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Research Paper

Design and analysis of skip fire valve strategies based on electromagnetic valve train

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HIGHLIGHTS

- Four valve strategies are proposed to realize skip fire strategy.
- Pumping losses decrease as the amount of trapped gas decreases.
- Higher lift of exhaust valve opening strategy helps to reduce pumping losses.
- The exhaust valve opening strategy gets maximum BMEP with less control difficulty.
- The BSFC of optimum skip fire strategy decreases by 10–23% at 1200 rpm.

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ABSTRACT

Skip fire strategy is an effective technology to improve spark ignition engines' efficiency at part load. However, it is difficult to achieve skip fire strategy based on variable valve train, because valves require to be controlled stroke by stroke for switching frequently between valve deactivation and normal operation. While the application of moving coil electromagnetic valve train (EMVT) on engine intake and exhaust system, as a fully flexible variable valve train, provides a feasible approach to actualize skip fire strategy. Firstly, four new valve strategies, including two strategies of trapped exhaust gas, one strategy of trapped fresh air and one strategy of keeping exhaust valve open, are proposed to achieve skip fire strategy based on EMVT. Then the optimum valve timing and lift with the minimum pumping losses of four valve strategies are achieved according to the GT-Power engine model. Finally, by the comprehensive evaluations of the average BMEP and the difficulty of valve control, the strategy of keeping exhaust valve open is identified as the optimum skip fire strategy. At the condition of 1200 rpm, results show the fuel economy has been improved 10–23% compared with the prototype when the break mean effective pressure (BMEP) decreases from 0.42 MPa to 0.215 MPa.

1. Introduction

Cylinder deactivation (CDA) has been demonstrated as a reliable technology to improve fuel economy in spark ignited gasoline engines [1–4]. CDA systems usually fall into one of two categories: bank deactivation strategy or skip fire strategy. When CDA strategy shuts some of the cylinders, the remaining firing cylinders require more air and fuel to provide the same overall BMEP. Therefore the intake manifold pressure must be higher, so pumping work is reduced. Most current production CDA systems belong to bank deactivation strategy and usually provide the fixed CDA modes [5], such as V8-V4, V6-V4-L3. The fixed modes limit the CDA operating region and improvements of fuel economy. While the skip fire strategy allows changing load rate and the density of firing cylinder in proportion to the torque demand [6–8]. Besides, the skip fire strategy keeps all cylinders warm and mechanical balance by maintaining firing all of the cylinders within a short period [9,10].

Valve deactivation of current production CDA systems can be realized easily with the following options: switchable finger followers, switchable pivot elements, Cam shifting systems and

Abbreviations: EMVT, electromagnetic valve train; BMEP, break mean effective pressure; CDA, cylinder deactivation; iEGR, internal exhaust gas recirculation; IMEP360, gross indicated mean effective pressure; FMEP, friction mean effective pressure; EIVC, early intake valve closing; TDC, top dead center; ISFC, indicated specific fuel consumption; PI, port injection; DI, direct injection.

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so on. While it is difficult to apply above options to achieve skip fire strategy, because the cylinder switches frequently between skip cycle and firing cycle, requiring the valves to be controlled stroke by stroke to transform between valve deactivation and normal operation. So some skip fire strategies are implemented by indirect ways. Zhao et al. [11] achieve the skip cycle strategy by simply interrupting fuel injection to the skipped cylinders. But the air is sucked into the cylinder and then discharged into the exhaust pipe, leading to exhaust oxygen-rich and decreasing the efficiency of three-way catalysts. Kutlar et al. [12] investigated a skip fire strategy with additional rotary valves placed on the inlet and exhaust channels, but the results show the fuel and air leakage increases the hydrocarbons emissions. Besides, some investigations just mention that the valves of skipped cylinder should be deactivated to reduce pumping losses, but few of them illustrate when the valves of skipped cylinder are deactivated or reactivated. In other words, few researches analyze the pumping losses of skip cycle under different valve opening timing and valve closing timing to get the minimum pumping losses. However, the fact is that pumping losses of skip cycle take a certain influence on fuel economy benefits due to frequent switching between skip cycle and firing cycle. Millo et al. [13] propose a CDA strategy with internal exhaust gas recirculation (iEGR). They study the pumping losses of inactive cylinder and get the optimal intake valve closing timing. Although it is not a skip fire strategy, it gives a new perspective to optimize the skip fire strategy.

In this work, the investigation is focused on valve control of skip fire strategy. Based on EMVT, four new valve strategies are proposed to realize skip fire. Then, the optimum valve timing and lift of four valve strategies with minimum pumping losses are obtained. Besides, gross indicated mean effective pressure (IMEP360) and friction mean effective pressure (FMEP) are also analyzed. Lastly, the optimum valve strategy is achieved through the comparisons of four strategies.

