

Experimental Investigation of a Control Method for SI-HCCI-SI Transition in a Multi-Cylinder Gasoline Engine

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ABSTRACT

In HCCI engines, the Air/Fuel Ratio (AFR) and Residual Gas Fraction (RGF) are difficult to control during the SI-HCCI-SI transition, and this may result in incomplete combustion and/or high pressure raise rates. As a result, there may be undesirably high engine load fluctuations. The objectives of this work are to further understand this process and develop control methods to minimize these load fluctuations.

This paper presents data on instantaneous AFR and RGF measurements, both taken by novel experimental techniques. The data provides an insight into the cyclic AFR and RGF fluctuations during the switch. These results suggest that the relatively slow change in the intake Manifold Air Pressure (MAP) and actuation time of the Variable Valve Timing (VVT) are the main causes of undesired AFR and RGF fluctuations, and hence an unacceptable Net IMEP (NIMEP) fluctuation. We also found large cylinder-to-cylinder AFR variations during the transition. Therefore, besides throttle opening control and VVT shifting, cyclic and individual cylinder fuel injection control is necessary to achieve a smooth transition. The control method was developed and implemented in a test engine, and the result was a considerably reduced NIMEP fluctuation during the mode switch. The instantaneous AFR and RGF measurements could furthermore be adopted to develop more sophisticated control methods for SI-HCCI-SI transitions.

INTRODUCTION

Homogeneous Charge Compression Ignition (HCCI) is a promising concept for reducing engine-out NO_x emissions and fuel consumption in gasoline Internal Combustion (IC) Engines. In the 1970s, Onishi et al. and Noguchi et al.

conducted early research on HCCI in two-stroke engines [1][2]. In 1983, Najt and Foster achieved HCCI combustion in a 4-stroke engine by using intake charge heating [3]. Their results showed that the HCCI ignition process is governed by chemical kinetics with relatively little influence of turbulence and mixing. In 1989, Thring investigated the effect of AFR, EGR ratio, fuel type and compression ratio on the attainable HCCI combustion region[4]. Since then, there has been continuous interest in HCCI research, which is widely considered to be one possible technology for future IC Engines.

However, the operation range of a gasoline HCCI engine is limited by knocking at high load, and misfiring at low load. Although some progress has been made to enlarge the range in recent research [5][6][7][8], it is still far from covering the entire engine operating map. Furthermore, for HCCI engines which use trapped residual gas at high temperatures as means of initiating combustion, it is necessary for the engine to be in SI mode before a mode switch between SI and HCCI.

In 2003, Koopmans, et al. [9] demonstrated a transition between the un-throttled SI mode and the HCCI mode in a Volvo 5-cylinder engine which was equipped with electromechanical valve actuators. It was found that the operation in the initial cycles following a mode switch deviated significantly from that in steady state operation. Therefore a control parameter optimization is necessary. In 2005, Santoso et al. [10] and Milovanovic et al. [11] separately conducted SI-HCCI-SI transition tests in Port Fuel Injection (PFI) gasoline single cylinder engines, which adopted electromagnetic VVT systems. Valve timing and the injected fuel amount were investigated in Santoso's work and a control strategy was developed to implement a smooth



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mode switch. In Milovanovic's study, mode switches were performed at different engine loads and speeds. Although the experimental results suggested that by using an electromagnetic VVT system the transition from SI to HCCI could be performed smoothly in one engine cycle, the reverse transition (HCCI to SI) produced a considerable disturbance in the engine torque and total hydrocarbon (THC) emissions. However Zhang et al. [12], who performed SI-HCCI-SI switches in a single cylinder engine equipped with a fully variable 4-valve actuating system, suggested that the transition from HCCI to SI is easier than the reverse. Stable transition was achieved by them through a rapid and dynamic management of the residual gas fraction.

In 2008, Matsuda et al. [13] reported that a stable combustion region between SI and HCCI combustion can be obtained by controlling the ignition timing and the intake air pressure. A smooth transition is possible if the combustion process passes through this stable region. Kakuya et al. [14] investigated the SI-HCCI-SI transition by both simulations and experiments. The fluctuation of engine load was minimized by controlling the Air/Fuel ratio and internal residual gas fraction, with the additional support of spark ignition and double fuel injection.

