PERFORMANCE INVESTIGATION OF AN SI ENGINE WITH VARIABLE VALVE TIMING AND LIFT BASED ON A MAGNETO-RHEOLOGICAL VALVE

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ABSTRACT
Cylinder valve with variable timing and variable lift is a potential technology to improve engine performance. This research studied cylinder dynamics of a spark-ignition (SI) engine equipped with a new full variable valve system (VVS) based on an innovated magneto-rheological (MR) technology. An MR valve block was combined with a conventional inlet valve in this MR VVS. The study obtained many patterns of valve opening/closing by controlling current to the MR VVS, which controlled the MR fluid flowing through magnetic plate block. Magnetic simulations were performed for the new MR VVS to investigate the relationships among MR valve displacement, valve lift, and valve timing. Simulation results showed that the MR VVS provided high degrees of freedom of valve timing and lift for gasoline engine to produce different torque modes and high engine efficiency. The abilities of this MR VVS to become essential technique of high-efficiency engine were confirmed in the results.

Keywords: magneto-rheological valve; variable timing; variable lift.

ÉTUDE DE LA PERFORMANCE D'UN MOTEUR À ALLUMAGE PAR ÉTINCELLE ET UN SYSTÈME DE CALAGE ET DE LEVÉE DE SOUPAPE VARIABLE BASÉ SUR UN SYSTÈME DE VALVE À FLUIDE MAGNÉTO-RHÉOLOGIQUE

RÉSUMÉ
Les valves cylindriques avec dispositif de variation de calage et de levée de soupape est une technologie potentielle qui améliorera la performance du moteur. La recherche présente s'intéresse à la dynamique des cylindres d'un moteur à allumage par étincelle, équipé d'un système complet de valve variable (SVV) se basant sur la technologie innovatrice de la magnéto-rhéologie (MR). Un bloc de soupape MR a été combiné avec une valve d'entrée dans un SVV MR. Cette recherche a produit plusieurs modèles de valves qui s'ouvrent et se ferment en contrôlant le courant dans ce SVV MR, lequel contrôle la circulation du fluide magnéto-rhéologique à travers le bloc de la plaque magnétique. Des simulations ont été effectuées pour étudier la relation entre le déplacement de la valve MR, la levée de la soupape, et le contrôle de calage. Les résultats ont démontré que le SVV MR produit des degrés de liberté du contrôle de calage et de levée de soupape pour des moteurs à essence amenant ainsi différents mode de couple et un rendement du moteur plus élevé. La possibilité du SVV de devenir une technique essentielle du moteur à haut rendement a été confirmée par ces résultats.

Mots-clés : valve magnéto-rhéologique; variation de calage; variation de levée de soupape.

NOMENCLATURE

A_1	cross-sectional area of lower piston (m^2)
A_2	cross-sectional area of lower piston (m^2)
A_c	cross-sectional area of lower piston (m^2)
A_p	effective area of piston (m^2)
B	flux density that passes through MR fluid (T)
c_1	parameter value at 2.07 $\sim$ 3.07 ($c_1 = 2.07 + \frac{12q\mu}{12q\mu + 0.4wh^2\tau_y}$)
F_c	force given by cam (N)
F_{spring}	spring force (N)
h	the space between upper and lower plates (m)
L	lenght of magnetic passage (m)
$\dot{x}$	velocity of flow (m/s)
Greek symbols	
τ	shear stress (N/m^2)
τ_y	dynamic yield stress (N/m^2)
μ	coefficient of viscosity (mPa-s)
$\dot{\gamma}$	shear rate (1/s)

1. INTRODUCTION

With the rapid increase of vehicles all over the world, the emission of greenhouse gases increases drastically as well. The current trend worldwide is towards reducing gasoline usage and further saving carbon emission. Several innovations, like hybrid, electric or fuel cell vehicles, were invented to solve the emission problem. However, the shortcomings of battery charging and its capacity are still unsolvable. It is, hence, relatively important to improve the gasoline usage in traditional internal combustion engines to obtain better efficiency of energy usage. The techniques of high efficiency and low energy consumption developed for engines can not only contribute to more excellent performance of traditional gasoline cars, but can also be applied to hybrid vehicles and range-extended electric vehicles. Therefore, it is much more essential to develop the technology of low energy consumption engines.

