Electromagnetic Valve Control in Internal Combustion Engines by PID

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ABSTRACT:
Engines with variable poppet valve timing systems are among numerous efforts that aim to reduce engine emissions and/or increase efficiency. In the present paper we have investigated the stability of a magnetic valve system in MATLAB. First we designed the magnet and interactive forces inside the electromagnetic valve system, then we produced a mechanical model for the system by using a two degree of freedom mass and spring system and finally designed a PID controller to maintain system stability. The results of the present study indicate that the controller had decreased the maximum valve displacement domain and duration from 2 mm to 0.001 mm and 0.1 seconds to 0.022 seconds, respectively. Poppet valve settling speed was 0.0126 and had a standard deviation of 0.1304 while the armature settling speed was 0.0184, with a standard deviation of 0.1363. Passes for the phases were -37.5 and -169, with gains of 10.3 and -9.35.

KEYWORDS: Electromagnetic poppet valve actuator, Variable poppet valve timing system, Magnetic capacity, PID controller.

1. INTRODUCTION

There have been numerous efforts to reduce engine emissions and/or increase efficiency including variable valve timing systems, direct fuel injection engines, smoke recirculation systems and exhaust smoke catalysts. Variable poppet valve timing systems are among the most recent technologies employed in internal combustion engines. This control mechanism can improve engine's volumetric efficiency, increase maximum torque range, decrease fuel consumption and reduce engine emissions. BMW was the pioneering company in designing and manufacturing of electromagnetic control systems. In 2012, Eid Mohammad studied, modelled and evaluated the performance of an electromechanical poppet valve driver in internal combustion engines. In this study, he revealed the importance of design and operational parameters on the actuator's movement and discussed the structure and workings of electromagnetic poppet valve actuator [1]. In 2011 Bo ping wen studied the optimization of hybrid solenoid valves using linear methods, in this article, they proposed a novel method based on sliding mode control [2].

The authors investigated the DC solenoid valves in electromagnetic puppet valves' structures. They compared the electromagnetic forces measured in the experiments with the forces obtained from tension tensor form Maxwell equations in finite element method. The comparison showed a good agreement, they are exact matches for distances between 2 and 8 millimeters and has an average deviation of just 0.01 after that [3-5]. Furthermore, there has been attempts, by other researchers, at designing and manufacturing an electromagnetic poppet valve engine. They recorded the engine torques for multiple engine speed spectrums and reported that variable timing poppet valves lead to increased engine torque [6-7]. In this study, they modelled the electromagnetic poppet valve's actuator as a two degree of freedom system and used a PID controller for system stability.

2. EQUATIONS GOVERNING THE ELECTROMAGNETIC SYSTEMS' DESIGNAND SIMULATION

Magnetic current in an electromagnetic poppet valve can be expressed by using the circuit analysis technique. The magnetic field vector (H), magnetic flux density vector (B_f) and total magnetic flux (λ_m) are the most frequently used quantities in a magnetic circuit. Magnetic field vector and magnetic flux density are expressed by equation (1).

$$B_f = \mu H = \mu_r \mu_0 H \tag{1}$$

Where μ is the total permeability, μ_r is the relative permeability and $\mu_0$is the free-space permeability. Energy systems usually use special magnetic materials that have particularly high permeability. These materials (iron, steel, nickel, cobalt, etc.), called "ferromagnetic materials", are highly efficient magnetic field conductors and their relative permeability can vary between a few to a hundred thousand. Furthermore, these materials are highly non-linear, meaning that relative permeability is not constant and depends on the magnetic field. Their dependence can be obtained from equation (2).

$$B_f = B_s * \operatorname{asinh}(h_s H) \tag{2}$$

Valve velocity and acceleration is defined in equation (3).

$$\begin{cases} \frac{dx}{dt} = v \\ \frac{dv}{dt} = a \end{cases} \tag{3}$$

Pre-saturation force created by the magnetic core can be obtained from equation (4).

$$F_m(x,i) = \frac{k_{ka} i^2}{(k_{kb}+x)^2} \tag{4}$$

$$\begin{cases} \frac{di}{dt} = \frac{V_{app} - Ri + Z_1(i,x)V}{Z_2(x)} \\ Z_1 = \frac{2k_{ka} i}{(k_{kb}+x)^2} \\ Z_2 = \frac{2k_{ka}}{(k_{kb}+x)} \end{cases} \tag{5}$$

Where x is armature displacement, I is the system current, R is the coil resistance, V_{app} is voltage and K_{ka} and $K_{kb}$are constants. Post-saturation magnetic force is nonlinear, therefore the effects of magnetic flux saturation and eddy currents must be taken into account. The electromagnetic poppet valve model is illustrated in figure (1).

