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Dynamic Characteristics of a Spool Valve Coupled with Electromagnetic and Mechanical Effects

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ABSTRACT

A spool valve as a flow direction control valve has usually been used in a hydraulic system. In recent years, some hydraulic actuator systems need high accuracy control of the spool valve in order to control the delivery precisely. For the reason, it is very important practically to know dynamic motion of the spool.

To analyze the dynamic characteristics of the spool valve, it is necessary to consider the dynamic motion of the spool. Springs, solenoids and working fluid, which is pressurized by the pump in the circuit, support the spool. The motion of the spool is governed complicatedly by pressure force, flow force, electromagnetic force and mechanical spring force acting on itself. As a result, it is difficult to analyze the dynamic motion of the spool, and therefore, any commercial code to calculate the dynamic characteristics of the spool valve dose not exist at present.

Final target of this study is to develop numerical code to predict precisely the dynamic motion of the spool valve. As the first step, dynamic characteristics of a spool valve coupled with electromagnetic and mechanical effects have been conducted in the present paper.

KEY WORDS

System Dynamics, Coupled Analysis, Spool Valve, Electromagnetic Analysis

Nomenclature

$\mathbf{A}$	:	Vector Potential	[Wb/m]
$\mathbf{B}$	:	Magnetic Flux Density	[T]
c	:	Damper Coefficient	[kg/s]
$\mathbf{F}$	:	Vector of Force	[N]
f	:	Force	[N]
$\mathbf{J}$	:	Current Density	[A/m^2]
k	:	Spring Coefficient	[kg/s^2]
m	:	Mass of the Conductor	[kg]
$\mathbf{n}$	:	Normal Vector	[m]
S	:	Surface of the Conductor	[m^2]
T	:	Maxwell stress tensor	[T^2]
$\mathbf{V}$	:	Vector of Velocity	[m/s]
V	:	Velocity of the Conductor	[m/s]
x	:	Displacement of the Conductor	[m]
ν	:	Reluctivity	[m/H]
σ	:	Electric Conductivity	[S/m]

INTRODUCTION

A spool valve as a flow direction control valve has usually been used in a hydraulic system. A spool in its valve is controlled by electromagnetic force. Therefore, it is necessary to predict behavior of the spool by analyzing dynamic characteristics of the spool valve.

As dynamic characteristics of the spool are affected by fluid force, electromagnetic force and mechanical force, the behavior of the spool is very complex. Hence, it is necessary to consider three forces as represented above to analyze completely the dynamic characteristics of the spool valve. However, any commercial codes to calculate the dynamic characteristics of the spool valve considering the above three forces dose not exist at present. So, it is important to establish a prediction way of dynamic behaviors of the spool valve coupled with the above three forces.

As the first step of the complete coupled analysis, the analysis coupled with electromagnetic system and mechanical system was carried out in this study. An electromagnetic field was three-dimensionally modeled by using a partial differential equation by the A-method. On the other hand, dynamic characteristics in a mechanical system were one-dimensionally modeled by using ordinary differential equations based on the Bondgraph method. In this paper, the following two steps were conducted to verify the coupled analysis;

(1) To develop an analysis code for an electro-magnetic field and to verify this program by comparing with the experimental results on a simple model.
(2) To establish a way coupling with the A-method and the Bondgarph method.
(3) A movable conductor which replaces the spool is connected to spring and damper. The behavior prediction of this conductor is simulated to verify the coupled analysis.

ANALYSIS METHOD

Analysis Method for Electromagnetic System

The electromagnetic analysis was carried out using the A-method. A vector potential is expressed as the following equation with a magnetic flux density.

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{1}$$

After Maxwell equations are transformed using Eq. (1), the governing equation for the electromagnetic field is shown by the following equation.

$$\nabla \times \left(\nu \nabla \times \mathbf{A}\right) = \mathbf{J} - \sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \left\{ \mathbf{V} \times \left(\nabla \times \mathbf{A} \right) \right\} \tag{2}$$

In the above equation, the second term of the right-hand side indicates an influence of eddy current. This term means that the eddy current is caused by a temporal change of the vector potential. And the third term of the right-hand side indicates an influence of speed electromotive force.

