Self Tuning Controller for Reducing Cycle to Cycle Variations in SI Engine

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***Abstract*—The cyclic variations in spark ignition engines occurring especially under specific engine operating conditions make the maximum pressure variable for successive in-cylinder pressure cycles. Minimization of cyclic variations has a great importance in effectively operating near to lean limit, or at low speed and load. The cyclic variations may reduce the power output of the engine, lead to operational instabilities, and result in undesirable engine vibrations and noise. In this study, spark timing is controlled in order to reduce the cyclic variations in spark ignition engines. Firstly, an ARMAX model has developed between spark timing and maximum pressure using system identification techniques. By using this model, the maximum pressure of the next cycle has been predicted. Then, self-tuning minimum variance controller has been designed to change the spark timing for consecutive cycles of the first cylinder of test engine to regulate the in-cylinder maximum pressure. The performance of the proposed controller is illustrated in real time and experimental results show that the controller has a reliable effect on cycle to cycle variations of maximum cylinder pressure when the engine works under low speed conditions.**

Keywords-cyclic variations; cylinder pressure; SI engines

I. INTRODUCTION

The reducing fuel consumption and emissions of SI engines depend strongly combustion process. Hence, observing and control of combustion process have a great importance. In addition, imbalance in the combustion process causes explicitly speed fluctuation and output power of engine.

The combustion process is begins before the end of the compression stroke with spark event. Then, this process continues through the early part of the expansion stroke and, ends after the point in the cycle at which the peak cylinder pressure occurs [1] [2]. Because of the combustion process cannot complete instantly and useful work can be obtained during the process, spark timing versus crank angle must choose precisely in spark ignition engines. If the air fuel mixture is ignited too early, there will be too much pressure rise before the end of compression stroke and power will be reduced. On the contrary, if the mixture is ignited too late, so is the work done on the piston during the expansion stroke, since all pressures during the cycles will be reduced.

Traditionally, optimum ignition timing is determined experimentally at different speed, load points and at different operating conditions. This technique is called open loop spark mapping. Generally, it usually requires an enormous amount of effort and time to achieve a satisfactory calibration. Open loop spark ignition control system cannot compensate for external disturbances. Therefore, in recent years, different closed loop engine control system strategies have been proposed based upon cylinder pressure measurement due to they are able to overcome these problems [3][4].

Individual-cylinder, cylinder pressure based closed loop control is an ideal method to optimize engine operating in the presence of changing engine and environmental conditions, because cylinder pressure can be used to characterize the combustion process for each combustion event. In addition, cylinder pressure based feedback control can adapt for random variations[5][6]. Because of these reasons, a closed loop control system based on cylinder pressure based feedback signal spark timing control should be preferred instead of open loop control systems.

On the other hand, one of the many factors that should be take account of modeling, design and control of spark ignition engines is the minimization of cyclic variability that occur in particular with highly lean and/or diluted mixtures. The cyclic variations appear in the consecutive cylinder pressure cycles even though the spark timing and other control parameters are constant. These variations reduce the power output of the engine, involving incomplete burns or even total misfires, leads to increased hydrocarbon emissions, operational instabilities, results in undesirable engine vibrations and noise, and may even cause the engine to stall [7].

Several sources of cyclic variations in a spark ignition engine have been identified. They include (a) turbulence intensity of the flow field in the cylinder, (b) variations in the fuel-air ratio, (c) stochastic structure arising from the effects of residual gases from previous cycles or recirculated exhaust gases in the cylinder, (d) spatial inhomogeneity of the mixture composition especially near the spark plug, and (e) spark discharge characteristics and flame kernel development. It has been estimated that elimination of the cyclic variations may lead to about 10% increase in power output for the same fuel consumption in a gasoline engine.

According to Ozdor, Matekunas and Heywood, the cyclic variations can be characterized by the parameters in four main categories; pressure related parameters, combustion related parameters, flame front related parameters and exhaust gas related parameters. Pressure related parameters are in-cylinder peak pressure (P_{max}) crank angle at which the in-cylinder peak pressure occurs (θ_{Pmax}), maximum rate of pressure rise $(dP/d\theta)_{max}$, crank angle at which the maximum rate of pressure rise occurs $\theta(dP/d\theta)_{max}$, indicated mean effective pressure (imep) of individual cycles.

The purpose of this study is to minimize the cyclic variations for consecutive cycles by controlling the ignition timing. Based on this one cycle P_{max} ahead prediction, and using ignition timing as the control input, feedback control is used to reduce the variance of the P_{max} variations. Thermodynamic and physical model development is more complex due to combustion is stochastic process. Firstly, an Autoregressive moving average with exogenous (ARMAX) model was established to express dynamic behavior between spark timing and maximum cylinder pressure (P_{max}) when the engine runs under the steady state operating conditions. This model and tuning parameters were estimated on-line system identification techniques. With this model, a one-step ahead prediction-based MVC (minimum variance controller) were used to regulate P_{max} fluctuations, where the reference signal is average of maximum cylinder pressure set point. The closed-loop control system was prototyped on cylinder 1 of four cylinder test engine while other cylinders were controlled by ECU.

