837. Dynamics of hybrid PM/EM electromagnetic valve in SI engines

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Abstract. Some previous studies demonstrated the advantages of electromagnetic valve train (EMV) for controlling variable valve timing (VVT) in SI engines. EMV allows valve timings and duration events are optimized in wide operating ranges. However, conventional EMV with solenoid actuator consumes a larger amount of energy in catching the valve at engine start and in keeping valve at open or closed position. A new EMV with hybrid permanent magnet and electromagnetic coil (PM/EM) has been proposed in this paper. An engine model with new EMV has been built to simulate the valve dynamics. Additionally, the effects of the flow gas resistance and damp coefficient have also been examined and analyzed. The results show that the new EMV can satisfy the valve dynamics in transition time, valve velocity, acceleration, energy consumption, etc. in controlling valve timing for SI engines.

Keywords: electromagnetic valve train, cam-less engine, variable valve timing, valve dynamics.

1. Introduction

In recent years, improving fuel consumption and emission in engines is an imperative issue for engine researches. An SI engine that uses electromagnetic valve train (EMV) valve train can control valve events without aid of camshaft. By this way, the valve timing and duration are variable for different operating conditions. Therefore, it can significantly improve engine performance and reduce fuel consumption and emission in engines. Study results showed improvement of fuel efficiency about 15 % to 23 % and emission reduction about 12 % to 15 % [1, 2].

Several devices have been proposed to perform variable valve timing in SI engines such as: mechanical, hydraulic, solenoid, electromagnetic actuators and motor-driven etc. Among these devices, mechanical and hydraulic devices rely on camshaft for controlling valve timings. Therefore, they only optimize valve timings and duration events for limited operating ranges. Meanwhile, conventional solenoid EMV with double E-coil is a popular design, and has been studied in [3, 4]. They modeled and analyzed the conventional EMV. The solenoid EMV has simple structure, and its valve is entirely actuated by electromagnetic force from coils to drive valve open or closed. Therefore, it needs a large amount of energy to catch valve at engine start and remains energy to keep valve at fully open or closed position. That’s why this EMV consumes large energy. An EMV with permanent magnet actuator (PM actuator) has been introduced to replace the double solenoids in controlling VVT in SI engines [5]. This EMV can overcome the disadvantages of conventional EMV about energy consumption. Additionally, the valve system has fast dynamic response and is suitable for an internal combustion engine. Another EMV design has also been mentioned in [6]. The study compared actuation energy between conventional solenoid EMV and PM EMV. The use of PM helps in catching armature from neutral to closed position at engine start, and no external energy needed to hold valve at fully closed or open position. Therefore, actuation energy in this PM EMV is reduced quite substantially.

In this study, a new EMV, which uses hybrid PM/EM together, is proposed. This new PM EMV improves conventional EMV by special designs in main structure, armature and electromagnetic coil. This improvement brings many advantages for EMV actuation and downsizing as described in [7]. There are two main parts in this paper. The first part expresses dynamic models about PM EMV system which includes electronic subsystem, mechanical subsystem and magnetic circuit subsystem. The second part illustrates dynamic analysis for the novel EMV. The effects of gas flow resistance within cylinder and damping coefficient on EMV system are also discussed.

2. EMV operation and models

2.1. Configuration and operation of EMV

The proposed hybrid PM/EM EMV is equipped with permanent magnet (PM), electromagnetic coil, armature, valve body, springs (actuating spring and valve spring) and spring retainer. The structure of novel EMV is shown in Fig. 1. The proposed EMV uses PM to hold armature at top or bottom. It means that no energy is further needed for holding valve at fully open or closed position. Therefore, it improves conventional EMV in consumption of actuation energy and transition time.

