Power consumption of electromagnetic valvetrain system

LIANG LIU, SIQIN CHANG
School of Mechanical Engineering
Nanjing University of Science and Technology
200 Xiaolingwei Street, Nanjing 210094, PR China
CHINA
liuliang@njust.edu.cn

Abstract: - The electromagnetic valvetrain (EMVT) has been widely investigated and considered to have great capability to improve the fuel economy, the emissions, and the torque output performance of the engine. While the mechanical camshaft driven valvetrain consumes mechanical energy to drive the valves, the EMVT consumes electrical energy. If the power consumption is not properly controlled, the improvement of engine fuel economy brought by camless valvetrain will be weakened. This paper focus on the power consumption of EMVT. The detailed power losses derivation of the EMVT was discussed and compared with conventional valvetrain. The power consumption and pumping losses at various valve operating modes are shown and compared, including various engine speed, variable transition time, variable valve lift, and valve deactivation. The result shows that the power consumption is almost proportional to the engine speed. At low engine speeds and low engine loads, the power consumption can be reduced by applying long transition time and small valve lift. The power consumption can also be reduced by deactivating half of the intake valves at low engine loads.

Key-Words: - Camless, Electromagnetic valvetrain, Power consumption, Variable valve, Pumping loss

1 Introduction

Camless valvetrains have great capabilities as new gas distribution devices for automobile engines. Since each individual valve is actuated independently, the valve timing, lift, event duration, and transition time can be optimized selectively for each operating condition. The load control of spark ignition engine can be realized by adjusting the valve open duration and valve lift. Thus the throttle valve can be eliminated, resulting in reduction of pumping losses [1]. The advantages of camless valvetrains over conventional valvetrains are mainly improved fuel economy, torque output and reduced emissions.

A plurality of solutions to camless valvetrain has been proposed, mainly including electromagnetic valvetrains (EMVT) [1-8] and electrohydraulic valvetrain (EHVT) [9-12] with varying configurations. Each valve is driven by electromagnetic or hydraulic force from the valve actuator. If the requirements of low seating velocity, transition time, and power consumption can be satisfied, both EMVT and EHVT will radically improve the engine's performance. A variety of control schemes for reducing seating velocity have been proposed and show great promise [3-5, 13, 14]. However, the power consumption of camless valvetrains is still a potential issue to be addressed. If the power consumption is not properly controlled, the improvement of engine fuel economy brought by camless valvetrain will be weakened. High power consumption will also bring potential thermal issues [1]. In previous investigations, Chladny and Koch [5] provided the energy derivation of the EMVT, and used an energy-based method to determine the required coil current. Cope and Wright [8] optimized the valve acceleration profile of EMVT to minimize the power consumption. Zhao and Seethaler [15] used an energy approach similar to [5] and [8] to minimize the power consumption of an EMVT with rotary actuator.

In this paper, moving coil linear actuators [16] are employed to actuate the valves. In contrast to typical EMVT, both the valve lift and transition time of proposed EMVT can be variable, which will significantly reduce the power consumption at certain engine operating conditions. This paper is organized as follows. Section 2 introduces the EMVT system. A detailed discussion of power losses derivation is presented in section 3. Section 4 provides a discussion of power consumption at various operating conditions, including various engine speed, transition time, valve lift and valve deactivation. Section 5 contains conclusions and future work.

2 Description of EMVT system

The experimental EMVT system shown in Fig.1 consists of a moving coil linear actuator, power amplifier, and electric control unit (ECU). The actuator specifications are shown in Table 1. The ECU of valvetrain receives the desired valve events command from the engine's ECU. A position sensor and current sensor are used to provide feedbacks for each valve. When the coil is energized, a Lorentz force linearly proportional to the current drives the valve to the open or closed position. The moving coil linear actuator is hysteresis free and has low time constant, which creates favorable conditions in valve motion control. An inverse system controller is used to control the motion of valve [17]. To achieve low transition time, the valve accelerates during the first half of the stroke, and then a reversed current is applied and the valve decelerates to achieve low seating velocity during the latter half of the stroke. When the valve is near the closed position, it is controlled to follow a desired trajectory, thus soft landing can be achieved. Since the valve position can be precisely controlled, all the factors of valve event can be flexibly variable, including valve timing, lift, event duration, and transition time. Thus the throttle for load control is cancelled to reduce the pumping losses. And the engine load will be adjusted by the EMVT.