The electric valve is one of the most prospective techniques among various kinds of potential engine techniques of low energy consumption. Traditional 4-stroke cycles adopt cam mechanism to drive valve. Due to the fixed cam profile, the traditional cam-driven engine has only one valve timing, which sacrifices its performance at low rpm and high rpm. Nowadays, mechanical systems of variable valve timing (VVT) or variable valve lift (VVL) have been developed, which can effectively enhance combustion efficiency and lessen fuel consumption to reduce engine emission. The study will elaborate further on the potential advantages and necessity for advanced VVT and VVL systems with a novel electric MR valve.

2. CONVENTIONAL ELECTRO-HYDRAULIC VALVE SYSTEM (EHVS)

A novel electric MR valve with a high degree of operational freedom developed in this study adopts an intelligent fluid: the magneto-rheological fluid (MRF), which has special rheological characteristics. When MRF is exerted on a external magnetic field, it will transform into near solid state instantly. Therefore, this study will employ such a characteristic to design a novel VVT valve. Conventional electro-hydraulic valve systems (EHVS) have been mentioned in many studies, and Sun [1] proposed a fully flexible valve actuation (FFVA) by adopting servo valve to control the fluid flow to make valve open and close precisely (Fig. 1). But FFVA has a complicated structure, a bulky volume, and a leakage problem. Besides, when an engine operates at a normal mode, the servo valve has to maintain operation, which causes problems of excessive energy consumption.

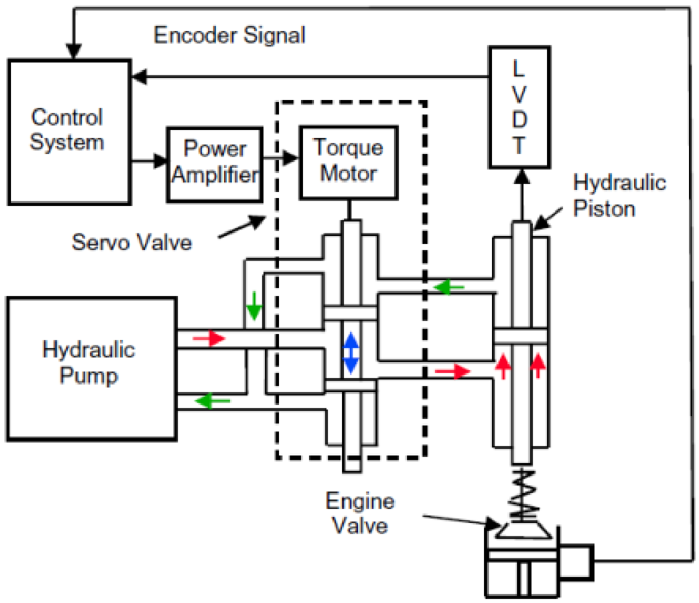

Fig. 1. Fully flexible valve actuation system [1].

Other EHVS employ voice coil motor to control the position of spool valve and mass flow of fluid to make EHVS achieve VVT and VVL functions (Fig. 2) [2]. A hydraulic supply is needed in order to push oil to the valve, which increases energy consumption and has the problem of an excessive system volume. A hydraulic supply is needed in order to push oil to valve, which process increases energy consumption. The hydraulic supply also has the problem of a excessive system volume.

There is another method to use digital three-way valve to control the high-pressure oil. When the servo valve opens, the high-pressure oil pushes valve and gets maximum valve lift. When the servo valve shuts down, the oil will return to oil reservoir and valve will rebound due to spring force (Fig. 3). However, to make the oil return to the digital three-way valve, the oil pressure system needs to be equipped with a hydraulic pump, which will increase the extra energy consumption.

3. NOVEL ELECTRIC MR VALVE

In this study, a novel electric MR valve is composed of an active block, a magnetic plate block and a buffer block as shown in Fig. 4.

1. *Active block*: An area which exerts normal force to MR fluid and press fluid downward into magnetic plate block and buffer block respectively by the movement of the upper piston. Mass flows of both blocks depend on the amount of applied magnetic flux penetrating through permeable plates.

2. *Magnetic plate block*: This area includes permeable coil core, permeable passage and permeable plates to make MR fluid produce high flow resistance in the flow mode. When an external magnetic field is applied to system, MR fluid will produce chain effect and high viscosity to regulate fluid mass flow.