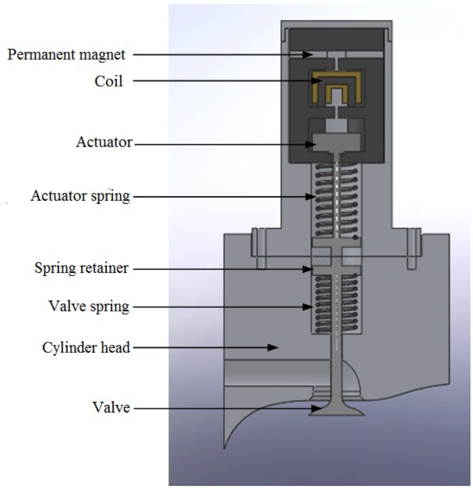


Fig. 1. Structure of hybrid PM/EM EMV

Fig. 2 describes operation principle of the novel EMV. The solid line expresses the magnetic flux generated by PM, while dotted line represents the magnetic flux produced by magnetic coil. Before engine starting, the armature is held at top position by PM magnetic force, and the valve is in its fully closed position Fig. 2(a). To release the armature, charging current is applied to magnetic coil to generate a magnetic flux (dotted line) to weaken the magnetic flux from PM. Concurrently, the magnetic flux (solid line) enters the coil to form a closed loop. By this way the magnetic force on armature is significantly reduced and actuating spring forces armature moving downward to open the valve Fig. 2(b). When armature reaches bottom position, PM magnetic force catches armature again and holds valve at fully opening position Fig. 2(c). Similarly, valve releasing from open to closed position follows the same process Fig. 2(d).

2.2. Electrical subsystem

The electrical subsystem consists of coil, resistance, induction coil and voltage power supply. The equivalent electrical circuit of EMV is shown in Fig. 3. Apply Kirchhoff law for circuit, we can estimate the electrical equation as following:

$$V_{in} = L\frac{di}{dt} + r \cdot i + \frac{d\lambda}{dt} \tag{1}$$

where V_{in} is supply voltage determined by control signal $d(t)$: $V_{in} = d(t) \cdot V$. i is charging current, r is electric resistance of circuit, L is external inductance of circuit, and λ denotes the flux linkage.