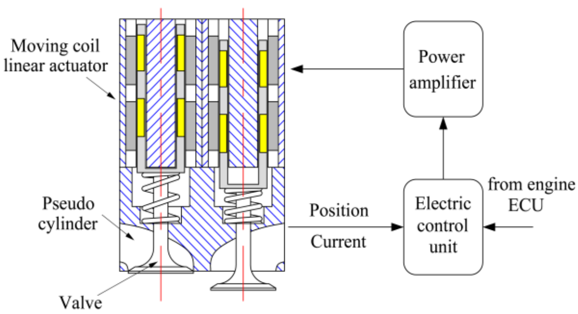

Fig.1 EMVT system structure

Two EMVTs were mounted on a pseudo cylinder head to drive two intake valves. The exhaust port was not taken into consideration. The valve lift profile and power consumption can be obtained from the dynamic experiment of EMVT. An 1-D computational model [18] of a four-cylinder 1.6L GDI engine with EMVT was developed to evaluate the performance of the engine. The valve lift profiles used in the model were obtained from experiment.

Table 1 Actuator specifications

Parameter	Value
Actuator diameter	39mm
Actuator height	70mm
Stroke	8mm
Mass of coil	71g
Resistance	0.7Ω
Inductance	0.38mH
Spring stiffness	2N/mm

3 Power flow and losses in EMVT system

In conventional engines, the camshaft driven valvetrains consume energy mainly to overcome the frictions between interfaces such as valve stems and guides, valve rocker shafts, cams and lifters, cam bearings, timing chains, and tensioners. In an engine with EMVT, the camshaft and related mechanical components are eliminated resulting in reduction of engine frictions, assembly complexity, and engine weight. The EMVT consumes energy only to overcome the friction between valve stems and guides. Moreover, the valve moves in the same direction as the actuating force. The friction between the stem and guide is small because of the absence of lateral force.

Compared with camshaft driven valvetrains, EMVTs need to consume certain electrical energy to actuate the valves. The losses that occur in EMVTs can be divided into three basic categories:

1. Mechanical losses. The mechanical losses are defined as the losses associated with mechanical effect, mainly including friction losses, windage losses, and losses due to cylinder gas force. When the EMVT actuates the valves to move, the work done by the electromagnetic force converts into the kinetic energy of the moving components, potential energy in the spring, friction energy losses between valve stems and guides, the windage energy losses caused by the friction between moving components and the air inside EMVT, and the energy losses due to cylinder gas force. The mechanical energy is given by

$$W_{mech} = \int F_{mag} \cdot v dt = W_k + W_s + W_f + W_w + W_g \quad (1)$$

where W_{mech} is the mechanical energy, F_{mag} is the electromagnetic force, v is the velocity of the valve, W_k is the kinetic energy, W_s is the potential energy, W_f is the friction energy losses, W_w is the windage energy losses, W_g is the energy losses due to cylinder gas force.

When an engine operating cycle ends, the valve returns to closed position as at the beginning of the operating cycle. So the kinetic energy and potential energy remains unchanged. The mechanical power can be given by

$$P_{mech} = F_{mag} \cdot v = P_f + P_w + P_g \tag{2}$$

where P_{mech} is the mechanical power, P_f is the friction power losses, P_w is the windage power losses, P_g is the power losses due to cylinder gas force.

2. Copper losses. Copper losses are defined as the losses that produced by the electrical current in the coil of the EMVT. This dissipated energy creates heat in the coil. The copper losses for the EMVT is given by

$$P_{cop} = I^2 R \tag{3}$$

where P_{cop} is the copper losses, I is the current through the coil, R is the resistance of the coil.

3. Core losses. Core losses consist of the hysteresis losses and eddy current losses occurring in the iron core of the EMVT. The hysteresis losses and eddy current losses result from the changing magnetization of the core material, dissipating energy as heat in the core. Since the magnetic fields in the EMVT are mainly produced by the permanent magnets and alter very little as the coil current varies. Thus core losses are neglectably small.

