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# Design of a High-Speed Electromagnetic Control Valve Using the Numerical Analysis

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**Abstract**

Unsteady three-dimensional compressible flow characteristics inside a control valve are investigated using numerical simulations. The motion profiles of the armature are obtained for the given electromagnetic forces using a finite element analysis. The three-dimensional unsteady compressible flow characteristics inside the control valve are studied using computational fluid dynamics simulation. It was found that flows patterns inside the valve are as follows: 1) accelerating subsonic flow, 2) choked flow at the throat 3) supersonic expansion, 4) curved strong shock, 5) decelerating subsonic flow. With the inlet pressure stepping up, the free falling time is decreased and the operation frequency is increased. It is believed that present results can be used for the design of high-speed switching electromagnetic control valves.

**Keywords**: Electromagnetic Control Valve, Numerical Analysis, High-Speed, Computational Fluid Dynamics

## 1 Introduction

Recently, the need of pneumatic control valves at the production line such as automobile, semiconductor, and flat panel display using high-speed pneumatic actuators is increasing [1]. The performance and reliability of the pneumatic system are strongly dependent on the accurate controllability of the control valves. A reliable dynamic model is required in order to handle accurately the electromagnetic, mechanical and fluid subsystems [2].

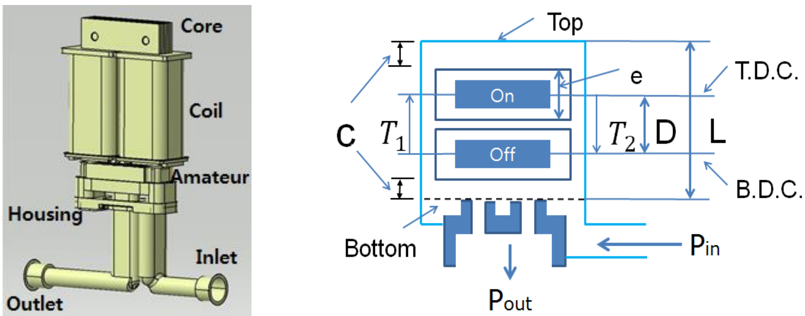
Most of the modeling studies have been done on the other types of valves [3-5]. Only a few studies were accomplished on the switching solenoid valve. Topcu *et al*. [6] investigated a dynamic model for describing the switching characteristics of the valve. Taghizadeh *et al*. [2] suggested a nonlinear dynamic model of a PWM-driven pneumatic fast switching valve by considering the interactions of electro-magnetic, mechanical and fluid subsystems. Ye and Chen [7] developed a dynamic model for a pilot-operated two-stage solenoid valve by coupling the motion of the valve spindle with fluid in the system.

The control valve in the present study consists of both electromagnetic and fluidic parts. With the up and down motions of an armature, the valve controls the flow. The armature is moved up by the electromagnetic force. When it falls down by gravity and aerodynamic forces, the effect of the aerodynamic force on the falling behavior of the armature is of critical importance to the operational characteristics of the valve. Thus, the modeling of the dynamic characteristics of fast switching solenoid valves should be done with the understanding of complicated unsteady compressible flow characteristics inside the valves. However, most theoretical and computational researches on solenoid valves are focused on using control methods [8, 9] without considering the coupled behavior of the electromagnetic valve. There were several works on the pseudo-static and transient performance of the electromagnetic valve using finite elements and other computational methods [10-13]. However, as illustrated in the previous literature survey, the studies on the unsteady compressible flow characteristics inside the switching valves could not be found in the published literatures.

Thus, the aim of the present paper is, as an initial stage to the development of the accurate and reliable dynamic model, to investigate the unsteady three-dimensional compressible flow characteristics inside a solenoid valve. The moving-up motions of an armature due to the electromagnetic force is computed. The moving-down motion profiles of the armature due to gravity and aerodynamic forces are also computed using fluid mechanics-dynamics coupling.

