Effect of Mechanical Damping and Electrical Conductivity on the Dynamic Performance of a Novel Electromagnetic Engine Valve Actuator

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KEYWORDS: Electromagnetic engine valve actuator, Mechanical damping, Electrical conductivity, Finite element analysis, Dynamic performance, Transition time, Landing velocity

We investigate the effect of mechanical damping and electrical conductivity on the dynamic performance of a new electromagnetic engine valve actuator that employs a permanent magnet. The key dynamic performance factors are the transition time and the landing velocity of the armature. Two-dimensional dynamic finite element analyses are performed to simulate a coupled system. The results show that mechanical damping and electrical conductivity have similar effects on the dynamic performance of the engine valve actuator. Subsequently, it is possible to replace the role of mechanical damping by controlling the electrical conductivity through the thickness and number of steel core laminations.

Manuscript received: March 6, 2008 / Accepted: May 28, 2008

NOMENCLATURE

A: magnetic vector potential
B: magnetic flux density
C: capacitance
F: magnetic force
H: magnetic field intensity
i: current
K: equivalent spring stiffness
m: moving mass
R: resistance
t: time
V: voltage
x: displacement
λ: flux linkage
μ: permeability

1. Introduction

One of the key environmentally friendly technologies in a combustion engine is variable valve timing (VVT). VVT technology can achieve valve events independently of crankshaft rotation, which is different from a conventional camshaft-driven engine valve system where the phase of the valve operation is controlled. Therefore, fuel economy, torque output and emissions are optimized at most engine operating conditions, resulting in a 15% improvement in fuel efficiency, 10% reduction in CO2 emissions and a 10% increase in torque output.[1,2] Two well-known VVT systems include Mazda's S-VT, which advances or retards the timing of the intake or exhaust valves, and Honda's VTEC, which switches between two sets of cams at a certain engine RPM. These systems, however, add complexity to the engine and do not result in large improvements to torque.[3] As a result, several automobile companies have been developing more advanced electromechanical systems. One example of this is a solenoid-driven actuator,[4,5] which suffers from heat dissipation due to the continuous use of electric power during operation and initial starting difficulties. New electromagnetic engine valve actuator designs have been introduced to overcome these problems.[6] These new systems employ permanent magnets. The residual induction of a permanent magnet initially holds the valve at the closed position. No power is required between valve events; current is only fed into the system during each valve transition period.

The key factors affecting the dynamic performance of the actuator are the transition time and the landing velocity of the armature. The transition time is the time required for the valve to travel from a closed to an opened position or from an opened to a closed position. The transition time of the valve must satisfy the design constraints of the engine so as to enable a new actuator to be employed. A smaller transition time allows the actuator to operate the engine valve at higher engine revolutions per minute (RPM) values. The landing velocity is the velocity of the armature connected to the engine valve at the end of travel. Without a soft landing, there are large impact forces, which make loud noises and can lead to armature failure.

Studies aimed at reducing the transition time of a solenoid-driven actuator have been performed.[4,5] However, important parameters such as the mechanical damping and the electrical conductivity of the actuator, both of which have a significant effect on the transition time and landing velocity, were neglected. In this paper, the effect of mechanical damping and electrical conductivity on the performance of a new actuator is investigated using finite element analysis (FEA).

2. New Electromagnetic Engine Valve Actuator

Figure 1 shows a schematic diagram of a new electromagnetic engine valve actuator for achieving the VVT proposed by Kim and Lieu.[6] It consisted of two pieces of a permanent magnet, an electromagnetic coil (solenoid), a laminated steel core with an armature, two springs and a valve body. Permanent magnets are employed in order to overcome the problems associated with a solenoid-driven actuator. The operating principle of the actuator is as follows. Initially, the armature is held at the upper end since the magnetic force is greater than the spring force (Fig. 2a). To release the armature (*i.e.*, to open the valve), the upper coil is energized to cancel the flux from the permanent magnet. The spring force then becomes larger than the magnetic force and the springs accelerate the armature downward using the stored potential energy (Fig. 2b). In the neutral position, the lower coil is energized to have the same flux flow as the permanent magnet. The magnetic force from both the coil and the permanent magnet together overcome the spring force and the armature is held at the lower end (*i.e.*, the valve is fully opened) (Fig. 2c). These events occur successively. The total traveling distance of the armature is 7.6 mm. By controlling the current of the electromagnetic coil, the holding time of the armature can be controlled and, as a result, VVT is achieved.