The power-flow diagram of the EMVT is shown in Fig.2. The electrical power is converted to mechanical losses, copper losses, and core losses. The input power Pin can be found in the equation

$$P_{in} = UI \tag{4}$$

where U is the voltage applied to EMVT.

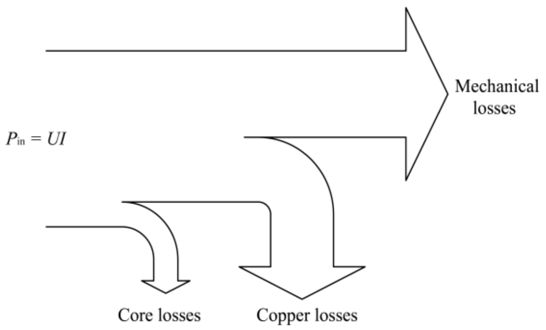

Fig.2 Power-flow diagram of EMVT

4 Power consumption of EMVT at various operating modes

Since the motion of valve is controlled by tuning the coil current, the EMVT consumes different amounts of energy at different operating modes. The EMVT consumes most of the energy at transition process, and only a small current providing a holding force is needed at the closed or open position. So the valve timing and valve event duration has little influence on power consumption of the EMVT if the transition process keeps unchanged. The engine speed, valve lift, valve transition time, and the number of operating valves will significantly affect the power consumption of the EMVT.

4.1 power consumption at various engine speeds

In conventional engines, the valvetrain consumes more energy to overcome friction torque at low engine speeds than that at high engine speeds per cycle. The valvetrain friction torque decreases as engine speed increases through effective lubrication [19]. The experimental energy and power consumption per intake valve of EMVT at various engine speeds is shown in Fig.3.

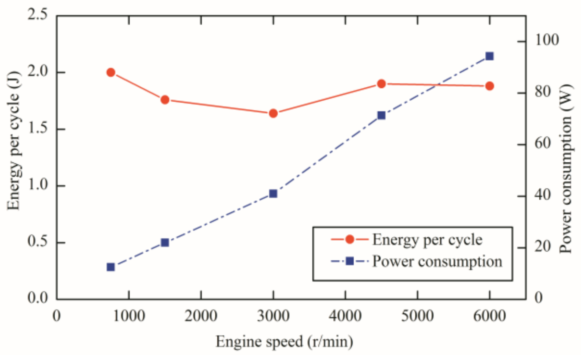

Fig.3 Energy and power consumption of EMVT at various engine speeds

The valve was set to open 8mm in a transition time of 4ms at all engine speeds. The figure shows that EMVT consumes almost the same energy per valve per cycle at any engine speed since the transition process keeps unchanged. At low engine speeds, the energy consumption decreases with an increase in engine speed. It is probably about the fact that at lower speeds, the time period for the closing phase is higher, so the EMVT consumes more energy to hold the valve closed. On the other hand, at high engine speed, the energy consumption increases because large current was applied to shift the EMVT from the opening to the closing process quickly, ensuring short valve opening duration to meet high engine speeds. The power consumption is almost directly proportional to the engine speed.

4.2 Influence of variable transition time on power consumption

The EMVT can achieve a transition time of 3.8ms [17], which is desired to improve the charging efficiency at high engine speeds. At low engine speeds, longer transition times are allowed, which will significantly reduce the power consumption of EMVT. However, the pumping losses will be increased by applying long transition times.

