fuel injected energy is held constant at 0.446 kJ with an octane number of 11. The valve timing events are documented in Table 2. The valve timing events are chosen heuristically such that stable operation for both cycle by cycle as well as steady state operation is achieved. The corresponding pressure traces are shown in Figure 2. The change in valve timing is apparent in the figure from the difference in the pressure traces. The potential for throtteless actuation as well as actuation for fast transients is thus apparent with this experimental setup.

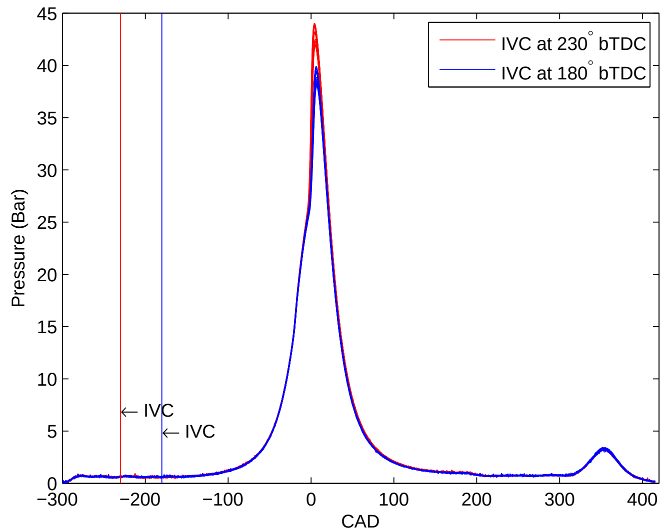

Figure 2: Pressure diagram for cycle by cycle switches of IVC for HCCI operation

Table 2: Valve timing for IVC switching

IVC [° bTDC]	180	230
IVO [° bTDC]	300	300
EVC [° bTDC]	-300	-300
EVO [° bTDC]	-180	-180

The effect of early IVC is to regulate the amount of charge taken in, ultimately effecting the volumetric efficiency [17] or effective compression ratio [18]. However, since the injected fuel is held constant, at IVC of 230° bTDC the equivalence ratio is higher so a slightly higher IMEP results.

A return map, which plots successive time series values versus each other, gives an indication of the inherent deterministic structure of a data set [19]. In this case, the return map of an ignition timing indicator is chosen as θ_{Pmax} [12]. This ignition timing parameter is found to be more reliable at identifying cycles of partial burn/misfire than the typical ignition timing method of CA50 (Crank angle of 50 percent mass fraction burned) [12][20]. The return map of θ_{Pmax} is plotted for the cycle by cycle change in IVC in Figure 3. A return map for the steady state case, where the valve timing is held constant, is shown in Figure 4.

The return maps of cycle by cycle actuation shows 300 cycles where the angle that maximum pressure occurs changes between the averages of 3.9 to 6.4 degrees after TDC. There are two zones for each valve timing, and no distinct pattern is seen in each zone. Thus cycle by cycle actuation does not create deterministic behavior in ignition timing that would indicate a multi-cycle interaction. However, Figure 4 does show that the ignition timing at steady state is different than that of cycle by cycle actuation. The cycle by cycle changes on the stability of ignition timing based on θ_{Pmax} is given in Table 3. The average for each case is given as well as the average indicated mean effective pressure (IMEP),average maximum rate of pressure rise ($ROPR_{max}$) and the range, taken as the largest difference of the location of peak pressure.

The effect of cycle-by-cycle actuation on ignition timing is clear by comparing Figures 3 and 4. During cycle by cycle actuation, θ_{Pmax} occurs earlier for both valve timing cases compared to steady state. Ignition timing is a complex function of the charge properties and heat transfer. For example the sensitivity of ignition timing to change in temperature, pressure, equivalence ratio, fuel octane number and exhaust gas recirculation is detailed in [21]. Changing IVC from 180° bTDC to 230° bTDC reduces the effective compression ratio and thus the charge pressure which should retard combustion timing. However, since there is less air but the fuel amount is constant, the equivalence ratio of the charge goes up advancing the combustion timing. These two competing effects result in the equivalence ratio influence being stronger in this case.