3. *Buffer block*: It is a buffer area to restore MR fluid which is pushed downward by the upper piston in active block. To guide MR fluid to buffer block, a strong magnetic field should be applied to

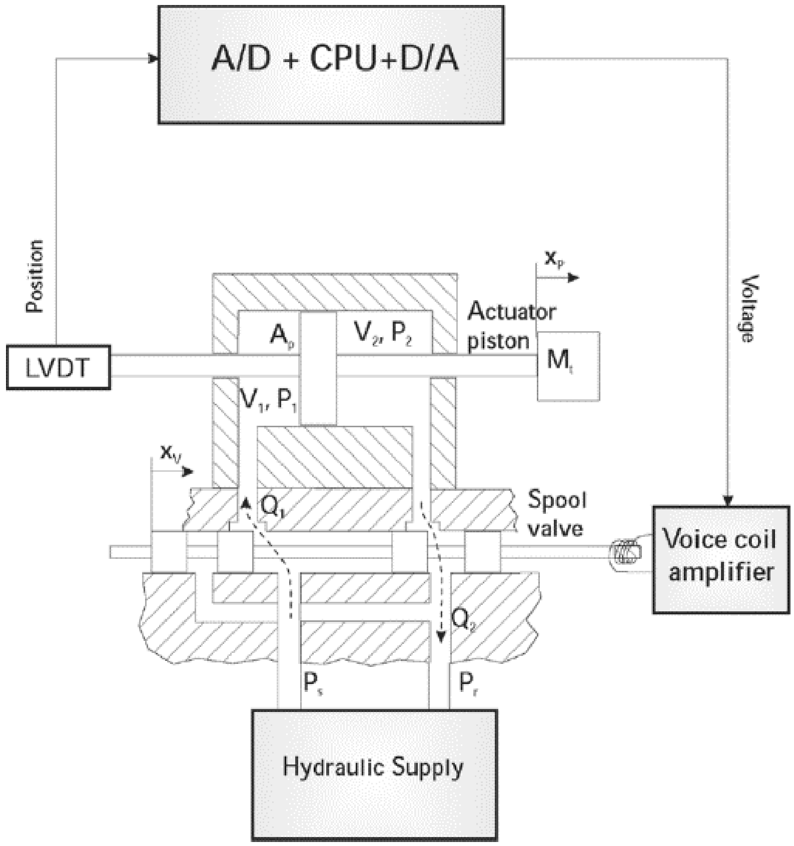

Fig. 2. Electro-hydraulic valve system (EHVS) [2].

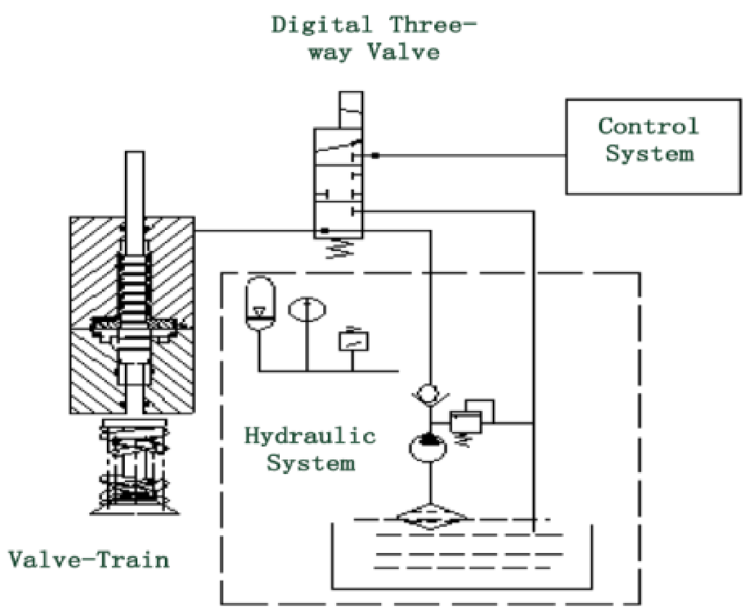

Fig. 3. Electro-hydraulic valve system (EHVS) [3].