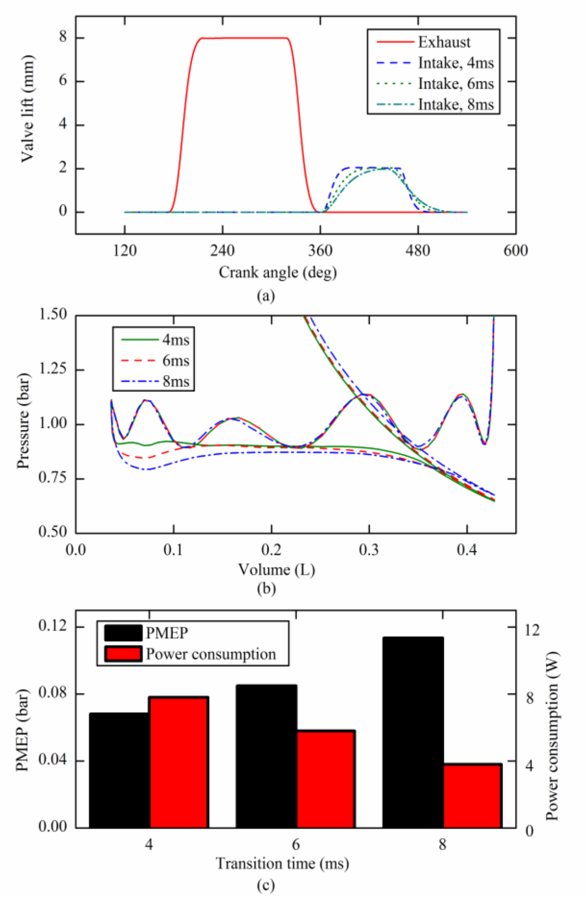

Fig.4 Pumping losses and power consumption of EMVT at various transition times: (a) valve lift profile; (b) pressure-volume diagram; (c) PMEP and power consumption

Figure 4 shows the pumping losses and power consumption at various transition times at the engine speed of 1500r/min and 70% of full load. The tested valve lift profiles are given in Fig.4 (a). The exhaust valve opens 8mm in a transition time of 4ms and keeps unchanged. The intake valve opens 2mm in transition times of 4ms, 6ms, and 8ms. The intake valve event durations were modulated to ensure equal engine power output. The simulated pressure-volume diagram during gas exchange strokes relatively to several transition times is plotted in Fig.4 (b). The pumping mean effective pressure (PMEP) and power consumption of EMVT are shown in Fig.4 (c). It is clear that the pumping losses increase as the transition time increases, whereas the power consumption decreases as the transition time increases. When a transition time of 6ms is applied, the PMEP increases by 25% compared with 4ms, and the power consumption decreases by 26%. At the transition time of 8ms, the PMEP increases by 34% compared to 6ms, and the power consumption decreases by 34%.

4.3 Influence of variable valve lift on power consumption

In a non-throttled engine, the engine load can be modulated not only by the valve event duration, but also by the valve lift. At low engine speeds and low engine loads operating conditions, small valve lift can be applied to improve the air-fuel mixing and reduce the power consumption.

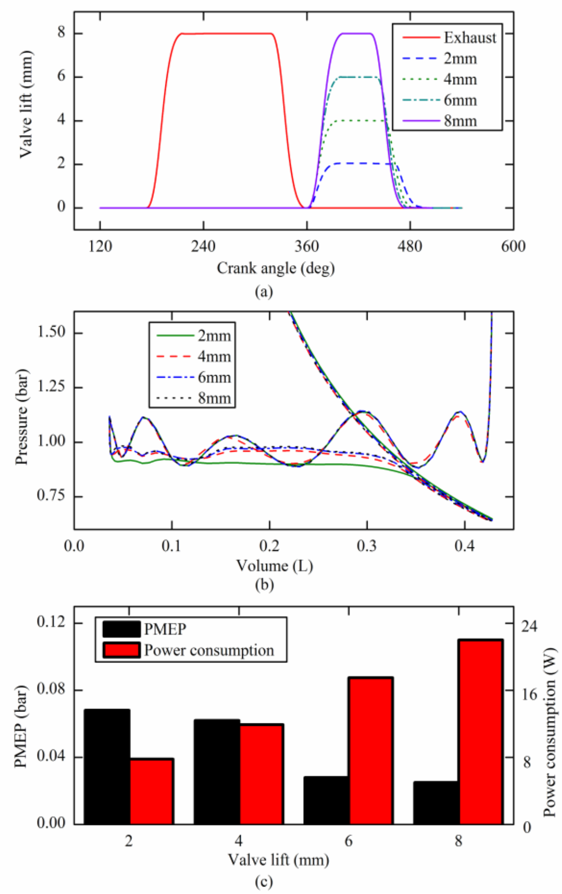

Fig.5 Pumping losses and power consumption of EMVT at various valve lifts: (a) valve lift profile; (b)

pressure-volume diagram; (c) PMEP and power consumption

The applied valve lift profiles are shown in Fig.5 (a). The maximum intake valve lifts are set to 2mm, 4mm, 6mm, and 8mm. The transition time remains 4ms. The pumping losses and power consumption are compared at the engine speed of 1500rpm and 70% of full load. When the maximum valve lift increases, the pumping losses decrease as the intake resistance decreases. However, the power consumption increases as more energy was taken to drive the valve. Figure 5 (c) shows that the PMEP at the valve lift of 6mm is similar to that at the valve lift of 8mm. But the power consumption at valve lift of 8mm increases by 25.7% over 6mm valve lift. The similar results happen between the valve lift of 2mm and 4mm.