The effect of cycle by cycle actuation is also apparent in other combustion metrics such as (IMEP). Figure 5 illustrates how

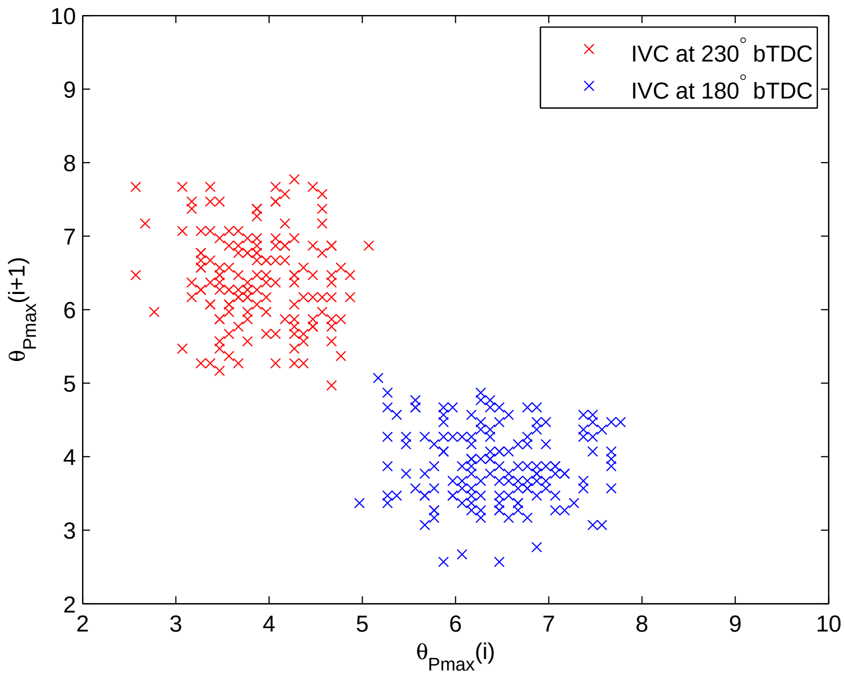

Figure 3: Return map of θ_{Pmax} for 300 cycle by cycle changes of IVC in HCCI

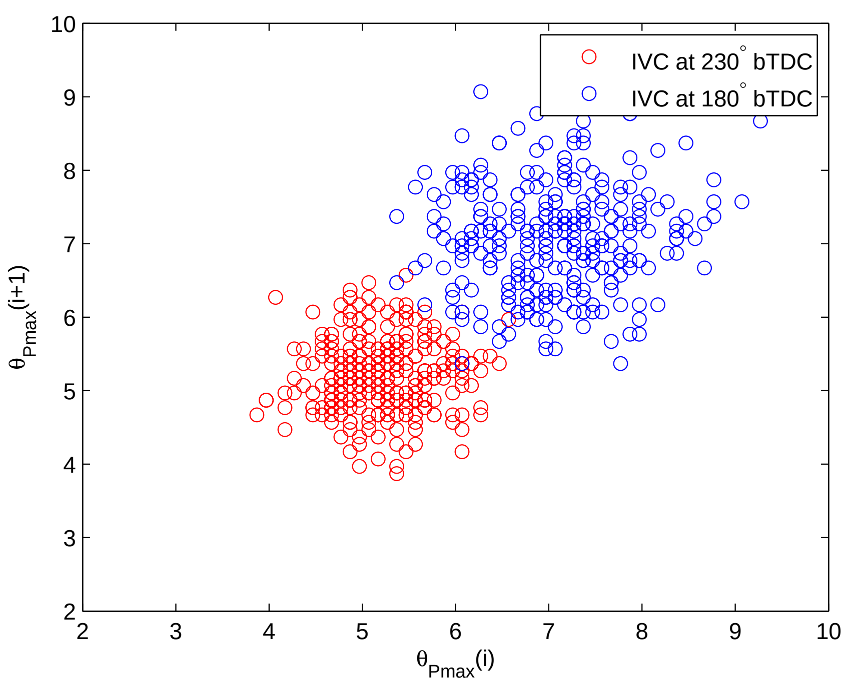

Figure 4: Return map of θ_{Pmax} for 300 cycles of steady state valve timing in HCCI

IMEP changes as a function of engine cycle. When IVC valve timing is constant, IMEP in both cases are both approximately 2.2 bar (lower two plots of Figure 5). IMEP changes on a cycle by cycle basis between the two values of 2.1 bar and 2.4 bar as IVC is cycled between 180° bTDC and 230° bTDC as shown in the top plot of Figure 5.