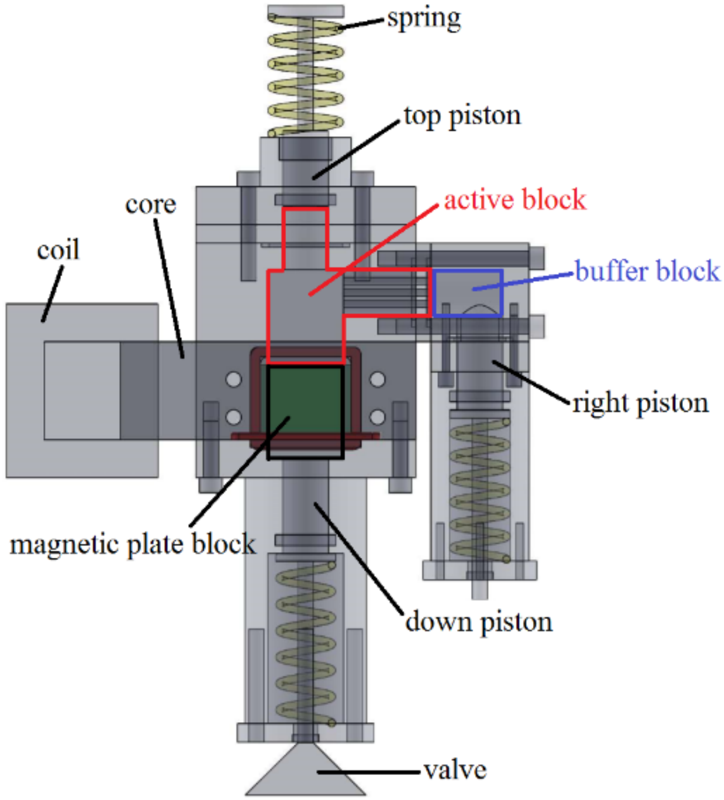

Fig. 4. Novel electric MR valve.

permeable plates to completely limit the fluid to pass through the magnetic plate block, and then fluid will flow into buffer block. If the level of magnetic field is controlled, the fluid flowing into this buffer block is also adjusted.

3.1. Actuation Principles

The novel electric MR valve is driven by a cam over the upper piston. The cam makes the upper piston move up and down, and then forces MR flow pressing the lower piston downward to push the cylinder valve open. The key element to control MR fluid valve is the magnetic plate block. The MR fluid produces change of viscosity very quickly under the application of magnetic field. Because of rule of incompressible flow and continuity equation, full (or partial) MR fluid will pass through the magnetic plate block to push cylinder valve open fully (or partially), and function of variable valve lift is achieved. Three operational cases, fully open, fully closed and partial open, are shown as below.

Case 1: Fully open

The cam presses the upper piston downward and then pushes the MRF in the active block. At this moment, no current is applied to coils and no magnetic field is produced across the permeable plates. Thus the MR fluid around permeable plates produces no chain effect and maintains low viscosity as the MR fluid in the buffer block. Therefore, liquid pressures of MRF in the magnetic plate block and buffer block are equal, and both mass flow rates are the same. MR fluid will evenly flow into the magnetic plate block and buffer block (Fig. 6), and result in complete valve open of the cylinder valve.

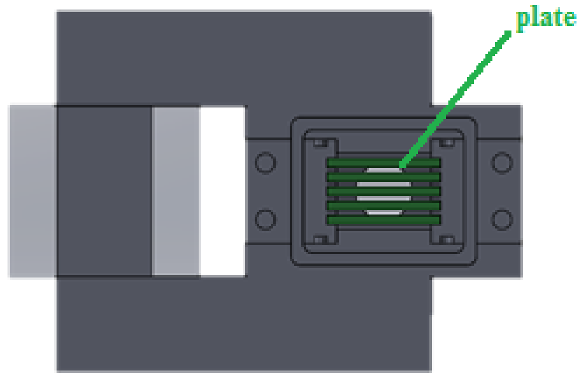

Fig. 5. Flow of MR fluid in permeable plates.

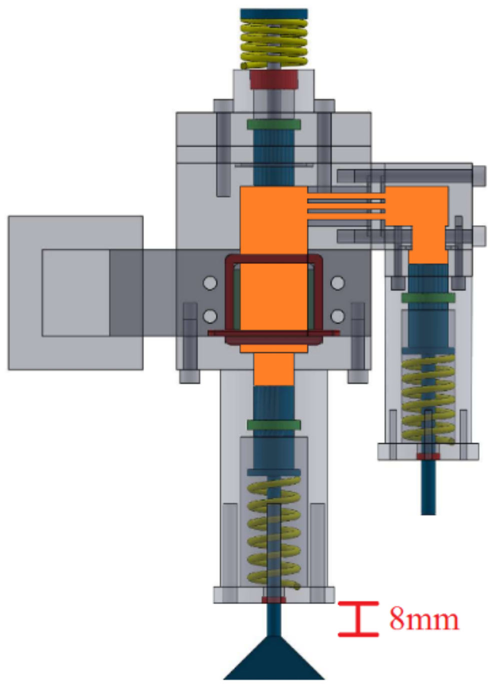

Fig. 6. Mode of fully open valve.