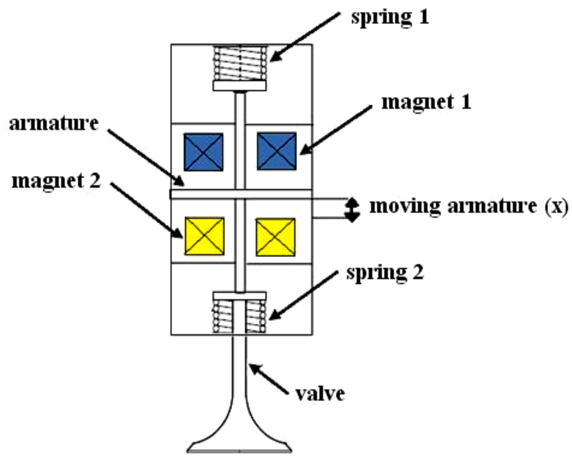

Fig. 1. Electromagnetic poppet valve model diagram.

Equation (6) relates current and magnetic flux.

$$\begin{cases} V = Ri + \frac{d\lambda(x,i)}{dt} \\ \lambda = N\phi = N(\phi_L + \phi_m) \end{cases} , \tag{6}$$

where $\phi_L = \frac{N_i}{R_i}$ and $\phi_m = \frac{N_i}{R_m}$ are the settling flux and magnetic flux respectively. For dynamic controlling, we had to use a nonlinear model for the flux settling (equation (7)).

$$\begin{cases} \lambda(x,i) = \lambda_s\left(1 - e^{-if(x)}\right) \; i \geq 0 \\ f(x) = \frac{2c_1}{(c_2 - x) + c_3} \end{cases} \tag{7}$$

Where λ_s is the maximum flux saturation and c_1, c_2, $c_3$are constant parameters. The electromagnetic force induction occurs in opposite direction of the generator's pole, therefore the generators has to exert work in order to charge the coil (the work is stored, in energy form, in the magnetic field). This energy can be calculated from equation (8).

$$E = \int_0^i \lambda(x,i)di = \frac{1}{2\mu_0} B_f^2 AL \tag{8}$$

Inductance is expressed by equation (9).

$$L = \frac{\lambda}{i} = \frac{N(\phi_L + \phi_m)}{i} \tag{9}$$

3. MASS ANDSPRING SYSTEM

As can be seen in figure (2), the electromagnetic poppet valve is modelled by a two degree of freedom system. The system consists of an armature mass (m_a) and a valve mass (m_v). The system is set up as follows: the armature mass is connected by spring hardness k_1, valve leg hardness $k_2$and the camper coefficient c_1, which connects the two masses, while the valve mass is set up by using a spring with hardness $k_3$and a damper with damping coefficient c_2.

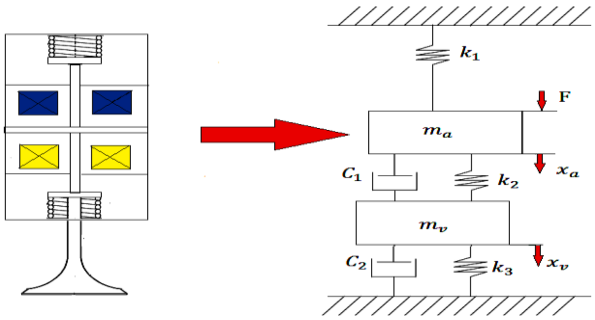

Fig. 2. Modelling the system as a two degree of freedom system.

Using the second law of newton and figure (3), we have:

$$\begin{cases} m_a\ddot{x}_a + c_1(\dot{x}_a - \dot{x}_v) + k_2(x_a - x_v) + k_1 x_a = \mathrm{F} \\ m_v\ddot{x}_v - c_1(\dot{x}_a - \dot{x}_v) - k_2(x_a - x_v) + c_2\dot{x}_v + k_3 x_v = 0 \end{cases} \tag{10}$$

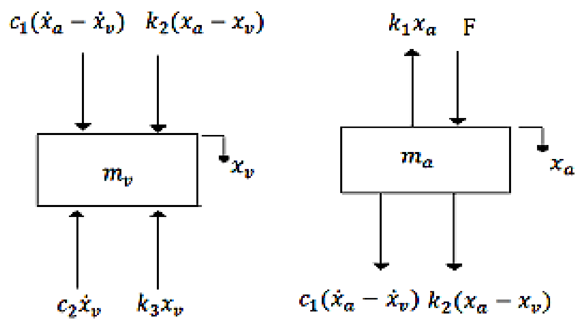

Fig.3. A schematic of decomposition of the forces.

