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On the strategy of event-driven injection and ignition synchronous control for SI engine

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***Abstract*—This work concerns on the spark-ignition and fuel-injection control strategy for Haima 479Q-BA four-cylinder four-stoke electronically controlled gasoline engine. By analyzing the synchronization work process between crankshaft, camshaft position signals and the sequence control of ignition and injection, a method is creatively proposed to realize position identification of missing teeth, and an event-driven based control strategy for injection pulse, ignition advance angle, injection and ignition timing control is also put forward. To insure the integrality of engine work sequence, a relative error correction mechanism is introduced to re-execute the failed event. The bench test results approve that the engine work process is stable and reliable under the developed control strategy, both the injection and ignition control signals are correctively performed, the timing control strategy is highly precise and effective.**

Keywords- SI engine，Injection，Ignition timing control，event driven，control strategy

I. INTRODUCTION

Along with the improvement of national dust emission standard and aggravation of the energy crisis, the automotive electronic control system which is based on fuel quantity and ignition timing control has been used widely for its fuel economy, power performance and high security[1]. Currently, the application field of automotive electronic control system has extended to many aspects which can affect the normal operation of the engine: exhaust gas re-circulation(EGR), evaporative emission control and so on.

while contactless or distributorless electronic ignition system is performed, the sequence control of ignition and injection is calculated depending on the accurate judgment of crankshaft position, so as to determine the action of fuel injector and ignition coil in underlying system, and then controls the normal operation of the engine[2,3]. Therefore, a scientific and effective injection and ignition timing control strategy can achieve the precise control of many operation parameters of the engine to keep the engine operating in optimum states and also give consideration to power performance and emission index.

In the fuel injection and ignition control research field, Yao Dongwei et al. worked on coordination control of injection and ignition timing control and crankshaft movement, but no error-correcting mechanism was adopted in their contributions [2]. Zou Bowen et al. also took their efforts on the synchronization process and the synchronization cycle of engine, and then presented a method for completing grouping and timing synchronization[3]. This work concerns on the Haima 479Q-BA engine (4-cylinder 4-stoke, 16-valve, grouping ignition, sequential injection), and puts forward an event-driven based control strategy for injection pulse, ignition advance angle, injection and ignition timing control.

II. POSITION IDENTIFICATION OF MISSING TEETH AND ENGINE SYNCHRONIZATION

The crankshaft position signal is the basis of ignition timing control, it is usually obtained by a contactless sensor installed on the engine. The engine management system judges the current position and speed of the crankshaft by magnetoelectric sensor equipped with permanent magnet and pulse discs made of ferromagnetic material[5-7]. The pulse disc, positioned on the crankshaft, has 60 uniformly distributed teeth, including 2 missing teeth. When the tooth disc rotates with the crankshaft, each tooth cuts magnetic line of the sensor, which can cause the variation of magnetic flux and in turns generate an alternating voltage. The amplitude of alternating voltage is inversely proportional to the distance between the sensor and the fluted discs. After filtering and shaping, crankshaft position signal is converted to a constant amplitude square-wave signal and then transmitted to the input capture module of ECU. When the edge-triggered signal is captured by main control chip, procedure of interruption service is executed and can calculate the current position and speed of the crankshaft. At the same time, the missing teeth which can be used to control engine synchronization is identified, and injection and ignition events are executed according to the event-teeth number calculated in advance[8,9].

During a four-stoke engine work cycle, the crankshaft completes two revolutions, so the injection and ignition events during an engine work cycle are driven by（60-2）*2=116 event-teeth. When the crankshaft rotates continuously and then triggers the interruption service procedure, the system provides digital time stamp service to record the current time. According to the time value recorded last time, the system can calculates the time interval T1, T2, T3, T4, T5(as shown in Figure 1) between every two adjacent time interval. By comparing the previous

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time interval, the system can determine the position of missing teeth, synchronize and assign the event-teeth number, this process can be represented by Figure 2.

If the current time interval is two times larger than the last one, the procedure will consider this signal as the missing tooth signal. Besides, the corresponding error correction mechanism is set up for the transient speed fluctuation. The camshaft speed of a four-stoke engine equals to half of the crankshaft speed, so the crankshaft completes two revolutions while the camshaft rotates one revolution in a work cycle. The camshaft position signal generated by an engine-installed hall sensor assures the exact distinction of compression and exhaust Top Dead Center(TDC) of one cylinder. When the camshaft position signal and the missing tooth signal are detected at the same time, the program judges that the point is TDC of compression, then assign the current tooth number and set the synchronization success flag.