Case 2: Fully closed
When the upper piston goes down and pushes MRF in the active block, large current is applied to coils to produce strong magnetic flux passing through the MR fluid around permeable plates. Consequently, MRF produces extremely high viscosity and retards fluid flow. Therefore, no flow can pass through the magnetic plates, and fluid pressure in the magnetic plate block will be much higher than that in the buffer block (Fig. 7). When the upper piston presses MRF down, all MRF in the active block will flow into the buffer block and no flow to the magnetic plate block. Thus the cylinder valve keeps closed under this operation mode.

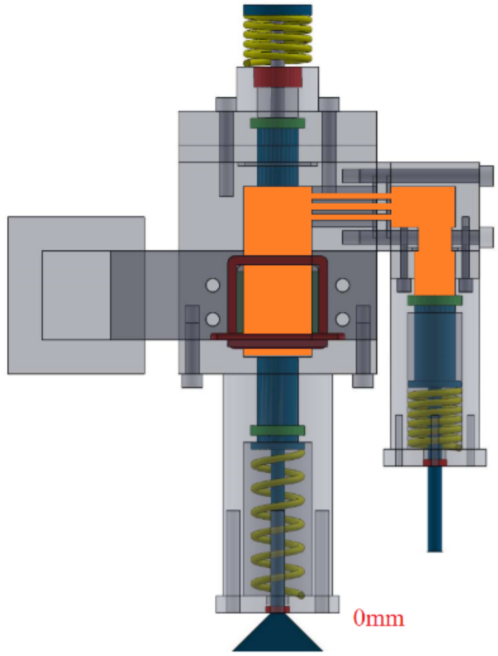

Fig. 7. Mode of fully closed valve.

Case 3: Partial open
If certain small current is applied to coils and produce small magnetic flux across the magnetic plates, MRF will have weak chain effect and medium viscosity. Then most MR fluid flows into the buffer block and the rest MR fluid to the magnetic plate block. The cylinder valve will open partially. If the current is well controlled and maintain fluid pressure at the magnetic plate block about 1.5 times of that at the buffer block, the mass flow into the magnetic plate block becomes half of that into the buffer block, and then makes cylinder valve half-open (Fig. 8).

3.2. Mode of Electric MR Valve

There are three kinds of mechanics for flow mode of MR fluid, including: shear mode, flow mode and squeeze mode. There are many kinds of applications for flow mode (Fig. 9), for example, servo valve, shock absorber, and damper. The novel electric MR valve in this study adopts flow mode.

When appropriate current is applied to coil, the produced magnetic flux penetrates MR fluid to increase shear stress of MR fluid, which results in the increase of flow resistance. If the magnetic field is removed, the shear stress, of course, will be effectively reduced. This process is reversible and responds very fast. The shear stress of MR fluid is represented by [4]

$$\tau = \tau_y(B) + \mu\dot{\gamma}. \tag{1}$$

Equation (1) is applied to the flow mode of MR fluid whose resistance force is

$$F = F_{dMR} + F_{dn}. \tag{2}$$

F_{dMR} is the chaining force under the application of magnetic field across MR fluid (Eq. 3). And MR fluid in flow mode also has its viscous force, which is shown in Eq. (4) [5].

$$F_{dMR} = \frac{\dot{x}}{|\dot{x}|}\left(\frac{c_1\tau_y L}{h}\right)A_p \tag{3}$$