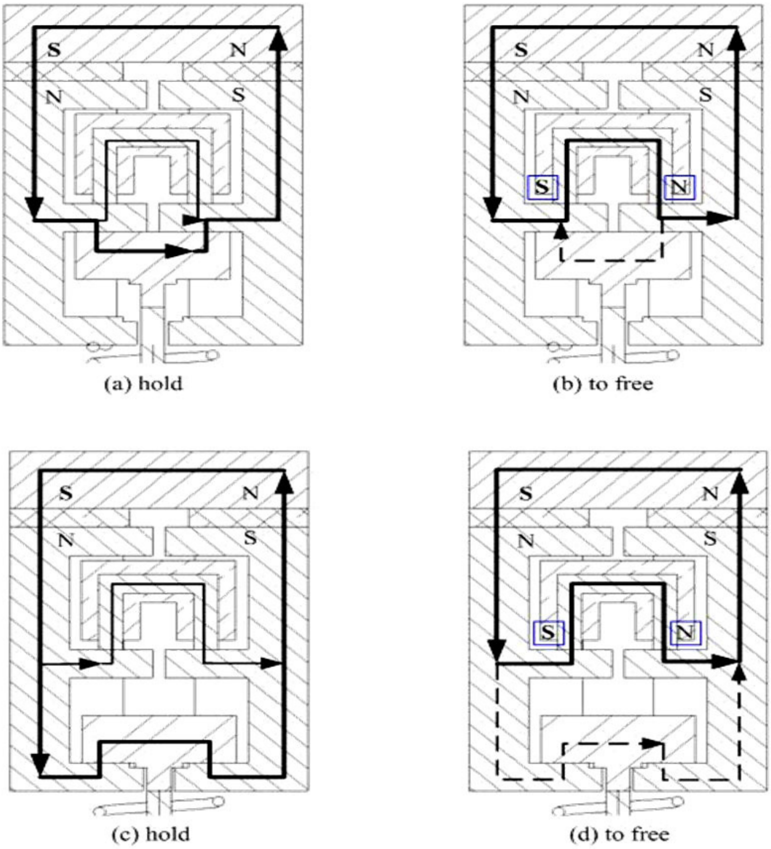


Fig. 2. The proposed EMV operation principle

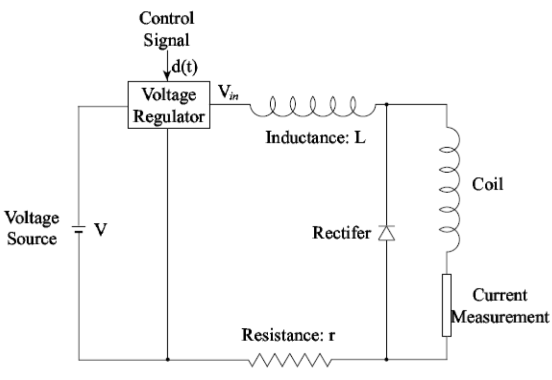


Fig. 3. The electrical subsystem of EMV

2.3. Mechanical subsystem

The mechanical subsystem and a free body diagram of EMV are described in Fig. 4. The moving masses of mechanical system includes armature, valve and spring container. In this study, we lump all moving parts into one mass because they move together during travelling. We apply the Newton's law for modeling the mechanical system.

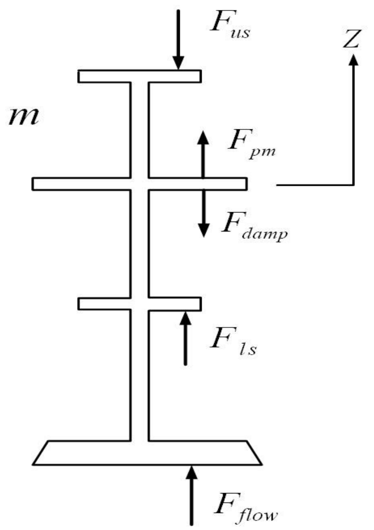


Fig. 4. The free body diagram of armature and valve in EMV

The dynamic equation for EMV is calculated as:

$$m\ddot{z} = F_{pm} - F_{damp} - F_{us} + F_{ls} - F_{flow} \tag{2}$$

where m is the mass of moving parts in EMV, z is moving distance of armature, F_{pm} is magnetic force, F_{us}, F_{ls} are spring forces by actuation and valve springs, respectively. F_{damp} is damping force in EMV due to friction, and F_{flow} is gas flow force that acts on the valve surface.

2.4. Electromechanical subsystem

In this EMV, the electromechanical subsystem can be expressed by equivalent circuit as shown in Fig. 5(a). The resistance, voltage and current in the circuit are equivalent to reluctance, magnetic force and flux in EMV, respectively. And then the magnetic circuit can be simplified in Fig. 5(b).

Kirchhoff law is applied for closed loops φ_1, φ_2, φ_3 in simplified magnetic circuit. We can estimate the energies of permanent magnet and coil as following:

$$W_{pm} = \frac{(2\times V_{pm})^2}{R_t} \tag{3}$$

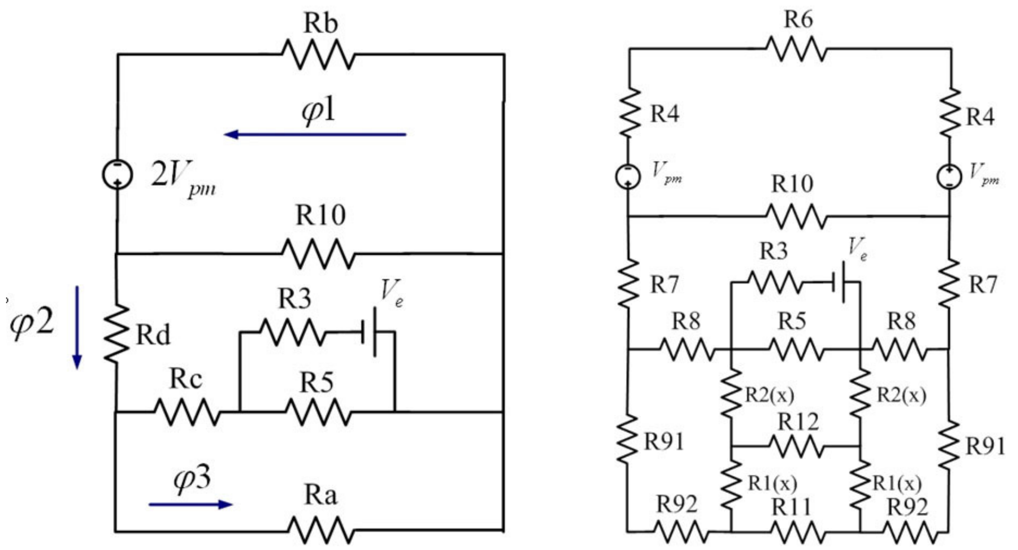
$$W_e = \varphi_2 \times V_e \tag{4}$$

The magnetic forces for permanent magnet and electromagnetic coil can be deduced from energies:

$$F_{pm} = \frac{\partial W_{pm}}{\partial x} \tag{5}$$

$$F_e = \frac{\partial W_e}{\partial x} \tag{6}$$

where R is reluctance, φ is the total flux and V_{pm}, V_e represent PM and electromagnetic coil voltages, W_{pm}, W_e are energies of PM and coil.



(a) (b)

Fig. 5. (a) The electromechanical subsystem in EMV system, (b) the simplified magnetic circuit

3. Simulation and analysis for EMV

3.1. Dynamic simulation

In this study, EMV models are built in Matlab/Simulink to simulate EMV dynamics. The use of EMV allows eliminating the throttle body, camshaft and cam-mechanism in SI engines. Engine load is controlled by valve timings. The models include three modules: mechanical subsystem, electrical subsystem and electromechanical subsystem modules as shown in Fig. 6. The inputs are camshaft signals and outputs are valve dynamics such as: displacement, velocity, acceleration of valve. Some parameters applied in the models are listed in Table 1.

Table 1. The operating parameters for EMV system

Engine speed	8000 rpm
Intake valve open	12^0 BTDC
Intake valve closed	56^0 ABDC
Spring constant	110 N/mm
Damping coefficient	1 kg/s

