A Equivalent Finite Element Model of Lamination for Design of Electromagnetic Engine Valve Actuator

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The electromagnetic engine valve actuator is a key technology to achieve variable valve timing in internal combustion engine and the steel core and clapper of the electromagnetic engine valve actuator are laminated to reduce the eddy current loss. To design and characterize the performance of the electromagnetic engine valve actuator, FE (finite element) analysis is the most effective way, but FE (finite element) 3-D modeling of real lamination needs very fine meshes resulting in countless meshes for modeling and numerous computations. In this paper, the equivalent FE 2-D model of electromagnetic engine valve actuator is introduced and FE analysis is performed using the equivalent FE 2-D model.

Keywords : eddy current, finite element analysis, linear actuator, solid model, equivalent model, lamination

1. Introduction

The electromagnetic engine valve actuator is the most advanced system to achieve variable valve timing which can improve engine efficiency up to 15%, reduce CO_2 emissions up to 10% and increase torque output up to 10% enabling optimization of these outputs at different engine conditions replacing the mechanically driven camshaft engine valve train [1]. Several electromagnetic engine valve actuators have been introduced and developed in past years [2-4].

The core parts made of steel used in the electromagnetic engine valve actuator are laminated to reduce the eddy current loss. This loss results from the electrical conductivity of core materials such as low carbon steel, silicon steel, nickel steel and other ferromagnetic materials those are most widely utilized in electromagnetic engine valve actuators. In the electromagnetic engine valve actuators, the eddy current is created by magnetic field that is changing with respect to time by both very rapid motion of moving clapper and the sudden change of current in the coil. The magnetic losses by eddy current exert bad influence on the performance. The steel cores, therefore, are laminated to reduce the eddy current effects. The conventional way for calculation of eddy current losses is

to use the material data provided by manufacturer, but it is confined to typical flux density and frequency. Practical application is different depending on its operating condition, and the data sheets from manufacturer are difficult to be applied to different condition of applications. Another method is finite element analysis [5, 6].

To design and characterize the electromagnetic engine valve actuator, finite element analysis (FEA) is the simplest and most effective method, but FE (finite element) 3-D modeling of real lamination i.e. each laminated core sheet includes the eddy current effects, but it needs very fine meshes from the surface to skin depth to achieve the accurate result. 3-D modeling, therefore, need countless meshes for modeling and results in numerous computation time and power [7]. A bulk with equivalent conductivity must replace a number of sheets to escape modeling of laminated core in sheet by sheet and apply lamination effect to FE 2-D model.

In this paper, the equivalent FE 2-D model of laminations to include the computation of eddy current effect is utilized for finite element simulation of electromagnetic engine valve actuator, and the lamination model are compared with the solid model.

1.1. Electromagnetic Engine Valve Actuator

Fig. 1 shows a schematic diagram of new electromagnetic engine valve actuator for VVT which was introduced by Kim and Lieu [4]. This actuator is composed of permanent

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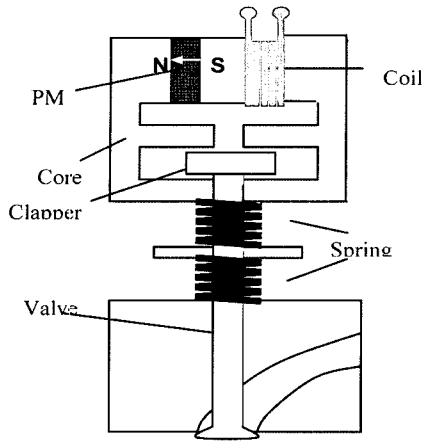Fax: +82-2-589-2280, e-mail: jinho@kistep.re.kr

Fig. 1. Schematic diagram of a new electromagnetic engine valve actuator.

magnet, steel-made core and clapper, two springs electromagnetic coil and the valve body. As the clapper moves up and down, the engine valve closes and opens because the clapper and the valve are single body. The main operating principle is mass-spring oscillation system and the valve timing is controlled by current control to the electromagnetic coil. At start, the valve is closed because the magnetic force exceeds the spring force. To open the valve, the coil is energized. As the flux of permanent magnet is partially cancelled, the spring force exceeds the magnetic force. The armature is accelerated upwards by the stored energy in the springs. After the neutral stroke position, the coil is reverse-energized to catch the clapper, and the clapper reaches the bottom end. The motion from the lower end to the upper end is the inverse operation of the steps above. The total travel distance of clapper between both ends is 8 mm and the transition time is than 4 milliseconds.