## 2 Configurations, Kinematics, and Numerical Method

Figure 1 shows the configuration and nomenclature of the solenoid valve in the present study. The inlet port is connected to a high pressure chamber. When the armature is at the bottom, the upper part of the armature (inner chamber) is filled with high pressure air. The outlet port is opened to the atmosphere. In the Figure 1(b), L represents the distance from the bottom surface to the top surface, e represents the thickness of the armature, D is the actual distance from the bottom dead center to the top dead center. When the armature is at the bottom, there is a significant pressure difference between the upper and lower surfaces of the armature. The core and coils should generate the electromagnetic force that could move up the armature in a designed motion. When the armature arrives at the top, suddenly the electromagnetic force is removed, and the armature starts to fall down due to the gravity and aerodynamic forces.



(a) configuration (b) nomenclature

**Fig. 1.** Configuration and nomenclature of the solenoid valve

As an electromagnetic actuator consists of electrical and mechanical components having electromagnetic circuit and armature (as shown in Figure 2), both electrical and mechanical characteristics of the subsystems should be considered. A voltage equation for electromagnetic circuits can be expressed as follows [14].

$$V = Ri + (L_e + \partial\lambda(x_g,i)/\partial i)di/dt + (\partial\lambda(x_g,i)/\partial x_g)dx_g/dt \quad (1)$$

where, $L_e$ is the inductance of the electromagnetic circuit, $\lambda$ is a flux linkage, $x_g$ is the air gap length, i is the current of the coil. Eq. 1 can be solved if the magnetic characteristics of the electromagnetic actuator are known.

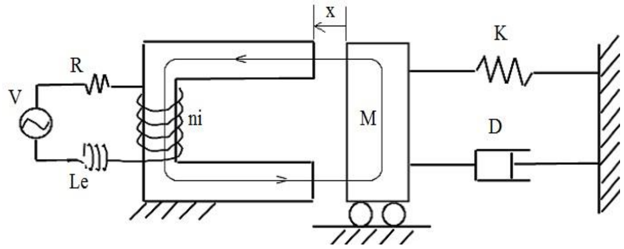



**Fig. 2.** Schematic diagram of the electromagnetic actuator

The moving part of the electromagnetic actuator can be represented by components of a mass, a damper, and a spring.

$$Mx'' + Dx' + Kx = F_t \quad (2)$$

where, M is a mass of the armature, D is a damping coefficient, K is a spring constant, and $F_t$ is a total forces acting the armature that are electromagnetic force ($F_e$) and aerodynamic force ($F_a$). In the control valve, D and K can be ignored.

From Eq. 1 - 2, the dynamic characteristics of the control valve can be obtained and represented as state equations

$$dx/dt = v \quad (3)$$

$$dv/dt = (F_e+F_a)M^{-1} \quad (4)$$

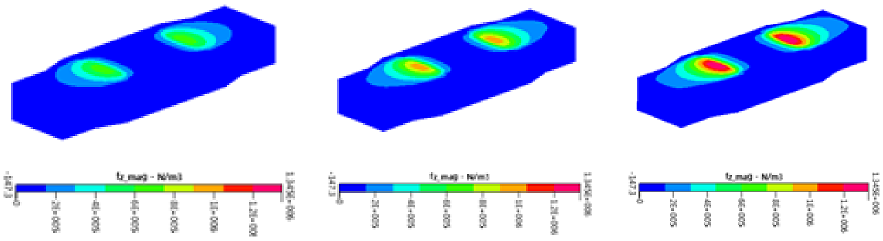
$$di/dt = (V - Ri - (\partial\lambda(x_g,i)/\partial x_g)dx_g/dt)(L_e + \partial\lambda(x_g,i)/\partial i)^{-1} \quad (5)$$

where, v is a velocity of the armature.