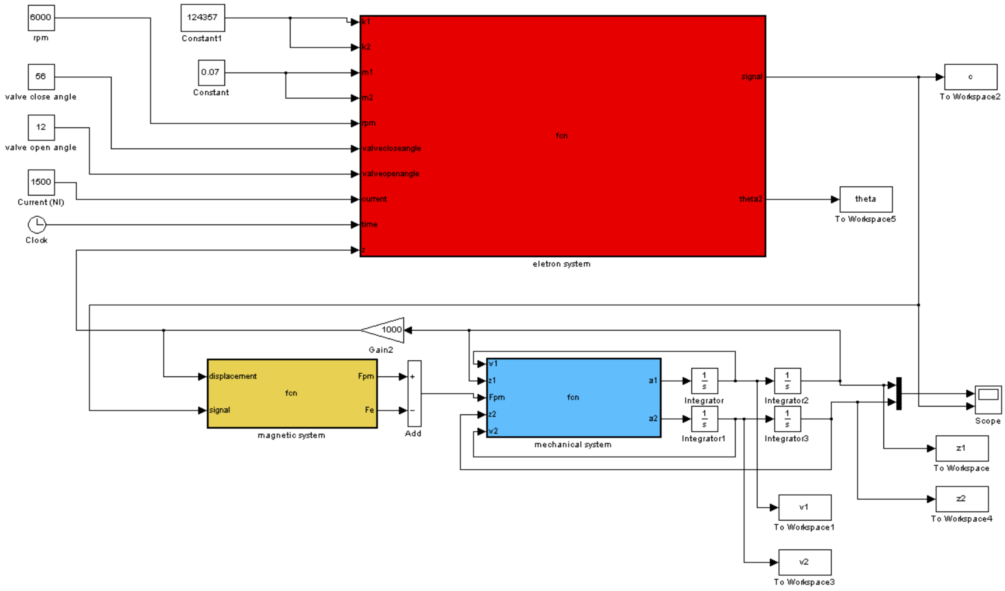


Fig. 6. Dynamic models in novel EMV

3.1. EMV dynamics

3.1.a. EMV releasing

Displacement and current profiles of EMV are shown in Fig. 7. These profiles are simulated at 8000 rpm engine speed. Total valve displacement is 8 mm from closed to open position. Simulation results show that the lifting time for one valve stroke is 0.002 seconds, which meets time requirement for operating at maximum 8000 rpm speed in SI engines.

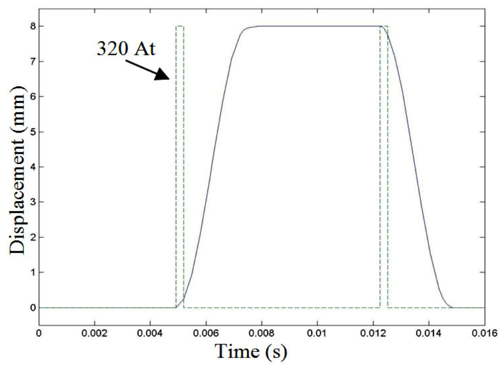


Fig. 7. Displacement and current profiles for EMV

Charging current (dotted line) about 6.4 A (50 turns and 320 At) are applied to coil to release the valve from closed to open position, or from open to closed position. The charging current is pulse current with the duration about 0.3 ms for releasing armature. When the armature locates at bottom position and valve is fully open, the electromagnetic coil is charged by pulse current after obtaining valve timing signal from engine crankshaft. The coil then generates a reversed magnetic flux to weaken PM flux through armature. So the holding force for armature is substantially reduced, and the spring forces armature running to opposite position to close the valve. Similarly, if a valve closing timing signal is received, current charges the coil again to release and force valve motion to fully closed position.

These pulse currents have time delays to reach the desired value. The time delay for the pulse currents occurs by changing current levels in the circuit, as estimated by Eq. (1). The current profile with 12 voltage source is shown in Fig. 8.

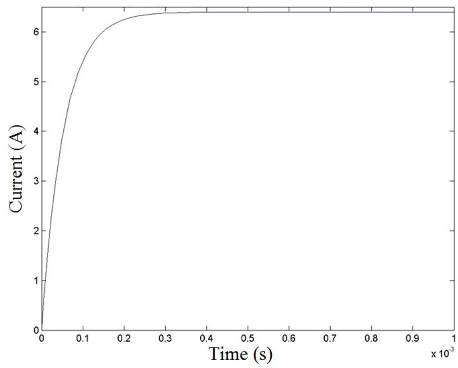


Fig. 8. The current profile

3.1.b. EMV velocity and acceleration

The acceleration profile of valve from open to closed positions is described in Fig. 9. Valve accelerations at fully closed and open positions are equal to zero. After the actuation current is applied to coil to weaken magnetic force by PM, the restored spring force pulls armature downward or upward. At this moment, armature acceleration increases from 0 to 6000 m/s^2. This large restored acceleration allow valve moving from open to closed states quickly. While the valve moves to near closed position, the magnetic force from PM will catch and hold armature. The valve acceleration increases from -5500 m/s^2 to 8300 m/s^2 rapidly and acceleration reaches its maximum value near closed position. Afterward valve acceleration reduces to zero value because armature is firmly held there by PM magnetic force.