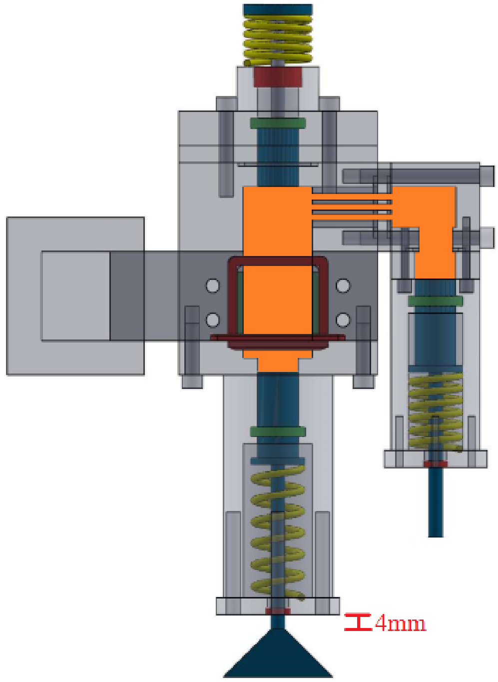

Fig. 8. Mode of half open valve.

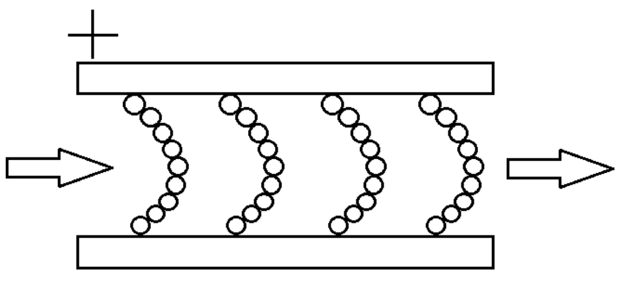

Fig. 9. Flow mode of MR fluid.

$$F_{dn} = \left(1 + \frac{wh}{2A_p}\right) \frac{12\mu L A_p^2}{wh^3} \dot{x} = (k_1) \frac{12\mu L A_p^2}{wh^3} \dot{x}. \tag{4}$$

The novel electric MR valve is a multi-layer mechanism. If MR valve has n layers of permeable plates, the action area of MR fluid is n times of one layer. In other words, the resistance force can be enhanced n times.

$$F_{\text{total}} = n(F_{dMR} + F_{dn}). \tag{5}$$

Because of flowing between two plates and the viscosity of the MR fluid, there is a corresponding flow resistance produced for the passing flow. Generally, this flow resistance is inverse ratio to the fourth power of length and diameter of a tube. Poiseuille's law can explain the pressure loss produced when fluid flows through a tube. There is a specific proportional relationship between the pressure loss, volume flow rate, dynamic viscosity, and the length and diameter of the tube:

Table 1. Values of parameters.

Parameter	Abbreviation	Value	Unit
Area of lower piston A_1, right piston A_2, upper piston A_c	A_1	0.000113097	m^2
Spring stiffness	k	10000	N/m
Space between upper and lower plates	h	0.001	m
Length of magnetic passage	L	0.02	m

$$\Delta P = \frac{8\mu LQ}{\pi r^4} = QR, \tag{6}$$

where R is the flow resistance and Q presents the flow.

$$R = \frac{8\mu L}{\pi r^4} \tag{7}$$

$$Q = \frac{\Delta P}{R}. \tag{8}$$

Combining Eqs. (5), (7) and (8), the total volume flow is obtained as

$$Q_{\text{total}} = \frac{\frac{F_c}{A_c} - \frac{nF_{dN}+nF_{MR}+F_{\text{spring}}}{A_1}}{\frac{8\mu L}{\pi r^4}} + \frac{\frac{F_c}{A_c} - \frac{F_{\text{spring}}}{A_2}}{\frac{8\mu L}{\pi r^4}}. \tag{9}$$

Because this novel electric MR valve is a closed system, its total mass flow is constant. We can employ appropriate current to control F_{MR}, and to control the timing and level of valve close or open to attain VVT and VVL functions.

4. SIMULATION ANALYSES OF ELECTRIC MR VALVE

This study aims to develop an engine valve with a high degree of freedom of valve operation. MR fluid is a kind of controllable fluid different from conventional fluid. Besides, flow resistance will occur if MR fluid is applied with small magnetic flux. Because the process is very rapid and reversible, MRF is very suitable to the application of hydraulic valve. This study adopts magnetic simulation to analyze the relationship between magnetic flux density of MR fluid and flow resistance. Moreover, the pressure of liquid given from cam is distributed to system to attain VVT and VVL function. The values of the key parameters are listed in Table 1.