1.2. Eddy Current and Lamination

The eddy current is created because the core material is electrically conductive. When the flux in the core varied with time, voltage is induced by Faraday's law which is defined by (1).

$$\oint_c \vec{E} \cdot \vec{dl} = -\frac{d}{dt} \int \vec{B} \cdot \vec{da} \qquad (1)$$

Where
 E: electric field strength
 B: magnetic flux density
 a: area

This voltage induced by time-varying magnetic field causes the current to flow through the core itself. This is the eddy current and the eddy current loss is I^2R. In electromagnetic engine valve actuator the eddy current is

created by magnetic field that is changing with respect to time by both motion of moving clapper of which maxim speed is over 4000 mm/sec and change of current in the coil.

The magnetic losses induced by eddy current exert bad influence on the performance of the actuator. To reduce the eddy current loss in magnetic devices, the core is laminated which is made of many thin sheets of ferromagnetic material. The electrically insulting material such as epoxy is inserted between the sheets, which have oxide coat at the surface, and the sheets are stacked. The magnetic flux flows parallel to each sheet, and eddy current is created perpendicular to each sheet. The electrically insulting material provides the interlaminar resistance and reduces the eddy current and loss. The thickness of lamination has large effects on reducing the eddy current, and the number of gauge represents the thickness of lamination. The gauge number increases with decreasing thickness. The most widely used thickness of lamination is 355.6 mm (29 gauge), 469.9 mm (26 gauge), or 635 mm (24 gauge). The core loss is trade off of the price. As the thickness of lamination is thinner, the loss decreases while the price of thinner lamination is higher and more laminations are needed for a given stack height [8].

2. Equivalent Lamination FE Model

2.1. 2-D FE model and Analysis

FE models are created and dynamic finite-element analysis was performed using the nonlinear FEM solver MAXWELL. The electromagnetic engine valve is composed of three subsystems: a mechanical system, an electrical system, and a magnetic system, which are all coupled to each other. The magnetic subsystem is governed by equation (2). The nonlinear magnetic B-H properties of silicon steel were assigned to the core and the clapper, and the magnetic properties of samarium cobalt (SmCo28) were assigned to the permanent magnet. Table 1 shows the specifications of the SmCo28 permanent magnet.

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \vec{A}\right) = \vec{J}_{ext} + \frac{1}{\mu} \nabla \times \vec{M} \qquad (2)$$

boundary condition $Az = 0$
 $\vec{A}$: magnetic vector potential
 μ : permeability
 $\vec{M}$: intrinsic magnetization density
 $\vec{J}$: current density

The mechanical system is governed by (3).

$$m\ddot{x} + 2kx = F_{magnetic} \qquad (3)$$

initial condition $x(0) = -4mm$, $\dot{x}(0) = 0$

Table 1. Magnetic properties of SmCo28 permanent magnet.

Br	1.02 T
Hc	-754176 A/m
μm	1.075

Table 2. Specification of mechanical system.

Mass	110 g
Spring stiffness	170 kN/m
Natural frequency (ωn)	1243

The moving mass clapper and the stiffness of springs are specified. The moving mass includes clapper, engine valve, keeper and a fraction of spring. Table 2 shows the specifications of the mechanical subsystem.

The electrical subsystem consisted of the coil, capacitor, voltage power supply and toggle switch. The equation (4) is governing equation and initial condition. Table 3 shows the specifications of initial charge voltage, capacitance, coil turns, and coil resistance.

$$\frac{d\lambda(i,x)}{dt} + Ri + \frac{1}{C}\int i\,dt = 0 \tag{4}$$

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

Two different 2-D dynamic finite-element models were created to assist in modeling these coupled systems. One is solid model and the other is lamination model. To avoid real 3D modeling of laminated core, 2D equivalent model of lamination is created to include eddy current effect in the model. According to J. Xu *et al.* [7], conductivity of n-laminated core where each lamination has conductivity σ is replaced by equivalent conductivity σ_{eq} which is defined by (5)

$$\sigma_{eq} = \frac{\sigma}{n^2} \tag{5}$$

24-Gauge silicon steel lamination that has 0.025-inch thickness is utilized for core material. The core is 1.5 inch in perpendicular direction of flow of magnetic flux, therefore 60 laminations needs to be stacked.

$$n = \frac{1.5}{0.025} = 60$$

Table 3. Specification of electric subsystem

Voltage	100 V
Capacitance	100 μF
Coil turns	170
Resistance	0.85 Ω

Conductivity of silicon steel is 6.7×10^5 Ω^{-1}/m, and equivalent conductivity of 60 laminations is 200 Ω^{-1}/m.

$$\sigma_{eq} = \frac{\sigma}{n^2} = \frac{6.7e05}{60^2} = 200$$

In result, 6.7×10^5 Ω^{-1}/m is assigned to conductivity of core and clapper of solid model, and 200 siemens/meter is assigned of lamination model.