3. Simulation Model

The proposed system consists of magnetic, mechanical and electric subsystems; these systems are coupled with each other. The governing equations and initial boundary conditions of each subsystem are shown in the following equations, and their physical properties are listed in Table 1. A two-dimensional finite element model of the actuator was created to model the coupled systems with the transient FEM solver MAXWELL. Transient analyses were performed with parametric variations to predict the effect of various design parameters on the dynamic performance of the system.

The magnetic subsystem is governed by

$$\nabla\times\left(\frac{1}{\mu}\nabla\times\vec{A}_Z\right)=\vec{J}_{ext}+\frac{1}{\mu}\nabla\times\vec{M} \tag{1}$$

boundary condition: $A_z = 0$

The nonlinear magnetic *B-H* properties of silicon steel were assigned to the steel part while the magnetic properties of samarium cobalt (SmCo28) were assigned to the permanent magnet. The nonlinear *B-H* curve of steel 1010 was assigned to the armature and stator.

The mechanical subsystem is governed by

$$m\ddot{x}+c\dot{x}+2kx=F_{magnetic}+F_{gravity} \tag{2}$$

initial condition: $x(0) = -3.8mm$ and $\dot{x}(0) = 0$

The total travel distance between both ends of the engine valve was 7.6 mm.

The electrical subsystem consists of a resistor and inductor, governed by

$$\frac{d\lambda(i,x)}{dt}+Ri+\frac{1}{C}\int idt=0 \tag{3}$$

initial condition: $V_c(0)=V_i$ and $i(0)=0$

To investigate the effects of mechanical damping and electrical conductivity on the dynamic performance factors, such as the displacement, transition time and landing velocity, the dynamic motion of the armature from the lower end to the upper end of the stroke (-3.8 mm to +3.8 mm) was simulated using a time step of 10 μs over the transition period.