The left-hand side of Eq. (2) has a high degree of freedom. Solutions of the vector potential should be specified under the coulomb gauge condition, which it is usually necessary to constrain the vector potential. However, to consider the coulomb gauge condition is not necessary in this analysis because the magnetic flux density, which is obtained by the vector potential using Eq. (1), has the uniqueness.

In this analysis, a movable conductor which replaced a spool moves temporally. In order to realize this situation, it was necessary to change the shape of grids temporally. Therefore, Eq. (2) was transformed according to a curvilinear coordinates system. After that, discretization of the equation was carried out using the finite differential method. In addition, a way of backward difference was used for digitization of time.

Electromagnetic Force

In the present study, the electromagnetic force is obtained by Maxwell stress tensor. The tensor is expressed as follows;

$$T = \begin{bmatrix} {B_x}^2 - \frac{1}{2}\mathbf{B}^2 & B_x B_y & B_x B_z \\ B_y B_x & {B_y}^2 - \frac{1}{2}\mathbf{B}^2 & B_y B_z \\ B_z B_x & B_z B_y & {B_z}^2 - \frac{1}{2}\mathbf{B}^2 \end{bmatrix} \tag{3}$$

where, subscripts x, y and z indicate each direction in the coordinate system. Using this tenor, the force which is acting on the conductor is expressed as following equation.

$$\mathbf{F} = \nu_0 \int T \bullet \mathbf{n}\, \mathrm{dS} \tag{4}$$

The integration path of dS in the Eq. (4) is surface of the conductor. However, the magnetic flux density on this surface is apt to change steeply because the magnetic permeability has a big difference about hundreds times between the conductor and the air. Consequently, because accuracy of the force calculation which is derived from Eq. (4) depends on the integration path, the path needs to keep away from the conductor surface.

ELECTROMAGNETIC ANALYSIS FOR THE STATIC MODEL

Analysis Model

A calculation code developed for the electromagnetic field is verified using three-dimensional verification model which is proposed by Institute of Electrical Engineers of Japan (hereafter, Test-model). Figs. 1 (a) and (b) show the top view and the side view of the Test-Model, respectively. The unit in Fig. 1 is millimeter. Hatched areas indicate the conductor, the outline area indicates the coil area and the otherwise is the air area.

Analysis Condition

Analysis conditions are shown in Table 1. Here, the elative magnetic permeability of the conductor is constant. In order to achieve accurate force calculation, nonlinear electromagnetic analysis in which the reluctivity changes against B is required. However, the linear analysis was conducted in the present study because this study stands on the first stage. The difference between linear and nonlinear analyses will be clarified near future.

As the boundary condition, the vector potential should be equal to Zero at the infinite distance from the conductor. In this study, the calculation area sets up as an square one side of which is five times more than that of the conductor. And the boundary condition of the calculation area is $\partial \mathbf{A}/\partial \mathbf{n} = 0$. Consequently, the effect of the boundary condition was diminished and dose not influence to the calculation result. The number of calculation grids is 51*51*71 and shape of grids is unequally spaced grid.

Table 1 Parameters for Static Analysis

Parameters	Amount of Parameters
Current of Coil	3000 [AT]
Relative Magnetic Permeability of the Conductor	1000 [-]
Boundary Condition	$\partial \mathbf{A}/\partial \mathbf{n} = 0$
Number of Grid	51*51*71

Result

Figs. 2 and 3 show results of the magnetic flux density at x = 31.25 [mm], y = 31.25 [mm], z = 100 – 200 [mm] and x = 46.875 [mm], y = 60 [mm] z = 0 – 200 [mm], respectively. In these figures, the abscissa axis shows the distance in the z direction [m] and the ordinate axis shows the magnetic flux density [T]. The solid line means the calculation result and the rhombic symbols means experimental results[1].