By reducing the degree of equations (10) and reformulating them in state space, we have:

$$\left.\begin{aligned} x_1 &= x_a x_2 = x_v \\ x_3 &= \dot{x}_a x_4 = \dot{x}_v \\ \dot{x}_3 &= \frac{F}{m_a} - \frac{c_1}{m_a}(x_3 - x_4) \\ &\quad - \frac{k_2}{m_a}(x_1 - x_2) \\ &\quad - \frac{k_1}{m_a}x_1 \\ \dot{x}_4 &= \frac{c_1}{m_v}(x_3 - x_4) + \frac{k_2}{m_v}(x_1 - x_2) \\ &\quad - \frac{c_2}{m_v}x_4 - \frac{k_3}{m_v}x_2 \end{aligned}\right\} \tag{11}$$

Laplace transform is a linear operator that converts a function, from time domain, to frequency domain. By applying the Laplace transform to equation (10), we get:

$$\begin{cases} m_a s^2 x_a(s) + c_1 s(x_a - x_v) + k_2(x_a - x_v) + k_1 x_a = \mathrm{F(s)} \\ m_v s^2 x_v(s) - c_1 s(x_a - x_v) - k_2(x_a - x_v) + c_2 s x_v + k_3 x_v = 0 \end{cases} \tag{12}$$

Table 1 shows the values of the main parameters used in the two degree of freedom system

Table 1. The main parameters used in the two degree of freedom system.

Parameter	Mark	value
Spring StiffnessTop	k_1	$75(\frac{kN}{m})$
Valve Stem Stiffness	k_2	$250(\frac{kN}{m})$
Spring Stiffness Down	k_3	$75(\frac{kN}{m})$
Damping Coefficient Between the Armature and the Valve	c_1	$60(\frac{N.s}{m})$
Damping Coefficient Between the Valve and Valve Guide	c_2	$60(\frac{N.s}{m})$

4. CONTROL SYSTEM

This system utilizes an electromagnetic force to open/close the valve and uses a controller to enforce the desired time-dependent movements. The system is regulated and stabilized by using a PID controller placed in a closed loop (figure (4)).

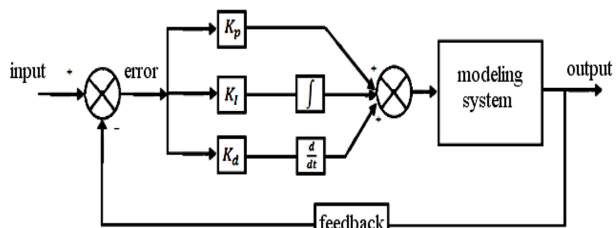

Fig.4. Schematics of the PID system.

Designing the PID requires finding the appropriate values for coefficients k_P, k_I, k_D. As per equation (13) coefficient, k_P is multiplied by error e, k_I is multiplied in the error integral while k_D is multiplied by the error derivative and the output of the controller is the sum of these multiplications. The predicted error (e) is sent to the PID controller and the controller calculates the derivative and integral of the desired input (R) and actual output (y).

$$y(t) = K_p e(t) + K_I \int_0^T edt + K_D \dot{e}(t) \tag{13}$$

In the present study we used the electromagnetic valve model illustrated in figure (5), wrote the code inside a single block and recorded the outputs. By exerting the electromagnetic forces on the valve (using them as input) and measuring the outputs, we have effectively calculated the valve and armature lifts. Thus the controller gives us the values for forces fa and fv, these forces are then used as inputs for the poppet valve model and the outputs xa and xv (drafts) are obtained. These values are then compared with the desired values, the error is fed to the controller and the process is repeated until the error approaches zero.

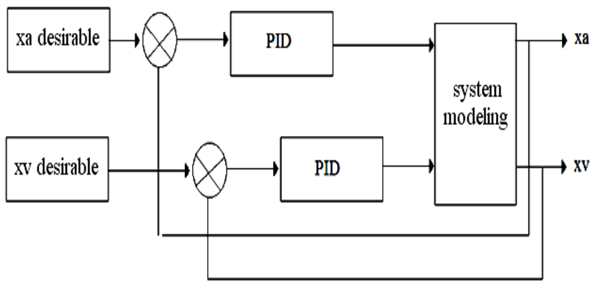

Fig.5. Block diagram of the electromagnetic poppet valve system model.