2. Test of the EMVT and model validation

2.1. Test of the EMVT

Self-developed EMVT is a highly flexible camless valve train system that offers flexible variable valve timing, valve duration and valve lift, which provides a feasible approach to actualize skip fire strategy. The test bench of engine cylinder head with EMVT and the inside structure are shown respectively in Figs. 1 and 2.

With several updates, the EMVT has met the requirements of fast transition time, low impact velocity and low power consumption [14,15]. It has been proved that EMVT can be applied on exhaust system by increasing the transient currents in windings during exhaust valve's opening motion [16]. The EMVT engine can adopt early intake valve closing (EIVC) strategy to control the load, which reduces the pumping loss obviously at partial load.

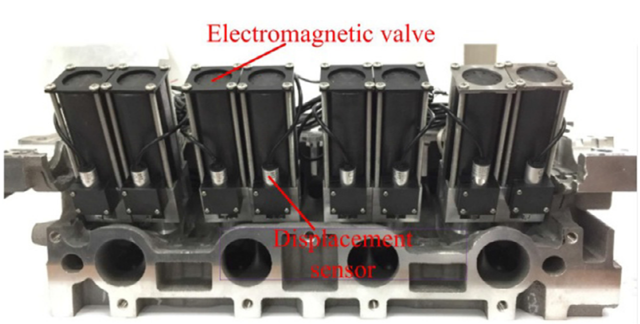

Fig. 1. Test bench of engine cylinder head with EMVT.

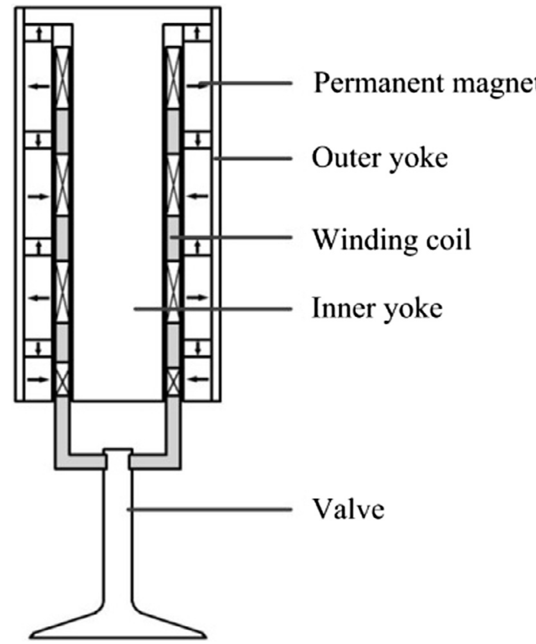

Fig. 2. The inside structure of the EMVT.

In addition, the charge motion in cylinder can be enhanced by adopting low intake valve lift, asymmetric valve control, and double intake valve lift (multi-lift) and the intake quantity can be improved by flexibly adjusting the valve timing, valve lift and transitional time [17]. Besides, the application of EMVT provides new potential to realize a high compression ratio [18].

Fig. 3 shows the excitation current and valve lift by experiment. As we can see, the current during holding stage is close to 0 A. The power consumption of the EMVT is mainly concentrated in the stages of opening and closing and less power is consumed during holding stage. Therefore, the power consumption of the EMVT mainly depends on the total number of valve opening and closing, which can be provided to evaluate the skip fire strategy in below.

2.2. Model validation

One dimensional model of the four-cylinder inline gasoline engine is carried out in GT-Power while the main characters of the prototype are listed in Table 1. In simulation model, Wosch-

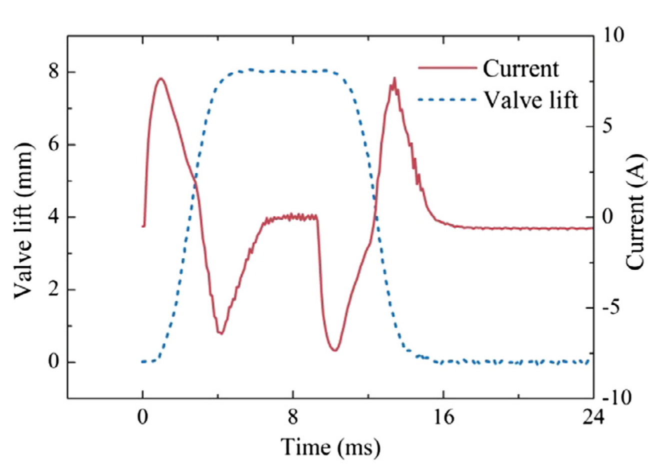

Fig. 3. Diagram of current and valve lift by experiment.