II. Main Components

A. Experimental Set up

A schematic diagram of the engine test bed system is shown in Figure 1. The experiments were performed on a FORD MVH-418 spark ignition engine with electronically controlled fuel injectors. The engine uses electronically controlled ignition system with two ignition coil and has no mechanical distributor. The engine specifications are given in Table 1.

Before the experiments, the test engine was run for a time to reach the steady state operating conditions. Then, the throttle was opened at about ¼ position, and the engine was loaded. During the tests, the engine speed and brake torque were 1650 rpm and 60 Nm, respectively. Since the cyclic variations decrease with increasing engine speed, the experiments have been carried out at lower engine speed and load. The ignition timing was adjusted to yield minimum spark advance for MBT.

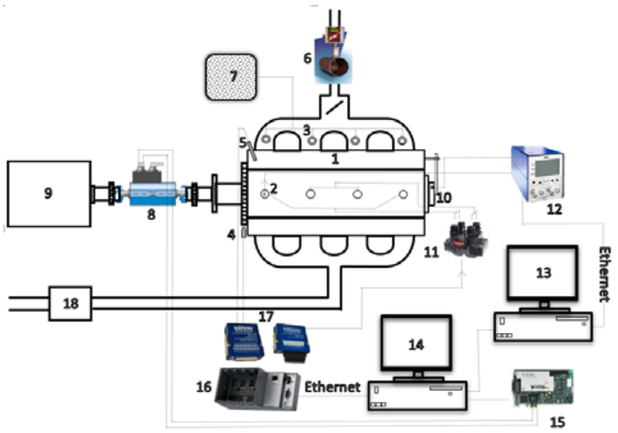

FIGURE I. THE SCHEMATIC DIAGRAM OF ENGINE TEST BENCH SYSTEM

1- Engine	10- Crank encoder set
2- Spark Plugs	11- Ignition coil
3- Fuel Injectors	12- Pressure transducer
4- Crankshaft sensor	13- Computer I
5- Camshaft Sensor	14- Computer II
6- Air flow meter	15- Data acquisition card
7- Fuel tank	16- FPGA real time chassis
8- Torque Sensor	17- Spark driver module
9- Hydraulic Dynamometer	18- Muffler

TABLE I. ENGINE SPECIFICATIONS

Engine type	Ford MVH-418, fuel injected
Number of cylinders	4
Compression ratio	10:1
Bore (mm)	80.6
Stroke (mm)	88
Displacement volume (dm^3)	1.796
Max. power	93 kW at 6250 rpm
Max. torque	157 Nm at 4500 rpm
Cooling system	Water-cooled

B. Model Development and Control Algorithm

In this study, ARMAX model to describe between dynamic of spark timing and maximum cylinder pressure is discrete in time, representing full cycle that includes from intake to exhaust stroke as a single event. The ARMAX model is parametric model and it is obtained using system identification techniques that involves building mathematical model of dynamic system based on measured input and output data samples set. In this study, spark timing and maximum cylinder pressure data is obtained from the engine under constant 60 Nm torque and speed of engine is about 1650 RPM and fuel injectors are controlled by ECU.

The following ARMAX (autoregressive moving average with exogenous input) model in Equation (1), (2), (3) and (4) is considered to describe dynamics between spark timing and maximum cylinder pressure.

$$A(z^{-1})P_{max}(k) = z^{-d}B(z^{-1})ST(k) + C(z^{-1})e(k)$$

$$= B(z^{-1})ST(n-k) + C(z^{-1})e(k) \qquad (1)$$

$$A(z) = 1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + \cdots + a_{n_a} z^{-n_a} \qquad (2)$$

$$B(z) = b_0 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} + \cdots + a_b z^{-n_b} \qquad (3)$$

$$C(z) = 1 + c_1 z^{-1} + c_2 z^{-2} + c_3 z^{-3} + \cdots + c_{n_c} z^{-n_c} \qquad (4)$$

where P_{max} denotes the system output (maximum cylinder pressure), ST represents system input (spark timing), i notation denotes data of the k - th cycle and n_a, $n_b$and $n_c$are the order of *A*, *B* and *C*, $e(i)$is error, respectively.

To identify the model for the engine test bench, the degree of polynomials are chosen as$n_a = 3, n_b = 2, n_c = 0.$, and the recursive least squares algorithm is applied. As a result, the following 3nd-order model is determined and parameter values are calculated as

$$a_1 = -0{,}7865, a_2 = -0{,}0679, a_3 = 0{,}1844, b_0 = 0{,}3379, b_1 = 0{,}16506$$

Figure 2 illustrates spark timing that is induced with the random both amplitude and width, and maximum pressure (P_{max}) of cylinder 1.