4.4 Effect of valve deactivation on power consumption

Since each individual valve is actuated independently in the EMVT, any valve of the engine can be deactivated. All the valves of some certain cylinders can be deactivated to deactivate the cylinder, thus the frictional power losses will be reduced [20]. One of the two intake valves of each cylinder can also be deactivated at part load, which will benefits the charge motion [21]. The emissions and fuel consumption will be reduced at part load due to valve deactivation. Since some of the valves keep closed, the power consumption of EMVT will also be reduced.

One of the intake valves of each cylinder was deactivated at the engine speed of 1000rpm and 10% of full load. The valve lift profile is shown in Fig.6 (a). A maximum valve lift of 2mm was applied at low engine speed and load. When only one intake valve works in each cylinder, long valve opening duration was applied to ensure air inflow. As shown in Fig.6 (b), the pumping losses of 1 valve is larger than that of 2 valves. When one of the intake valves is deactivated, a holding force should be applied. Thus the power consumption of intake valves contains both the power consumption of the activated valve and the deactivated valve. By using valve deactivation, the PMEP increases by 86%, where as the power consumption decreases by 31%.

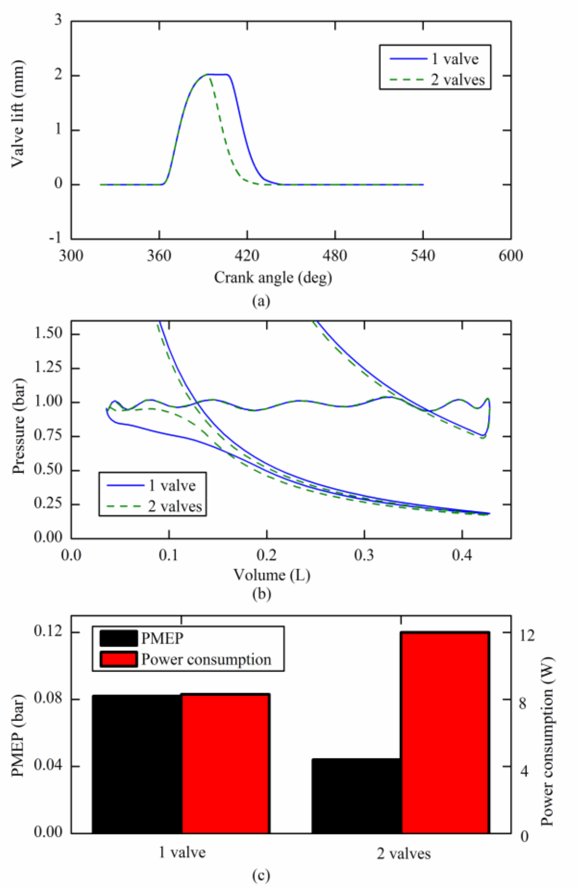

Fig.6 Pumping losses and power consumption of EMVT at valve deactivation: (a) valve lift profile; (b) pressure-volume diagram; (c) PMEP and power consumption

5 Conclusions

The energy consumption of electromagnetic valvetrain has been analyzed in this paper. The energy consumption of EMVT consists chiefly of mechanical losses and copper losses, both of which dissipates energy mainly as heat. Unlike conventional valvetrains consumes more energy at low engine speed, the EMVT consumes the same energy at any engine speed if the valve transition process keeps unchanged. And the power consumption is almost proportional to the engine speed. When variable transition time, variable valve lift, and valve deactivation were applied at low engine loads, the energy consumption was significantly reduced. However, the pumping losses increased.

As future work, the operating modes of EMVT will be optimized taking both engine performance and power consumption into consideration. The energy consumption of exhaust valve should also be tested considering the influence of cylinder gas pressure.

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