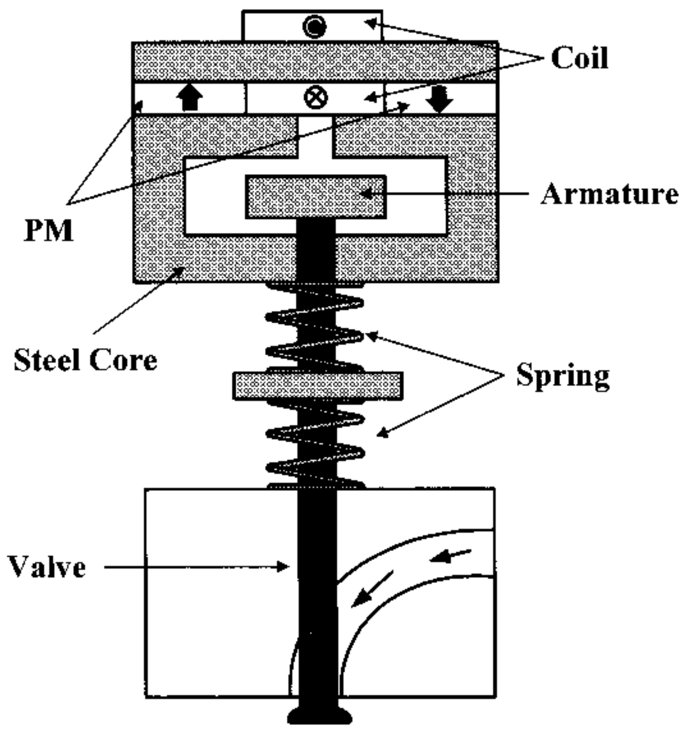
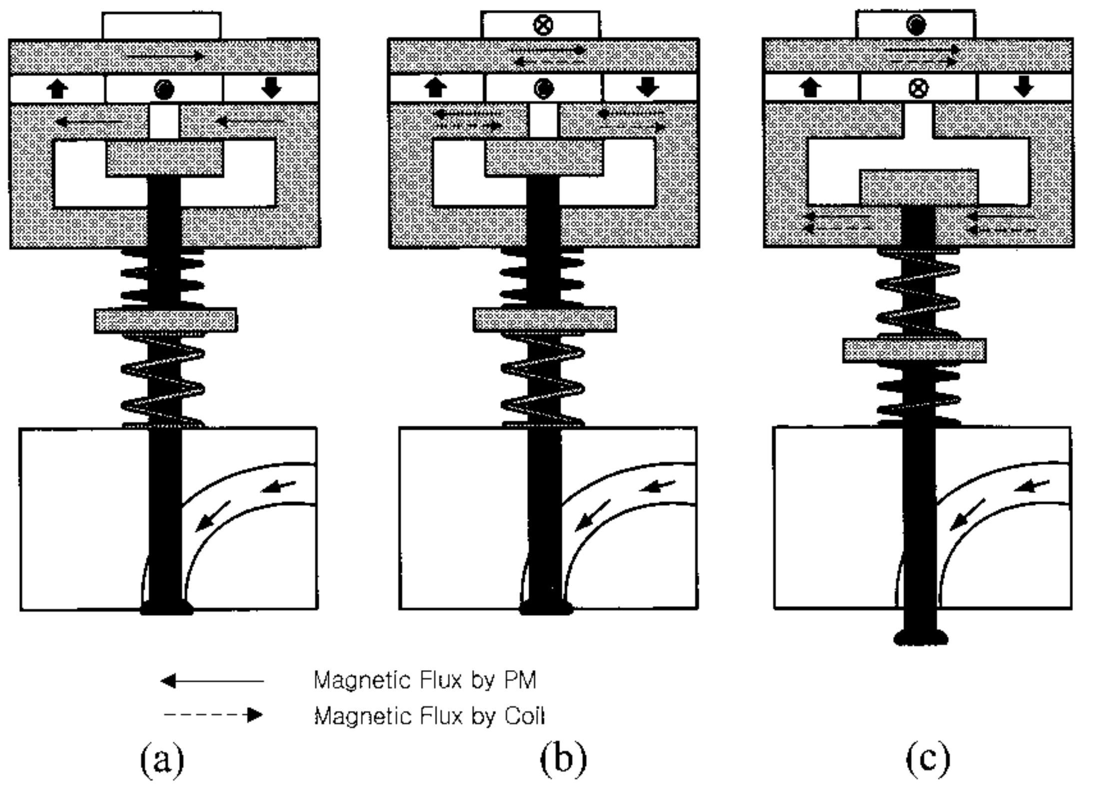


Fig. 1 Schematic diagram of the proposed electromagnetic engine valve actuator (PM = permanent magnet)



(a) (b) (c)

Fig. 2 Principle of operation with the armature at the (a) upper end, (b) initial position and (c) at lower end

Table 1 Physical properties

Magnetic system	Residual induction	1.0188 T
	Coercivity	-754176 A/m
Mechanical system	Mass	0.28 kg
	Equivalent spring stiffness	362.5 kN/m
Electric system	Initial voltage in capacitor	200 V
	Number of coil turns	200 turns
	Resistance	1 Ω
	Capacitance	100 μF

4. Simulation Results

4.1 Mechanical Damping

To study the effect of mechanical damping, the mechanical damping coefficient (ξ) was varied and the other parameters in the equations were fixed while 200 S of electrical conductivity was assigned to both the steel-made core and the armature. The transition time and the landing velocity obtained from various mechanical damping coefficients are shown in Table 2.