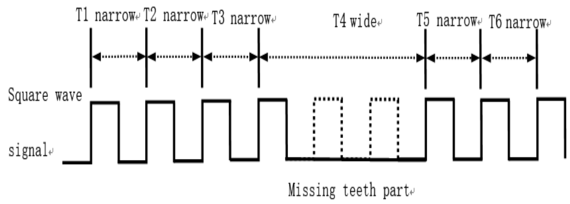

Fig.1 Position synchronization between engine and crankshaft

III. QUANTITATIVE CALCULATION OF FUEL INJECTION AND IGNITION TIMING

A. Calculation of fuel injection pulse width and ignition advance angle

Engine management system obtains the air intake quantity information directly or indirectly, and determine the target air-fuel ratio according to the sensor signal and the fuel injection strategies pre-written in the system. After converting the air-fuel ratio into fuel injection quantity, the injection pulse width can be calculated by the characteristics of fuel injector[10]. In this paper, the fuel injection pulse width is calculated by the velocity-density method, and the effective injection time is modified according to the battery voltage. Due to the non-linearity and time variation of the engine working process, it is difficult to establish a precise mathematical model. In engine control system, the look up table method is widely used to achieve real-time control.

The ignition advance angle is of great significance to the power and emission performance of the engine. Therefore, the ignition control problem revolves around the calculation of the ignition advance angle. So the ignition system control concerns on the calculation of the ignition advance angle. The ignition advance angle is calculated by ECU according to the speed and the load information obtained from ignition advance angle characteristic field, and then modified according to the knock information etc. The optimal ignition advance angle can ensure engine output maximum torque during the combustion propulsion process and prevent engine from knocking.

B. Calculation of ignition and injection sequence

The crankshaft and the camshaft signals contain abundant information of engine working conditions and can provide judgment basis for generating fuel injection and ignition timing signal. The engine used in this paper is four-cylinder, the crankshaft completes two revolutions during a work cycle, so the fuel injection and effective ignition events occur four times in this process. Cylinder piston will locate at the TDC every time the crankshaft rotates 180°, the fuel injection and ignition time are also calculated on the basis of the TDC. The program determines the event execution time according to the engine fuel injection and ignition duration time as well as the ignition advance angle, and then calculate the corresponding fuel injection or ignition event tooth number. When the crankshaft interrupt occurs, the teeth number is detected and the corresponding injection or ignition event is performed.

The calculation method of the injection teeth position is shown in Fig.3 (1), and the fuel injection start position is obtained by the differences of TDC and injection pulse width Tpulse (the timer value). The ECU executes fuel injection and ignition event when the crankshaft interrupt (rising edge of the crankshaft signal) occurs, so the positive rising edge before fuel injection time is detected and its corresponding teeth will be considered as the fuel injection event tooth, the time interval(Tpre) between this event tooth and injection start position is recorded. The crankshaft has 60 uniform distribution teeth, including 2 missing teeth. During every work, there are 116 teeth (numbered 0~115 after the missing teeth) worked and each tooth rotates 6 degrees. So the relationship between the crankshaft angular velocity and the engine speed can be represented by:

$$\omega = 6 * N \tag{1}$$

Where N (r/min) represents the engine real time speed; ω(deg/s) represents the angular velocity.

Considering the mechanical deviation of the engine installation, it is assumed that the TDC teeth number is m, the timer counts per second is C, and the fuel injection pulse width corresponds to the angle interval can be shown by:

$$Ang_{\text{fuel}} = \frac{t_{\text{pulse}}}{C} * \omega = \frac{6Nt_{\text{pulse}}}{C} \tag{2}$$

In order to improve the control precision, the value except integer or multiples of 6 is used to calculate the angle interval, then the angle interval between the fuel injection event tooth and fuel injection start time is calculated by the following formula:

$$Ang_{\text{Pre}} = \left(6 - [Ang_{\text{fuel}}]\%6 - \left(Ang_{\text{fuel}} - [Ang_{\text{fuel}}]\right)\right) \tag{3}$$

Where [Ang] means keeping the round number, [%] means keeping the remainder.