Electromechanical valve systems provide full flexibility of variable valve lift and variable valve timing control, hence make it easier to achieve smooth transitions. But because of their high cost, they may be unattractive for production engines. Therefore two-stage cam profile valve systems have been adopted to implement SI-HCCI-SI mode transitions. In 2007, Tian et al. [15] investigated the mode transition in a GDI 2 cylinder engine, equipped with such a two-stage cam profile valve system. The system switched from a normal SI valve profile to a HCCI valve profile in one engine cycle. Slow throttle opening control was used to stabilize the transition process. Cairns et al. [16] used SI/HCCI combined combustion mode to achieve a smooth transition between SI and HCCI in a 4 cylinder gasoline engine which was also equipped with a Two-Stage Cam Profile system. In this study external EGR was found to be beneficial for reducing peak pressures and the maximum pressure rise ratio during the transition.

In the following, the experimental setup is described, followed by an illustration of a technique for making cyclic AFR and RGF measurements. Finally, mode transitions along with a detailed data analysis are discussed and a suitable engine control strategy which helped to achieve a smooth mode transition is demonstrated.

EXPERIMENTAL SETUP

The engine used for this study was a Ford 2.0L 4-cylinder GDI engine, which is equipped with hydraulic two-stage profile camshafts. There was no external EGR loop. The

configuration of the engine and facility is almost the same as reported in a previous study [17]. The engine speed is controlled by a dynamometer and a torque output reading is given by a dynamometer load cell. Each cylinder is fitted with a Kistler 6123 piezoelectric pressure transducer coupled to charge amplifiers. An optical encoder provides engine rotational position information, triggering ADC cards for high-frequency data recording. Thermocouples attached to the intake and exhaust manifolds provide temperature readings. The fuel flow rate was obtained from a Coriolis-type flow meter. Engine specifications are listed in Table 1 and the valve timing is illustrated in Figure 1.

Table 1. Engine Specifications

Displacement	1.996 liters
Bore	87.5mm
Stroke	83mm
Connecting Rod Length	146.25mm
Nominal Compression Ratio	12:1
Fuel Injection Type	Direct Injection
Variable Valve Timing	35° CA (Inlet), 55° CA (Exhaust)
Inlet Cam Profile	2.7mm, 128° CA / 7.5mm, 228° CA
Exhaust Cam Profile	2.7mm, 128° CA / 7.5mm, 228° CA

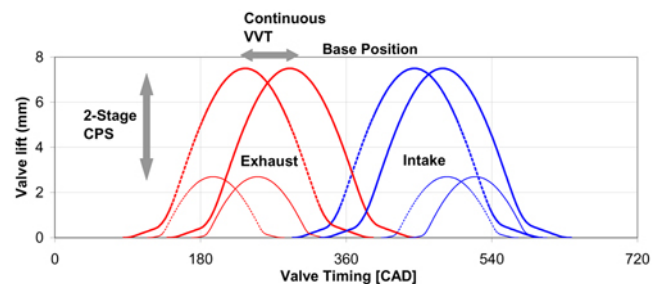


Figure 1. Valve Timing of the two-stage profile camshafts.

To be able to determine the cyclic AFR of each cylinder, four fast response Universal Exhaust Gas Oxygen (UEGO) sensors [21, 22] were connected to the exhaust manifold via sample capillaries located close to the exhaust ports. Details of the fast UEGO (fUEGO) sensor and cyclic AFR measurements are discussed in the next section. To measure instantaneous RGF, two Cambustion NDIR500 fast response Non-Dispersive Infrared (NDIR) analysers were used to measure the cyclic concentration of CO₂ in the compression stroke and in the exhaust. The NDIR unit sampling in-cylinder gas is connected to a Cambustion CSV high speed sampling valve, which itself is connected directly to the combustion chamber of Cylinder 4, via a small hole drilled in the cylinder head, just above the face. The CSV enables a timed gas sample to be extracted during the main compression stroke. The second NDIR analyser is connected

to the exhaust manifold of Cylinder 4 by sharing the same sample capillary as fast UEGO 4. Details about instantaneous RGF measurements are outlined below. The entire sampling system is shown in Figure 2 and a picture of the setup is shown in Figure 3.

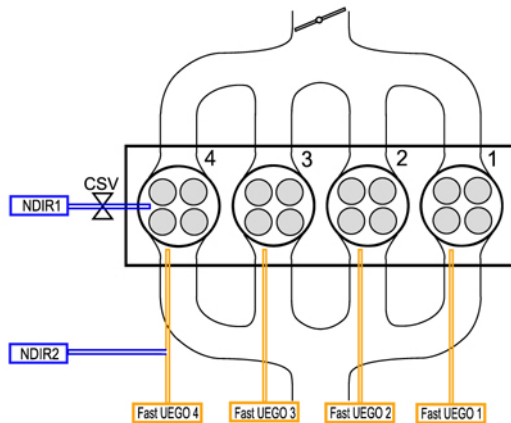


Figure 2. Gas Sampling System.