Table 2 Effect of the mechanical damping coefficient on the transition time and landing velocity

Damping coefficient (ξ)	Travel distance (mm)	Transition time (ms)	Landing velocity (m/s)
0	7.6 (max.)	3.96	1,826
0.02	7.6	4.26	1,248
0.04	7.6	5.38	283
0.06	6.86 (90%)	-	-
0.08	6.66 (87%)	-	-
0.1	6.15 (81 %)	-	-

As the mechanical damping increased, the transition time was lengthened while the landing velocity of the armature at the end of its stroke was reduced. The armature reached only 90% (6.86 mm) of the complete travel distance (7.6 mm) when the damping coefficient was 0.06. Hence, the maximum moving distance of the armature became shorter as the mechanical damping increased. If the moving distance of the armature is shorter than the complete travel distance, the armature will exhibit damped oscillations and will eventually rest at the neutral position of the stroke. This means that the engine valve cannot operate properly.

4.2 Electrical Conductivity

To study the effect of electrical conductivity, dynamic finite element analysis runs were performed by varying the electrical conductivity of the steel parts, such as the core and armature, between 0 and 2×10^6 S while keeping the mechanical damping coefficient at zero. The results are shown in Table 3. As the electrical conductivity of the steel was increased, the time for the armature to complete the transition was lengthened but the landing velocity of the armature was reduced. When the steel core was prescribed with 2×10^6 S of conductivity, the armature was not even released, as indicated by the observed zero travel distance. With 2×10^5 S of conductivity, the armature was released, but only reached 82% (6.26 mm) of the complete travel distance. These effects were due to the eddy current loss in the electrically conductive steel core induced by a magnetic field that was changing with time, by the rapid motion of the moving armature and the sudden change of current in the coil. As the electrical conductivity of steel was increased, the eddy current loss became larger, resulting in a longer transition time of the armature and a smaller landing velocity. The eddy current effect could be minimized by designing the steel core to produce an appropriate the electrical conductivity value, which depends on the thickness and number of laminations in the steel core. According to Xu et al.,[7] the conductivity of an n-laminated core, where each lamination has conductivity σ, is replaced by the equivalent conductivity σ_{eq}, defined by

$$\sigma_{eq} = \frac{\sigma}{n^2} \tag{4}$$

Table 3 Variation of transition time and landing velocity with conductivity

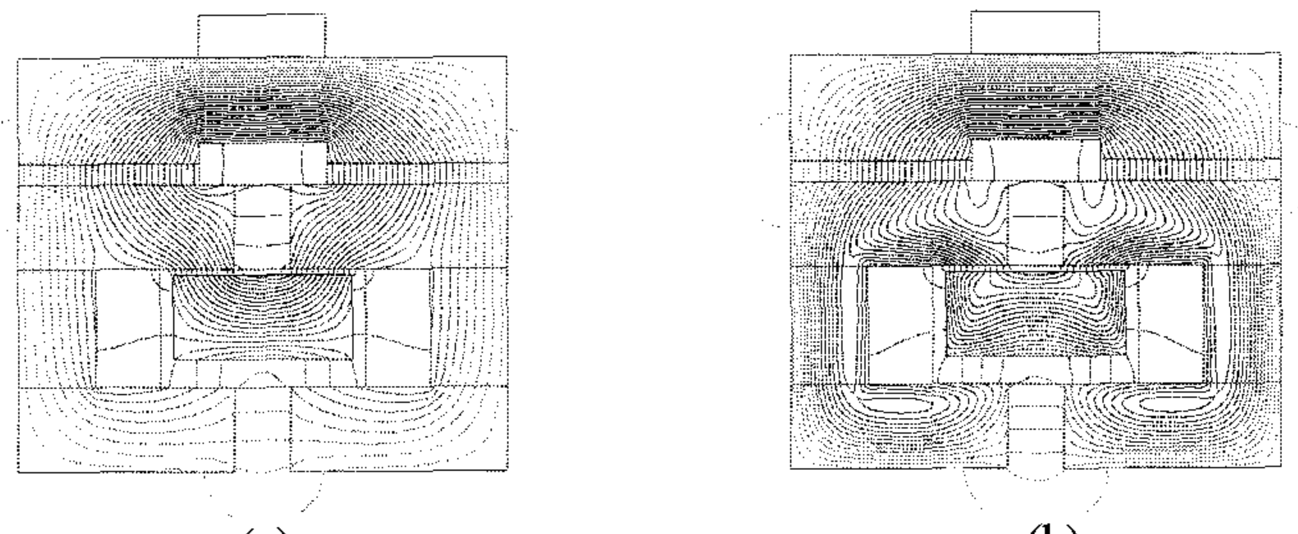
Conductivity (S)	Travel distance (mm)	Transition time (ms)	Landing velocity (m/s)
0	7.6 (max)	3.94	1,839
2×10^2	7.6	3.96	1,826
2×10^4	7.6	4.5	1,124
2×10^5	6.26 (82 %)	-	-
2×10^6	0 (0 %)	-	-