The dynamic motion of the clapper from the lower end to the upper end of stroke was simulated. The analysis is performed with 10 μs time steps over a period of 4 ms. The magnetic force exerting on the moving clapper was computed through virtual work principle method.

3. Results

Fig. 2 and Fig. 3 shows the profile of position of solid model and lamination model respectively. The delay time of solid model before the release of clapper is 1.22 milliseconds while the delay time is 0.85 milliseconds. The time delay of solid model is 0.37 milliseconds longer that lamination model even though three times voltage of
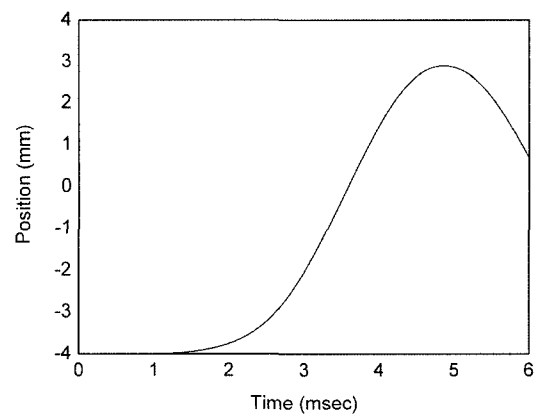
Fig. 2. Profile of position of solid model.
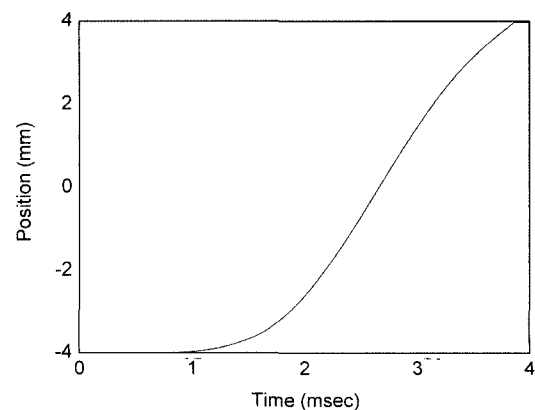
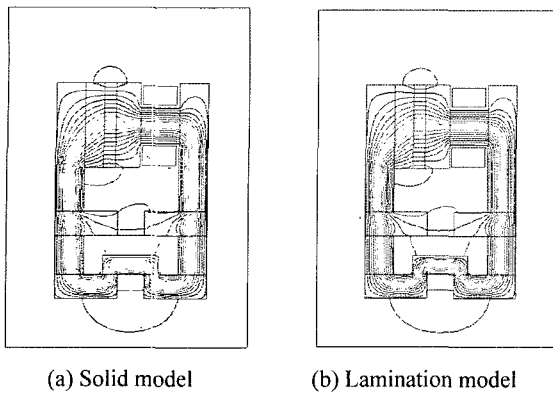**Fig. 3.** Profile of position of lamination model.

(a) Solid model   (b) Lamination model

Fig. 4. Magnetic flux plot at lower end position before release.
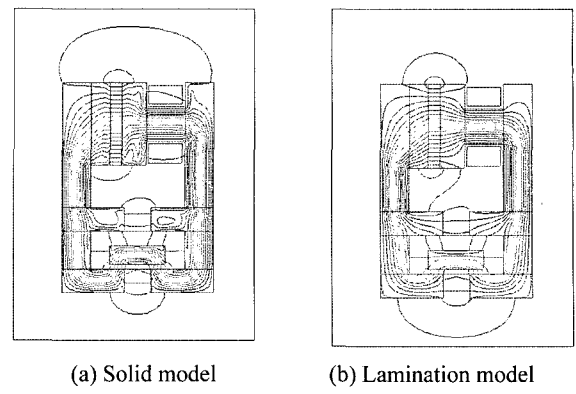

(a) Solid model   (b) Lamination model

Fig. 5. Magnetic flux plot at 2 mm above the lower end.

lamination model is charged in the capacitor than lamination model. The clapper of the solid model reaches just only 2.9 mm and goes down while the clapper of lamination model reaches the upper end. These are the results of eddy current loss. In real solid core, there is another time delay due to diffusion phenomena. The flux density is different depending on position and time i.e. the flux density is function of position and time. When a coil around steel core is energized and resulting current create magnetic flux density, there is a certain amount of time delay for the flux density to penetrate into the center of core, and it take certain time for the flux density to be uniform in the steel core. Therefore, for a high-speed application, lamination of core is required not only to reduce the eddy current loss, but also to produce the flux quickly [25]. Fig. 4, Fig. 5, Fig. 6 and Fig. 7 show the magnetic flux line plot of solid model and lamination model at each position respectively. Fig. 4 shows the magnetic flux line plot at the lower end before the coil is energized.