5. DISCUSSIONS

If the valve opens and closes fast enough, the current limit will be removed, which will in turn improve efficiency, therefore it is imperative that the valve reaches maximum lifts as fast as possible. Figure (6) shows the effects of armature distance on electromagnetic force under various current.

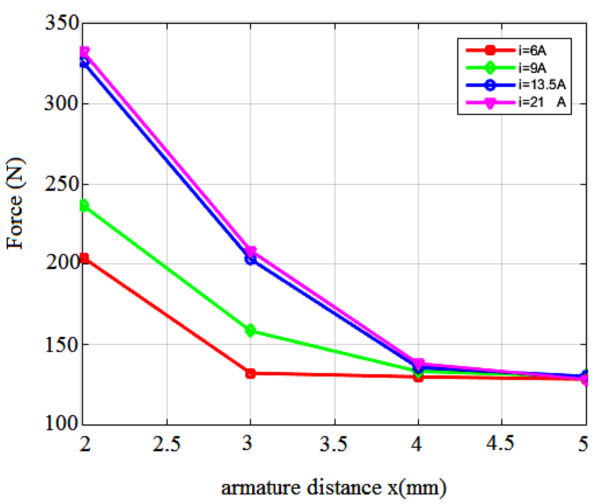

Fig.6. Effects of armature distance on magnetic force under various currents.

Figure (7) demonstrates the system response in time domain. Figure (7a) shows the displacement response of the armature and valve. The blue and orange curves represent the armature's displacement and valve's displacement, respectively. The results show that the armature and valve are dampened after 0.1 seconds but the armature has a larger rise domain. Figure (7b) shows the velocity response for the armature (blue) and valve (orange). The rise of the armature and the poppet valve are the same and equal to 0.8 m/s and they both reach the dampened value in 0.1 seconds.

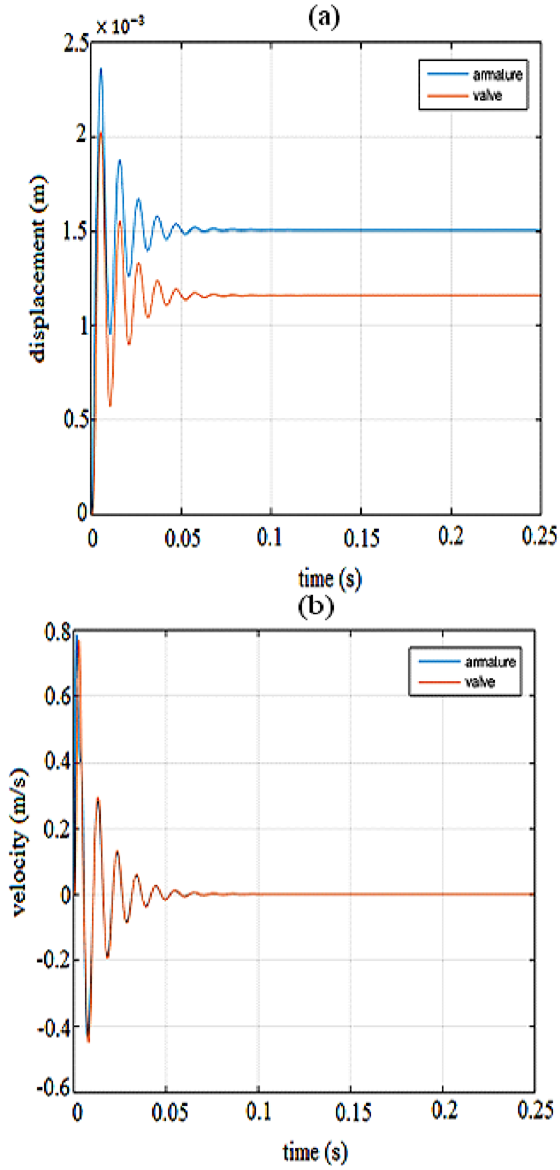

Fig.7. System response in time domain for zero current.

Figure (8) shows the system response after calculation of the controller coefficients. Figures (8a) and (8b) show the displacement response of the controlled armature and poppet valve respectively. Comparison of the figures (8a) and (8b) revealed that rise time of the armature is lower than the valve but the armature has a higher jump. One of the reasons behind this phenomenon is the delay time of the electromagnetic poppet valve. The settling time of the armature and valve were mostly satisfying. The designed feedback controller reduced maximum valve displacement range from 2mm to 0.001 mm and time until maximum displacement from 0.1 seconds to 0.022 seconds.