The formula for calculating the fuel injection tooth is based on the TDC:

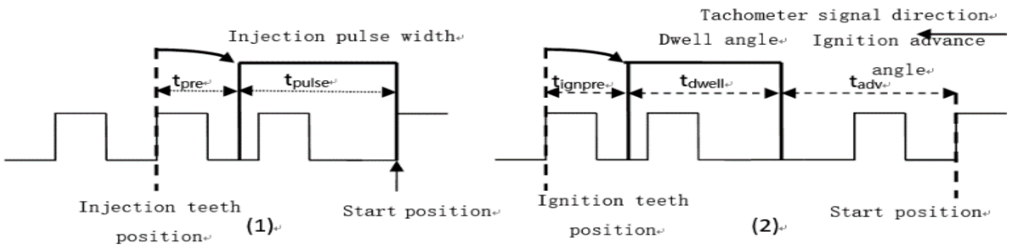

Fig.3 Computation of ignition and injection teeth

$$\begin{cases} Tooth_{\text{fuel}} = m-([Ang_{\text{fuel}}]\%6+1) & when: m>[Ang_{\text{fuel}}]\%6+1 \\ Tooth_{\text{fuel}} = m+116-([Ang_{\text{fuel}}]\%6+1) & when: m<[Ang_{\text{fuel}}]\%6+1 \end{cases} \quad (4)$$

The formula for calculating the ignition tooth number is shown in Fig. 3(2). The optimal ignition advance angle calculated by the current operating conditions is tadv , the difference of TDC and ignition advance angle is ignition end time, the difference of ignition end time and ignition close angle calculated by coil charging time is ignition start time. The positive rising edge before ignition time is detected and its corresponding tooth will be considered as the ignition event tooth, and the time interval between the ignition event tooth and the ignition start time is recorded.

The angle Ang_{ign} between ignition start time and TDC can be calculated by the following formula:

$$Ang_{\text{ign}} = \frac{t_{\text{adv}} + t_{\text{dwell}}}{\text{C}} * \omega = \frac{6N(t_{\text{adv}} + t_{\text{dwell}})}{\text{C}} \quad (5)$$

The angle Ang_{ignpre} between ignition event tooth and ignition start time can be calculated by the following formula:

$$Ang_{\text{ignpre}} = \left(6 - \left[Ang_{\text{ign}}\right]\%6 - \left(Ang_{\text{ign}} - \left[Ang_{\text{ign}}\right]\right)\right) \quad (6)$$

Meanwhile, the position of the ignition teeth can be calculated according to the TCD teeth number:

$$\begin{cases} Tooth_{\text{ign}} = m-([Ang_{\text{ign}}]\%6+1) & when: m>[Ang_{\text{ign}}]\%6+1 \\ Tooth_{\text{ign}} = m+116-([Ang_{\text{ign}}]\%6+1) & when: m<[Ang_{\text{ign}}]\%6+1 \end{cases} \quad (7)$$

If the fuel injection ignition event can not be executed timely, the engine misfire will occurred. To avoid this phenomena, an error correction mechanism is introduced in the program. Its principle is as follows: add the event skipping flag in the program and set it to 1, the flag is cleared when event is executed. When executing the event, it is necessary to detect that whether the flag is 1. If the flag equals to 1, this indicates that the event has not been executed. So it is necessary to calculate the teeth which have missed according to the current tooth number and the target event tooth number, and then determine whether the missed event should be re-executed. If necessary, the event will be executed later(usually 1-2 teeth) to ensure the integrity of work sequence within the loop and the error correction mechanism flow is shown in Figure 4.