4.1. VVT of Electric MR Valve

The novel electric MR valve employs the flow mode of MR fluid. When magnetic field is applied to system, magnetic field will pass vertically through permeable plates and MR fluid, which will make MR fluid produce controllable flow resistance. The level of flow resistance will determine the timing and percentage of valve open.

4.1.1. Full Lift

If a 4-cylinder car attempts to maintain engine operated at high speed to have maximum power and torque at full load, valve has to maintain its maximum lift (Fig. 10). To have maximum valve lift, the novel electric MR valve is not activated by current and magnetic flux. Maximum valve lift is achieved by the novel electric MR valve not to be activated by current and magnetic flux.

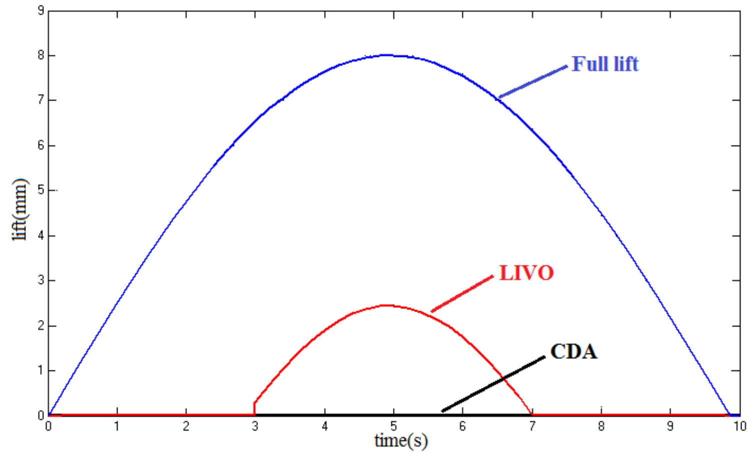

Fig. 10. VVT function of the novel electric MR valve.

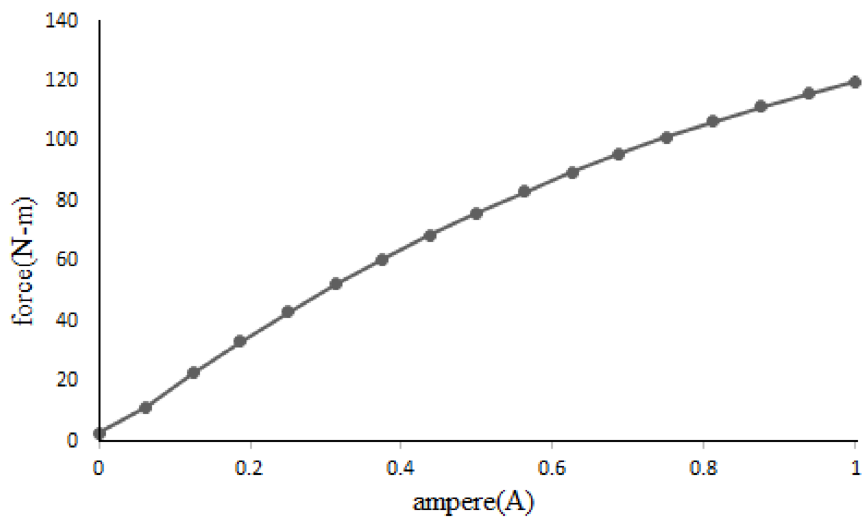

Fig. 11. Resistance force of MR fluid for different current.

4.1.2. Late Intake Valve Opening (LIVO)

To make engine improve its starting performance and enhance the stability at idle speed, the opening of intake valves of novel electric valve needs to be delayed. At this time, MR fluid needs to be activated by current, which makes resistance produced by MR fluid equal to the normal force from cam. Therefore, there will be no pressure difference for active and magnetic plate block. In other words, there is no flow through the magnetic plate block. When current is removed, pressure difference will occur and further make flow increase, which delays the opening of valve as shown in Fig. 10.

4.1.3. Cylinder Deactivation (CDA)

A 4-cylinder engine at medium load can conduct 2-cylinder cylinder deactivation (CDA), which can significantly improve its fuel consumption. Besides, an engine at low load will conduct single-cylinder deactivation, which can make good fuel consumption. Simulation results show that when the amount of valve current increases to 0.51 ampere, it will make cylinder valve close completely to obtain cylinder deactivation.