Figure 3 shows the magnetic flux distribution 6.26 mm from the lower end of the valve during the transition with different values of electrical conductivity for steel. A change in the magnetic flux distribution due to the eddy current could be observed in the actuator when the electrical conductivity of steel was high.

Figure 4 shows the position profiles of the armature according to changes in the mechanical damping coefficient and electrical conductivity. These profiles illustrate the trends observed: (i) more mechanical damping or electrical conductivity increased the transition time of the armature and (ii) if the value of the mechanical damping coefficient or electrical conductivity was above a certain threshold, the armature failed to complete its stroke.

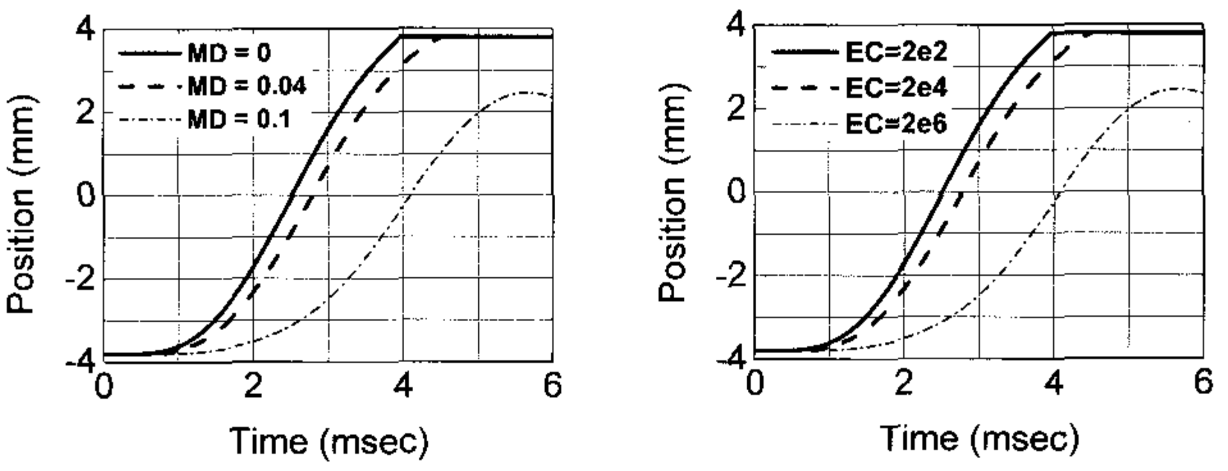
5. Conclusions

The effect of critical parameters, *i.e.*, damping in the mechanical subsystem and conductivity of steel in the electric subsystem, on the dynamic performance of a proposed electromagnetic engine valve actuator was investigated with finite element analysis. The results demonstrated that both the mechanical damping and electrical conductivity had similar effects on the dynamic performance of the actuator. More mechanical damping and more electrical conductivity of steel caused an increase in the transition time of the armature and a decrease in the landing velocity. It is therefore possible to control the electrical conductivity of steel by choosing its thickness and number of laminations, and thus replace the role of mechanical damping in reducing the landing velocity to create less noise and wear during impact.



(a) (b)

Fig. 3 Magnetic flux distribution 6.26 mm from the bottom end of the valve during transition with (a) 200 S of conductivity and (b) 2×10^5 S of conductivity



(a) (b)

Fig. 4 Armature position profile using (a) mechanical damping and (b) electrical conductivity

ACKNOWLEDGEMENT

This research was supported by Yeungnam University research grants in 2007.

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