IV. EXPERIMENTAL VALIDATION

This paper has completed bench validation for the injection and ignition synchronous control strategy and the ECU used in the experiments is independent-developed. The engine steadily works at two randomly-selected conditions, one is idle condition (throttle closed, idle speed at 1000rpm), another is medium speed and load (throttle opens at 30%, speed at 2000rmp). MSO2014B mixed signal oscilloscope is used to measure the fourth cylinder crankshaft camshaft position signal and fuel injection ignition control signal during this two working conditions. Before the experiment, the angular difference between the missing teeth and the nearest TDC after missing teeth is measured to be 108 degrees(18 teeth), so the fourth-cylinder compression stroke TDC corresponds to the 18th tooth(for calculating ignition teeth) and the exhaust stroke TDC corresponds to the 106th tooth(used to calculate injection teeth). During the experiment, ECU internal parameters are monitored online by ATI VISION calibration software: under the idle condition, the fuel injection pulse width is 4ms, the dwell angle is 5.9ms, and the ignition advance angle is 15°. As shown in Fig.5, the end of the ignition signal is located between the 15th tooth and the 16th tooth, and is about 2.5 teeth(the corresponding degree is 15 degrees) away from compression stroke TDC, the ignition closing angle is about 6ms, the fuel injection pulse width is 4ms. These data is consistent with the data monitored online. In addition, the end position of the fuel injection is consistent with the exhaust stroke TDC, which further shows the validity of the time sequence output.

The bench test shows that: the quantitative and timing calculation methods of fuel injection and ignition used in this paper can generate accurate and effective control signal. During the experiment, the engine operates steadily and there is no knock, misfire or other phenomena found.

V. SUMMARY

This paper introduces an event-driven based injection and ignition timing control strategy for electronically controlled gasoline engine. The bench test shows that the control strategy can judge the position of missing teeth accurately according to the crankshaft signal, and the fuel injection and ignition event tooth number of each cylinder can be calculated. An error correction mechanism is introduced in the program to re-execute the failed event and ensure the

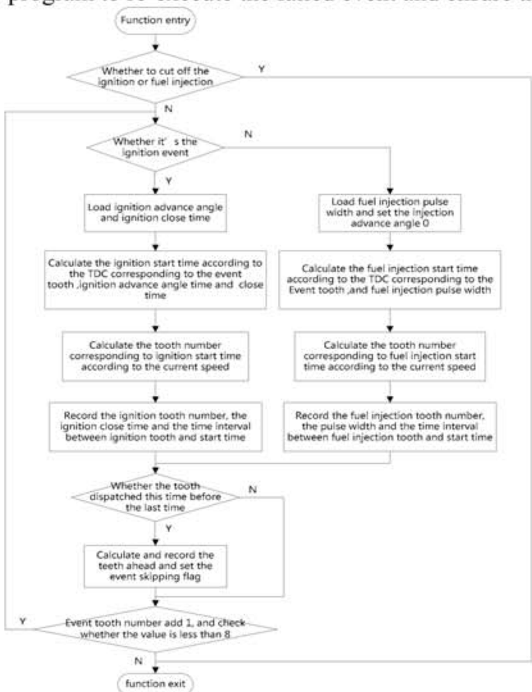

Fig. 4 Schedule of ignition and injection teeth

integrality of engine work sequence. The control strategy can achieve precise synchronizing control of the fuel injection and ignition, it not only can be used to generate gasoline engine fuel injection and ignition signal, but also can be used for CNG engine management system.

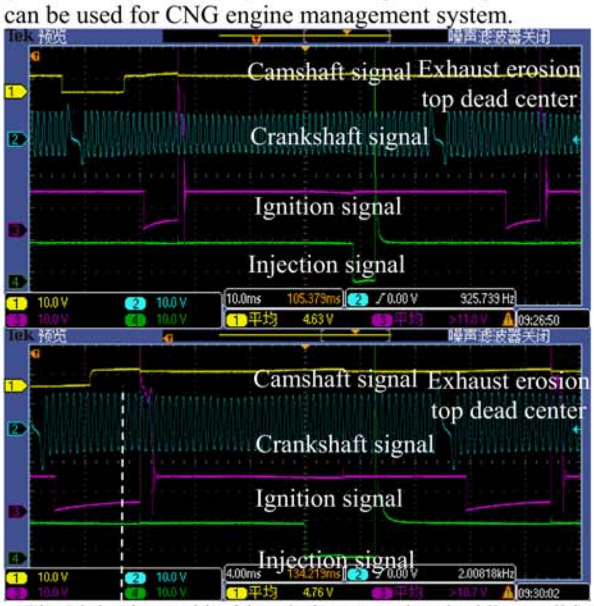

Fig.5 injection and ignition timing control under idle condition

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