In order to investigate the unsteady compressible flow characteristics inside the solenoid valve, Navier-Stokes equations with Reynolds time averaging are solved by coupling with continuity and energy conservation equations. Ideal gas law is utilized for density calculation. The armature is assumed to be made of iron and its density is 7,870 kg/m$^3$. A standard *k*-ε turbulence model [15] is used for turbulence modeling. The *k*-ε turbulence model can provide independent transport equations for both the turbulence length scale and the turbulent kinetic energy.

## 3 Results and Discussion

Figure 3 and 4 shows the electromagnetic force acting on the armature according to current flow through the coil and the upstroke motion profiles of the armature due to the electromagnetic force. It can be found that the increase in the magnitude of the electromagnetic force has an effect of decreasing the rising time of the armature.



(a) 0.9A (b) 1.0A (c) 1.1A

**Fig. 3.** Electromagnetic force acting on the armature according to current flow through the coil

Based on the computed results using the finite element analysis, a sinusoidal function for the armature's upward motion (upstroke) is assumed for the numerical computations of the aerodynamic forces using computational fluid dynamics simulations.

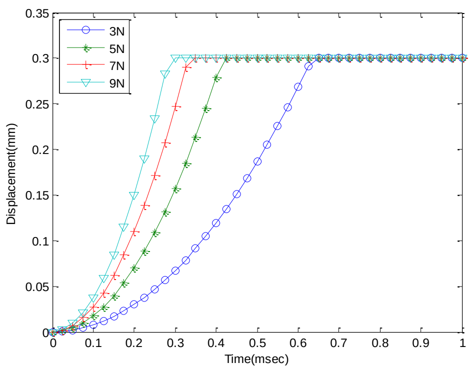


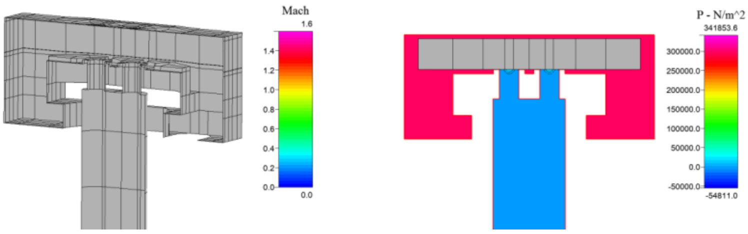

**Fig. 4.** Upstroke motion profile of the armature in the air gap according to electromagnetic force

$$z(t)=0.5D\sin(\omega t-\pi/2)+0.5D, \quad 0<t< T_1 \tag{6}$$

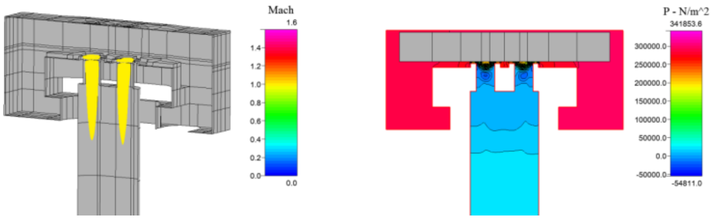
where, $\omega$ represents the angular frequencies and has the value of $\pi/T_1$. $T_1$ represents the time required for upstroke motion and $T_2$ means the free falling time. Thus, the total period for one cycle up and down motion of the armature is T which is the sum of $T_1$ and $T_2$ [16].

Figure 5 shows the unsteady compressible flow characteristics inside the solenoid valve due to the upward motion of the armature. Pressures at both inlet and outlet ports are set to 4 bar and 1 bar, respectively. Before t=0, as an initial volume condition, it is assumed that the air at the upper part of the armature has the same pressure as that at the inlet port, and the air at the lower part of the armature has the same pressure as that at the outlet port. As shown in Figure 5(a), there is no flow inside the valve. The pressure difference between the upper and lower surfaces of the armature is large. Thus, it can be said that a large electromagnetic force is required in order to move the armature up. As the armature moves up, the accelerated air flow just below the armature's lower surface reaches sonic speed and a supersonic flow region is generated. The expanded high speed air is, due to a back pressure at the outlet port, compressed again and makes a strong curved shock (see Figure 5(b)). After forming a strong curved shock, the compressed air decelerates in order to match its pressure to the exit pressure. When the armature reaches to the T.D.C (Figure 5(c)), the flow at the throat maintains sonic speed and the size of the supersonic flow region increases. It is expected that the required electromagnetic force for moving the armature up will decrease with the pressure differences between the upper and lower surfaces of the armature stepping down. In the region passing through the base, there still exists a very low pressure region owing to flow acceleration. Thus, after the armature approaches to the T.D.C, it falls down.