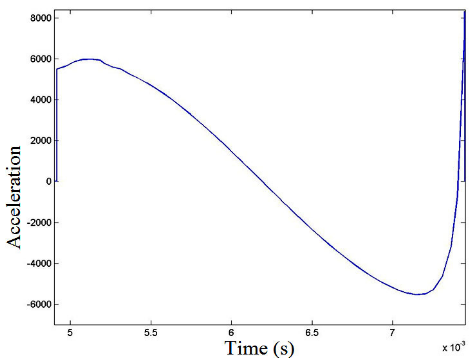


Fig. 9. The valve acceleration profile in proposed EMV

Moreover, velocity of valve from fully open to closed position is described in Fig. 10. Results show that the profile of valve velocity is near to parabolic shape. When valve moves to near closed position, valve velocity suddenly increases due to the strong catching magnetic force from PM. After armature is held at top position, valve stays in fully closed position with zero velocity at this state.

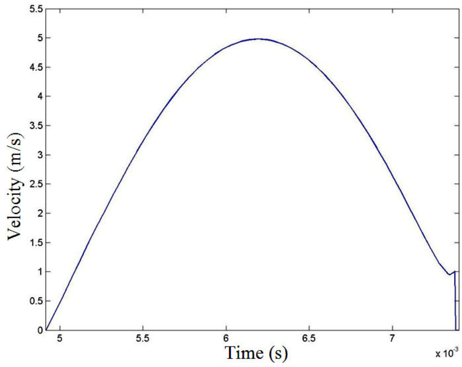


Fig. 10. The valve acceleration profile in proposed EMV

The valve dynamic profiles of proposed EMV are shown in Fig. 11. The valve displacement from open to closed positions meets requirement of transition time at high engine speed.

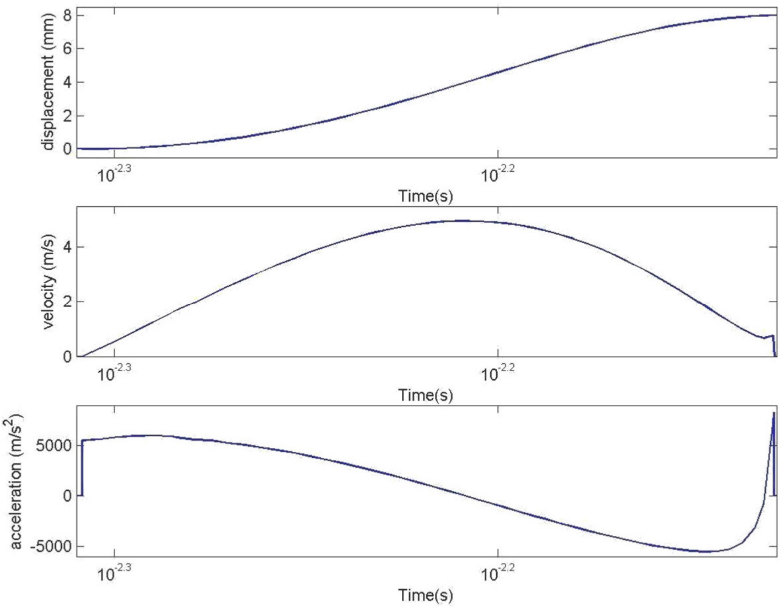


Fig. 11. The valve acceleration profile in proposed EMV

3.2. Effects of factors on EMV dynamics

3.2.a. Effects of gas flow resistance on valve dynamics

The PM EMV uses magnetic and spring forces to control valve at open or closed positions. Magnetic force, which is generated by PM, catches valve to closed or open position. Meanwhile, the valve is also acted by gas flow force from the moving of inlet mixture. This force acts on valve surface, but it has small value compared to the spring and magnetic forces. Thus, the gas flow force often ignores in EMV models. However, this resistance does affect valve dynamics in EMV system. Fig. 12 describes the gas flow force in EMV system from open to closed positions. The open position in EMV is set at displacement of 0 mm, while the closed position is at 8 mm. Since inlet mixture flows into cylinder continuously during engine inlet stroke, gas flow resistance on valve continuously increases during valve opening period. And there is small change in gas flow force during valve closing period. The maximum gas flow force is 24 N and -10 N for open and closed periods, respectively.