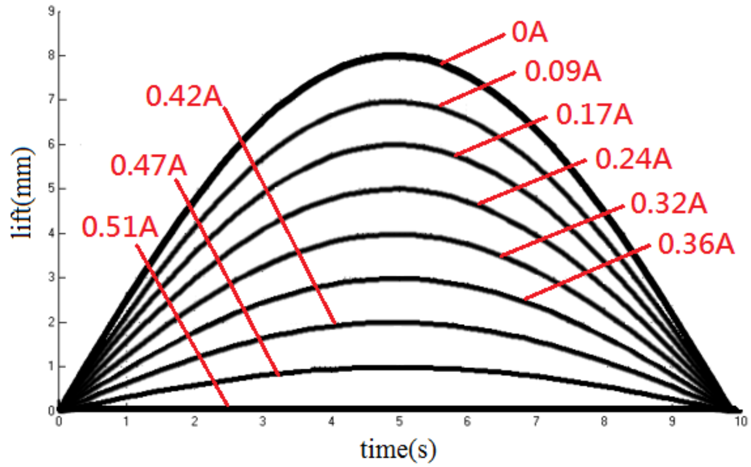

Fig. 12. VVL function of the novel electric MR valve.

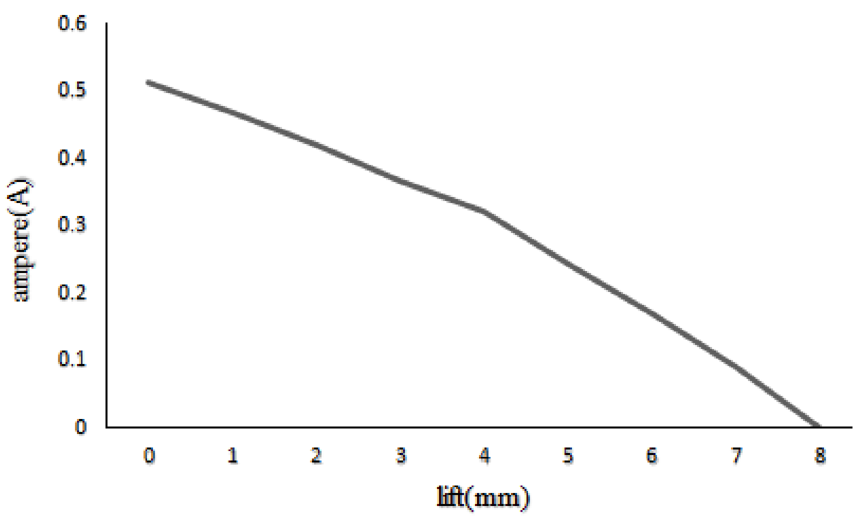

Fig. 13. Relationship between ampere and valve opening.

4.2. VVL of Electric MR Valve

This MR valve withstands the pressure of liquid given from cam by the flow resistance resulted from applied current. The pressure difference is adopted to determine the amount of the mass flow. The amount of mass flow is the level of VVL. This study uses magnetic simulation to deal with the force resistance produced by external current to MR fluid and difference of pressure given from cam to change VVL of electric MR valve.

We can see that when MR fluid is applied with current, its magnetic flux density will increase and further produce impedance shown from Eq. (1). As shown in Fig. 11, this electric MR valve adopts such a characteristic to obtain impedance to withstand the pressure from the upper piston. Moreover, as shown in Figs. 12 and 13, this electric MR valve employs the pressure difference of both to change and further obtain the opening degree of cylinder valve.

Simulation results show that the opening degree of VVL depends on the level of applied current. If an engine is at full load, it will need maximum opening lift (8 mm). At this time, MR fluid does not need to be actuated and exert any current to MR fluid. If engine is at medium load, the valve lift is 4 mm and the required current is 0.32 ampere. If engine is at low load, we can decide the opening according to the amount of currents and even CDA to achieve energy saving and carbon reduction.

5. CONCLUSIONS

This study targets on the design of a novel electric MR valve to withstand the normal force from cam according to resistance produced by MR fluid. The novel electric MR valve has different opening by different ampere through simulation analysis. When current is applied to the novel electric valve, it will make valve firmly close to conduct CDA at low load. To respond to different degree of engine load, the amount of current determines VVT and VVL. Besides, the novel electric MR valve has high variation range and successfully develops technology of high efficiency, low energy consumption for internal combustion engine, which can be applied to hybrid vehicle or electric vehicle and obtain better efficiency of fuel consumption and reduce carbon dioxide [1].

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