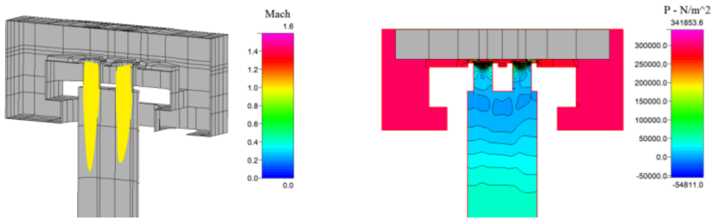
Figure 6 shows the effect of pressure differences between inlet and outlet ports on the falling motion profile of the armature. The upstroke time ($T_1$) is set to 0.5 milliseconds. As shown in Figure 6, the free falling time is decreased and operation frequency is increased with the inlet pressure stepping up.




(a) t=0 sec (bottom)

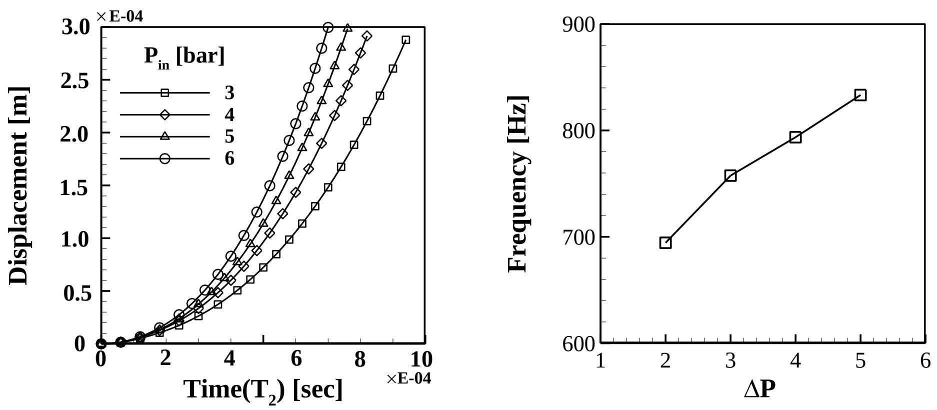



(b) t=2.5×10$^{-4}$ sec




(c) t=5.0×10$^{-4}$ sec

**Fig. 5.** The curved shock shapes and the pressure distributions.




(a) falling motion profile (b) operating frequency

**Fig. 6.** The falling motion profile and operating frequencies of the armature according to the change in the inlet pressures

## 4 Conclusions

Using the finite element analysis, the motion profiles of the armature is obtained for the given electromagnetic forces. With the obtained motion profiles, a sinusoidal upward motion of the armature is assumed and the three-dimensional unsteady compressible flow characteristics inside a high-speed solenoid valve are studied using computational fluid dynamics simulation with dynamics coupling capability.

From the study on the shock structures and pressure distributions due to the upward motion of the armature, it was found that, when the armature is moving up, flows inside the valve has following patterns: accelerating subsonic flow-choked flow at the throat-supersonic expansion-curved strong shock-decelerating subsonic flow. Comparing the motion profiles of the armature, it was also found that the free falling time is decreased and operation frequency is increased with the inlet pressure stepping up.

It is believed that present results can be used for the design of high-speed switching electromagnetic control valves. In future, the effect of the back pressure on the behavior of the motion profiles will be studied.

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