The clapper is held by the magnetic flux of permanent magnet. Fig. 5 shows the magnetic flux line plot at −2 mm position. The clapper is accelerated by the spring and moves fast upward. The motion of clapper and change of current in the coil with respect to time vary the magnetic field in the core, and the steel core senses the time-varying flux. In consequence, the eddy current is induced in the core opposing the changing magnetic flux and the resulting eddy current creates its magnetic field that 'is called reaction magnetic field. Fig. 6 shows the magnetic flux at mid position of stroke, and in solid model, there exists the magnetic flux created by eddy current. Fig. 7 shows the magnetic flux of 3 mm position where is the maximum position of the clapper of solid model. There is obvious difference in magnetic flux line plot between lamination model and solid model. In lamination model, the main magnetic flux by permanent magnet flows clear-
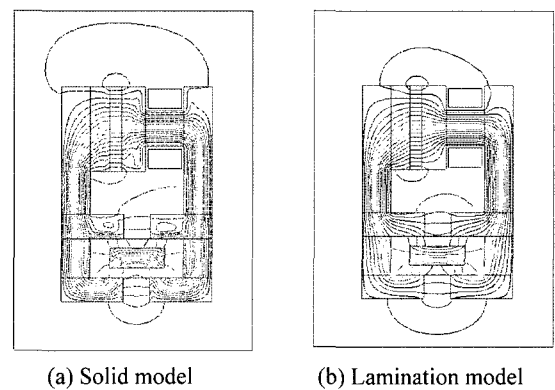

(a) Solid model   (b) Lamination model

Fig. 6. Magnetic flux plot at mid position of stroke.

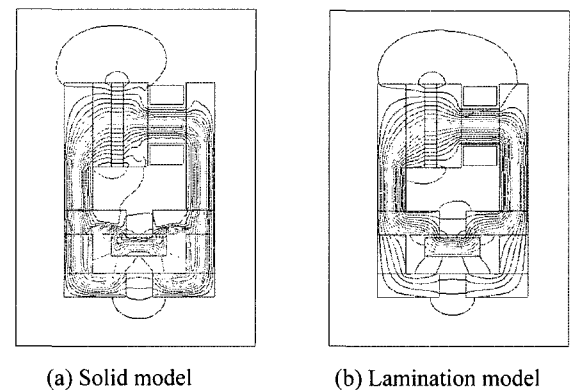(a) Solid model   (b) Lamination model

Fig. 7. Magnetic flux plot at 7 mm above the lower end position of stroke.

ly from upper core to clapper and catches the clapper to upper end while the magnetic flux is also produced at the lower core that is of no use and loss in operation. As a consequence, the clapper of solid model cannot reach upper end, but just only 2.9 mm that is 6.9 mm above from the lower end position of stroke (figure position profile of solid model). This is due to eddy current.

4. Conclusion and Discussion

Equivalent lamination model is presented to consider eddy current losses in electromagnetic engine valve actuator. The solid FE model and lamination FE model are created, and the dynamic analysis is performed during transition period. As the clapper of solid model is released and moves, the eddy current is produced within steel core and clapper. As a result of eddy current loss, the release time of clapper of solid model is longer than lamination model even though more electric energy is supplied to the system for release of clapper, and in addition, the clapper does not reach the upper end position of stroke. Lamination of steel core and clapper, therefore, is required to achieve complete operation of actuator.

References

[1] P. Barkan, and T. Dresner, SAE Technical Paper Series, Paper 891676 (1989).

[2] Y. Wang, T. Megli, M. Haghgooie, K. S. Peterson, and A. G Stefanopoulou, SAE Technical Paper Series, Paper 2002-01-1106 (2002).

[3] Y. Wang, M. Hammoud, M. Haghgooie, I. Kolmanovsky, and A. G Stefanopoulou, Proceeding of 5th International Symposium on Advanced Vehicle Control (2000).

[4] J. Kim and D. K. Lieu, Proceeding of International Electric Machines and Drives Conference (2005).

[5] K. Tani, T. Yamada, and Y. Kawase, IEEE Transactions on magnetics 35(3), 1830 (1999).

[6] K. Hollaus and O. Biro, IEEE Transactions on magnetics, 36(4), 1289 (2000).

[7] J. Xu, A. Lakhsasi, Z. Yao, and V. Rajagopalan, Proc. of Thirty-First IAS Annual Meeting, IAS '96 (1996).

[8] Hi-dong Chai. "Electromechanical motion devices," Prentice Hall, (1998).