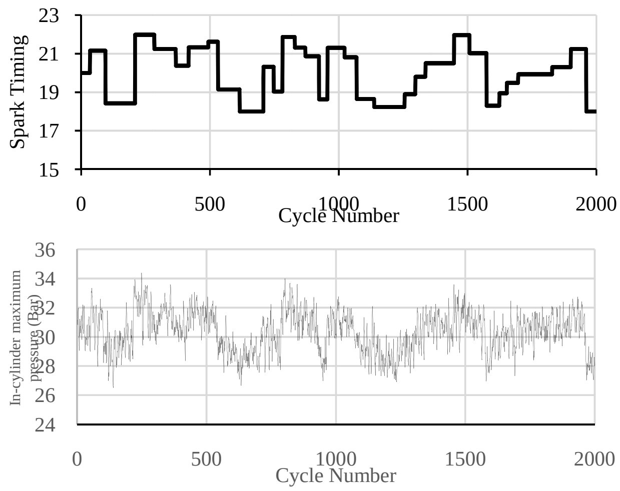

FIGURE II. EXPERIMENTAL DATA OF SPARK TIMING AND MAXIMUM PRESSURE OF CYLINDER 1 FOR 2000 CYCLE

The obtained model in Equation (1) is validated the model of the system by comparing the experimental measured result. Figure 3 shows the model output and measured cylinder peak pressure values.

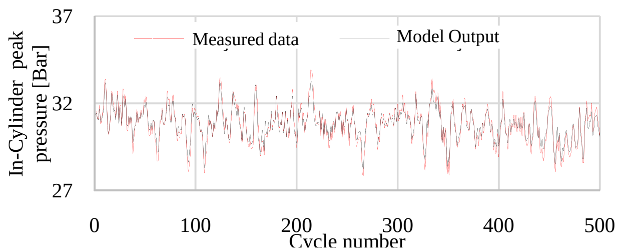

FIGURE III. COMPARISON OF PREDICTED AND MEASURED P_{MAX} FOR 500 CYCLE

In this study, the minimum variance control design procedure has been developed by Astrom and Wittenbark [8], and this control law is obtained by Equation 5.

$$ST(k) = \frac{a_1 P_{max}(k) + a_2 P_{max}(k-1) + a_3 P_{max}(k-2) - b_1 ST(k-1) + P_{max0}(k)}{b_0} \quad (5)$$

III. Results and Discussions

When test engine is worked under a steady-state operating condition, in steady-state operation engine speed, torque and throttle position are fixed to their nominal value, the model from spark timing to in-cylinder maximum pressure for cylinder 1 while spark timing of other cylinder is controlled by ECU is established. Then, the minimum variance and generalized minimum variance controllers are validated by experiments.

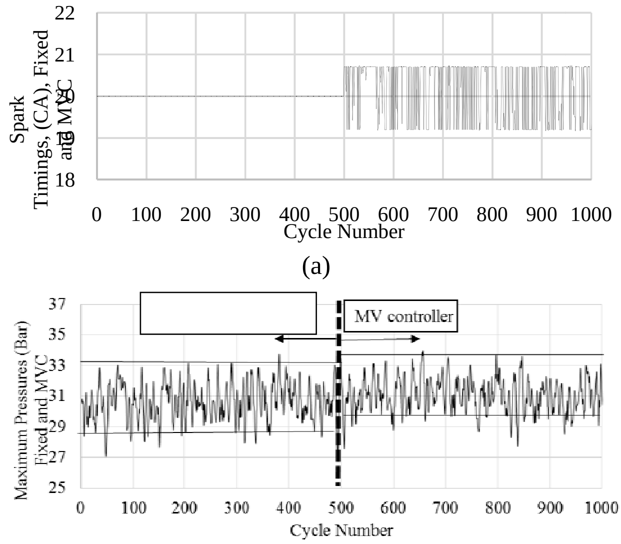

FIGURE IV. (A) CONSTANT-MVC SPARK TIMINGS AND (B) FIXED-MVC MAXIMUM PRESSURES FOR 500 CYCLES

Figure 4.a shows the spark timings for fixed at 20 CA and MV controlled operating conditions, and Fig. 4.b shows the in-cylinder maximum pressure values corresponding to fixed at 20 CA and MVC controlled spark timing operating conditions during the 500 consecutive cycles.

It can be seen from Figure 4.b that the in-cylinder maximum pressure values changes between ranges of 27-33 bar for fixed spark timing operating conditions. As shown in Fig. 4.b before the MV controller operates at cycle number 500, the variance of in-cylinder maximum pressure is 1,490, after MV controller switches on, the variance of in-cylinder maximum pressure 1,214 with about 18, 46% improvement in the performance. Additionally, while COV of in-cylinder maximum pressure is 3,989% for fixed spark timing conditions, it is 3,552% after MV controller operates.

IV. Conclusions

This paper presented self-tuning control approach to reduce variance of the in-cylinder maximum pressure. An ARMAX model was established to express dynamic behavior between spark timing and maximum cylinder pressure (P_{max}) when the engine runs under the steady state operating conditions. Experimental results shows that cyclic variations in SI engines can be reduced by controlling spark timing for consecutive cycles.

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