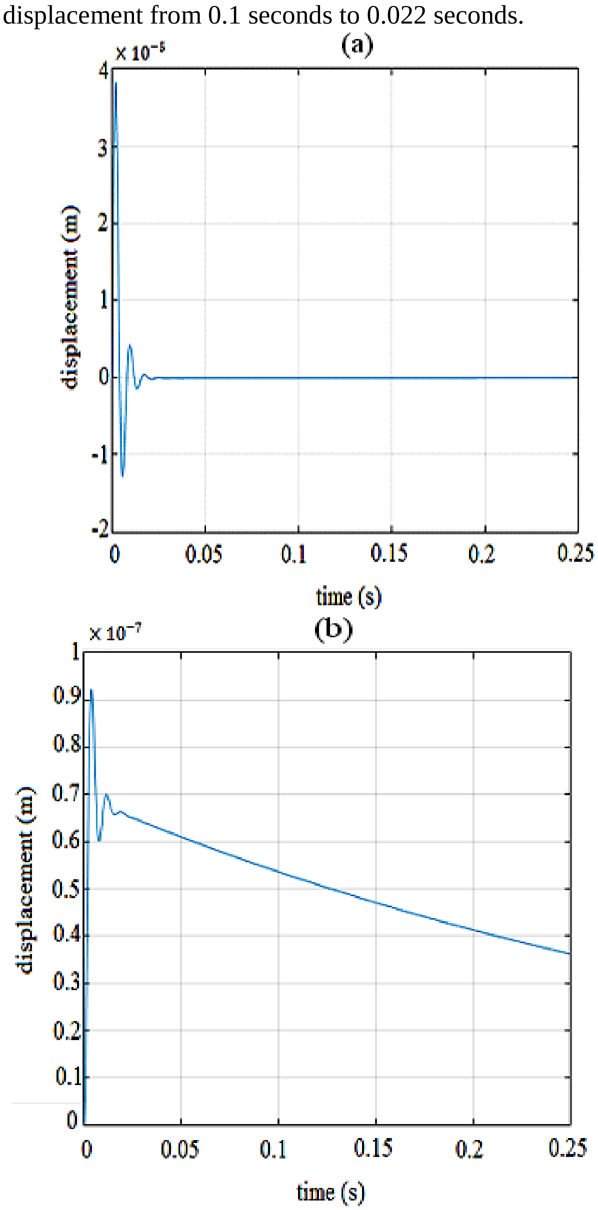

Fig. 8. Time domain response of the system with PID controller.

Figure (9) shows the response in frequency domain. The passes for the two phases are -37.5 and -169 and have gains of 10.3 and -9.35. The negative gain margin means that increasing the gains will destabilize the system, while a positive gain margin means that stability increases with gain.

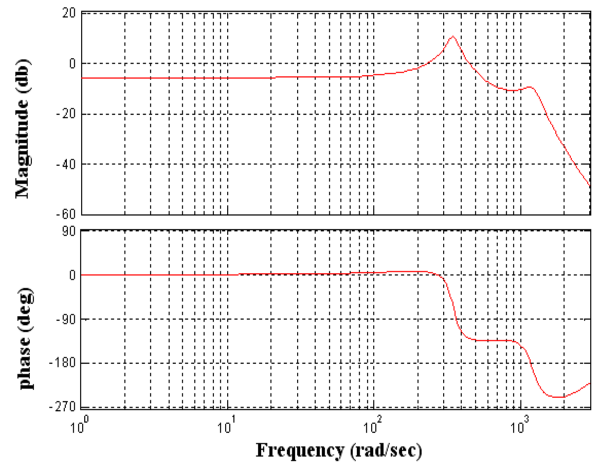

Fig.9. System response in frequency domain.

6. CONCLUSIONS

In the present article, we investigated the design and simulation of an electromagnetic poppet valve along with a closed loop PID controller which stabilized the movements of the valve. Designing and testing an engine, and its accessories, is a difficult and expensive process, therefore many investigations focus on improving valve movement control. This goal may be achieved through mathematic or computer simulations. The feedback controller designed in this study reduced the maximum poppet valve movement range from 2 mm to 0.001 mm and duration from 0.1 seconds to 0.022 seconds. The average settling time for the valve was 0.0126 and had a standard deviation of 0.1304, while the armature had a settling time of 0.0184 and a standard deviation of 0.1363. The average valve displacement was 0.0011 with a standard deviation of 0.0003 and the average displacement of the armature was 0.0015 with a standard deviation of 0.0003. The passes of the two phases were -37.5 and -169 while the gains were 10.3 and -9.35. The negative gain margin means that decreasing the gain will result in stability loss, while positive gain margins mean that stability is lost by increasing the gain.

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