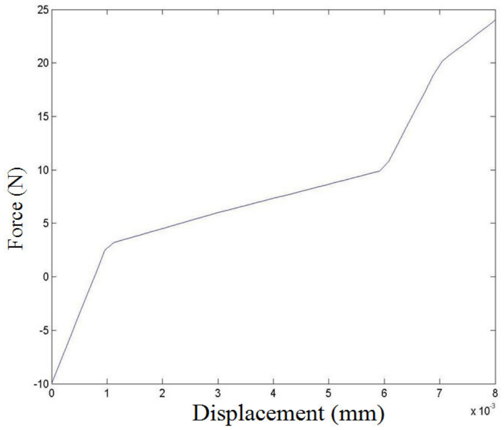


Fig. 12. The gas flow force from closed to open positions

The valve displacement profiles for EMV with and without gas flow force are described in Fig. 13. As the results, the gas flow force has minor effect on EMV during valve opening period because the magnetic force for holding armature is much larger than the gas flow force. However, when armature moves from open position to closed position, the gas flow force will make the valve fail to contact valve seat. So larger PM magnetic force must be considered in order to compensate the gas flow effect. The result shows the small impact at fully closed position due to the adding of gas flow force (red circles in Fig. 13).

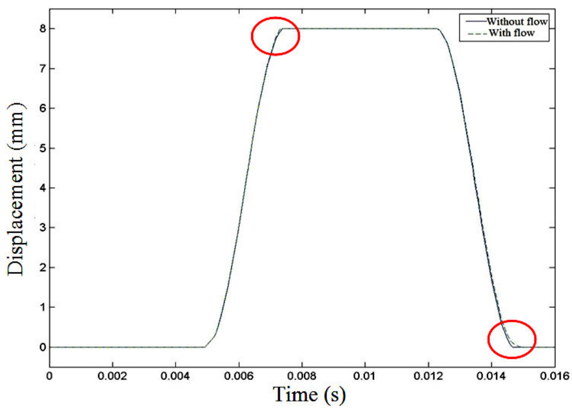


Fig. 13. The effects of gas flow force on valve displacement

3.2.b. Effects of damping coefficient

The damping coefficient also affects EMV performance. Various damping coefficients are examined in this study to find out maximum damping force in EMV. The effects of damping coefficient on EMV design are shown in Fig. 14. The solid line represented the valve displacement with damping coefficient of 1 kg/s (as Table 1) while the dashed line is for damping coefficient of 2.275 kg/s. The result shows that, with damping coefficient of

2.275 kg/s in EMV, PM magnetic force cannot catch the armature at closed position, and valve continuously oscillates between the fully open and closed positions. Hence, the damping coefficient in this EMV design is limited to 2.275 kg/s.

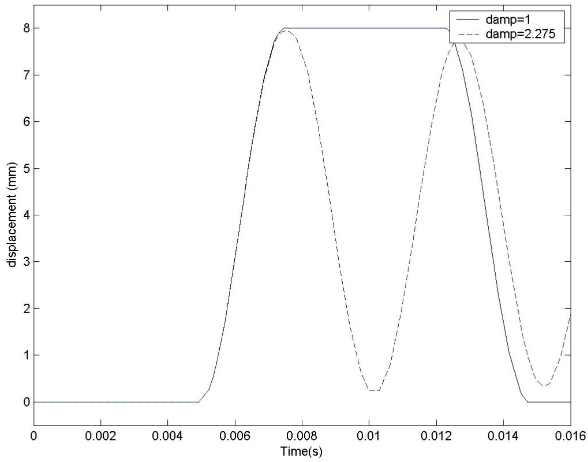


Fig. 14. The effects of damping coefficient on EMV

4. Conclusions

A novel hybrid PM/EM EMV, which uses permanent magnet and electromagnet together, is proposed to improve the drawbacks of conventional EMV. The special designed coil EMV then has benefits in easy control and low actuation energy. EMV Dynamics is modeled and simulated by Matlab/Simulink. The results show that this novel EMV meets the requirements of valve velocity and acceleration for application in internal combustion engines. Effects of gas flow force and damping coefficient on EMV dynamics are also examined for ensuring the EMV system operates stably.

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