At IVC equal to 180° bTDC there are more cyclic variations which are attributed to being closer to the misfire limit. These cyclic variations are lower when cycle-by-cycle actuation occurs. This is attributed to a slightly richer residual from the cycle

Table 3: Performance indicators for IVC switching

Valve timing (° bTDC)	θ_{Pmax} Range	θ_{Pmax} Average	IMEP Average	$ROPR_{max}$ Average
IVC at 180 During Cycling	2.8	6.4	2.1	2.4
IVC at 230 During Cycling	2.5	3.9	2.4	4.7
IVC at 180 Steady State	3.9	7.07	2.2	2.4
IVC at 230 Steady State	2.7	5.2	2.2	3.3

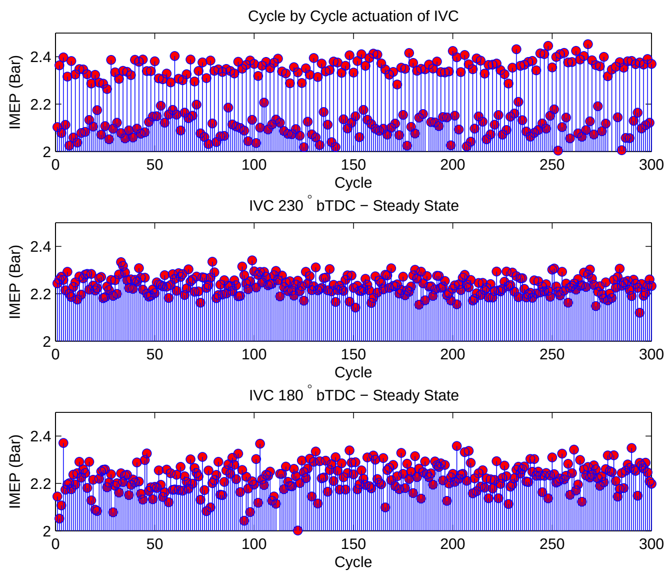

Figure 5: Comparison of IMEP for 300 cycles for cycle by cycle actuation and steady state operation

previous (IVC = 230° bTDC).

Another metric of combustion quality is the maximum rate of pressure rise, $ROPR_{max}$ which is an indication of the combustion speed and is used to indicate knock if the rate of pressure rise is greater than 10 bar/CAD [22]. It is determined by first filtering the pressure trace using a 5th order low-pass butterworth filter and determining the maximum value of the derivative of the pressure trace. The resulting values are shown in Figure 6 for 300 cycles.

The rate of maximum pressure rise for the steady state cases is different than that of cycle by cycle actuation. The highest and lowest rates of pressure rise rates can be found during the cycle by cycle actuation, following the same trend as the IMEP. Throughout all tests, the $ROPR_{max}$ is less than the knock limit of 10 bar/CAD. This illustrates the necessity for knowledge of previous cycles for HCCI control if combustion timing is to be controlled.

Conclusions

A fully variable valve timing system has been developed using electromagnetic actuators and implemented on a single cylinder engine. Cycle by cycle switching between an IVC of 180 degrees bTDC and 230 degrees bTDC are conducted to show robustness and capability of the valves, as well as their potential for combustion timing control and mode switching. A return map for the two cases indicate the switch of IVC changes the location of peak pressure, an indicator of combustion timing and that combustion timing during cycle by cycle switching is dependant on the previous cycle. The time history of the maximum rate of pressure rise and IMEP are plotted and show that the cycle-by-cycle switching of IVC timing is between two stable operating points with no periodic variations. The tests confirm that HCCI ignition timing is a complex function of the charge properties.

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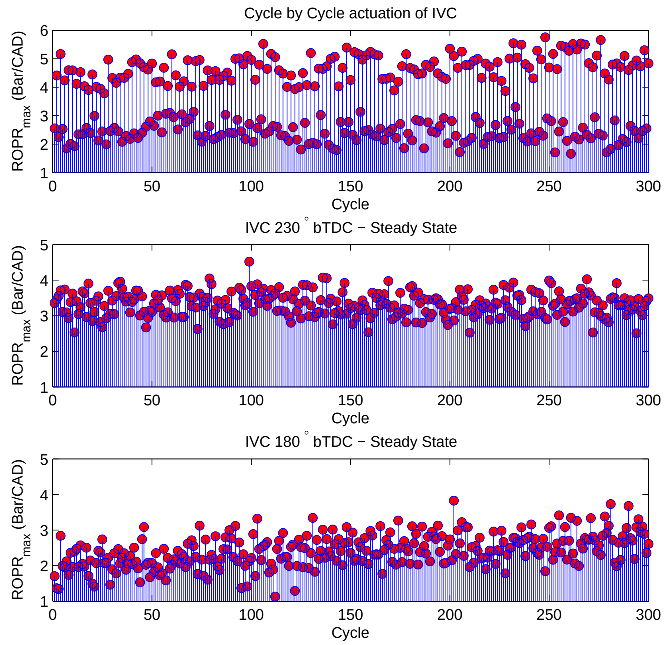

Figure 6: Comparison of $ROPR_{max}$ for 300 cycles for cycle by cycle actuation and steady state operation

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