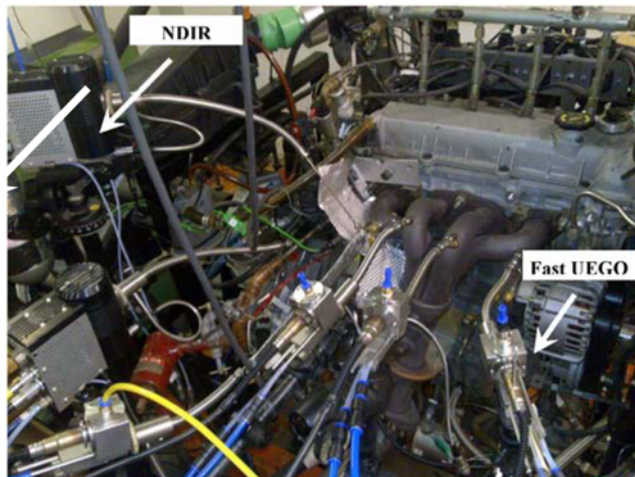


Figure 3. 4-cylinder GDI engine with fast UEGO and NDIR sensors.

INSTANTANEOUS AIR/FUEL RATIO MEASUREMENTS

If one can obtain cyclic AFR measurements, valuable insights into the mode transition process can be obtained. However, the standard UEGO sensor is unsuited to this task, as it has an inadequate time response ($\sim 50 - 100$ ms) and needs a significant quantity of gas to perfuse the sensor housing. To enable cyclic measurements on IC Engines, a fast UEGO sensor concept, the fUEGO, has been developed which enables AFR measurements with time constants in the region of 10ms τ_{10-90} [18][19][20]. A schematic of the fUEGO is shown in Figure 4.

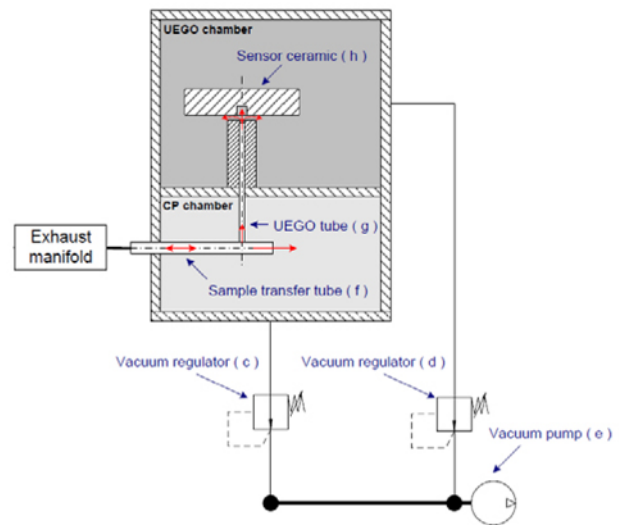


Figure 4. Fast UEGO System.

A vacuum pump (e) is used to evacuate two chambers, the Constant Pressure (CP) and the UEGO chamber. Both vacuums are controlled via vacuum regulators (c) and (d). Sample gas is extracted from the exhaust manifold through a sample line which connects to a capillary (f), ending in the CP chamber. Capillary (f) also connects to the UEGO capillary (g) whose inner diameter is much smaller than the one of (f). The UEGO capillary (g) connects CP and UEGO chambers and delivers sample gas to the diffusion hole of the UEGO sensor element (h). As a result, a very small and constant sample flow is delivered to the sensor element. Due to this design combined with custom control circuitry, the fUEGO sensor has a time constant of about 10 milliseconds [20]. This makes it possible to cyclically resolve the AFR fluctuations during SI-HCCI-SI transitions up to high engine speeds. The fact that the UEGO sensor is in a controlled pressure (and temperature) environment is a significant benefit, especially when attempting high frequency response measurements, where interference, especially from pressure changes, is significant.

The fUEGO sensor was calibrated by simultaneous exhaust gas measurements, where a production Horiba MEXA-700 λ unit served as a reference. The engine exhaust was varied from $\lambda=0.7$ up to $\lambda=4.0$ (via secondary air dilution) and the fUEGO output/ λ characteristic was recorded and formed the sensor calibration. It is worth noting here that the UEGO sensor does not measure AFR (or lambda) directly; it is inferred from a measurement which is closely related (for stoichiometric and lean mixtures) to the equilibrated oxygen concentration.