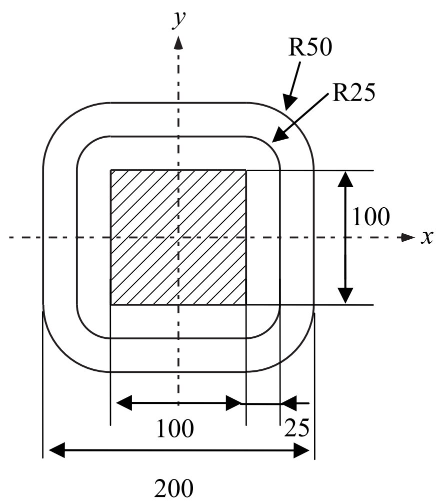
In Fig. 2, the calculation result on the magnetic flux density is a little higher than the experimental result. As the measurement point recedes from the conductor (as the value of z becomes bigger), the value of the magnetic flux density decreases. The calculation result and experimental result have the same tendency.

In Fig. 3, the calculation result is compared with the experimental result. These results have a little difference only at the z=100[mm], however, these results agrees well on the whole.

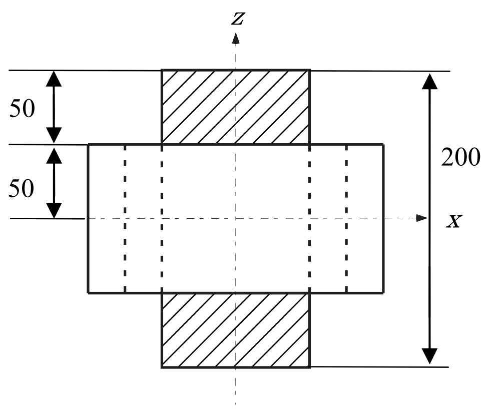
As the above discussion, the magnetic flux density of the calculation result and experimental result agree well, and the own-developed code is useful for the calculating the electromagnetic field.

ANALYSIS METHOD FOR MECHANICAL SYSTEM

The mechanical system was modeled by the Bondgraph method. This method is very convenient for modeling and simulation on various systems such



(a) Top View



(b) Side View

Fig. 1 Test Model for Static Analysis

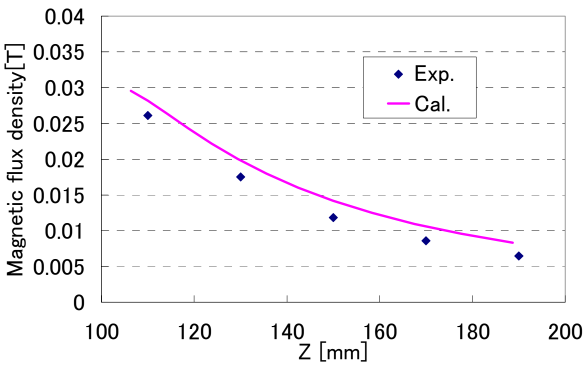


Fig. 2 Results at x=31.25[mm] y=31.25[mm]

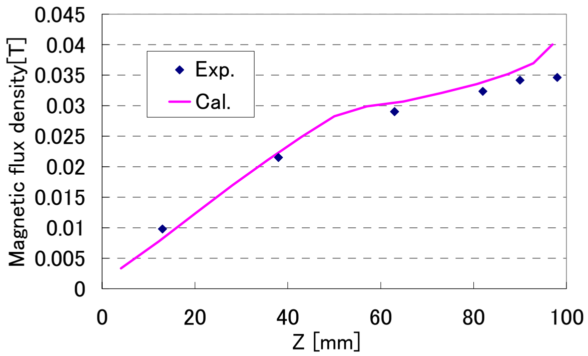


Fig. 3 Results at x=46.875[mm] y=60[mm]

as mechanical systems because the method is based on the power transmission. Fig. 4 shows the system Bondgraph model of Spring-Mass-Damper system which is a representative model of the mechanical system. In the figure, SF element corresponds to the wall velocity as the boundary condition, SE element to the external force similarly, I element to the inertia effect by the mass, R element to the energy loss at the damper, C element to the energy storage at the spring, respectively. Characteristic equations in the elements are shown in Table 2.

Table 2 Characteristic Equations

Elements	**Characteristic Equations**
SE	$f = electromagnetic\ \ force$
SF	$V = 0$
C	$f = k\int V\,\mathrm{dt}$
I	$V = \frac{1}{m}\int f\,\mathrm{dt}$
R	$f = cv$

In the Bondgraph method, state space equations of a system are derived by combining the relationships in Table 2. In this study the state space equations were calculated by Runge-Kutta method.

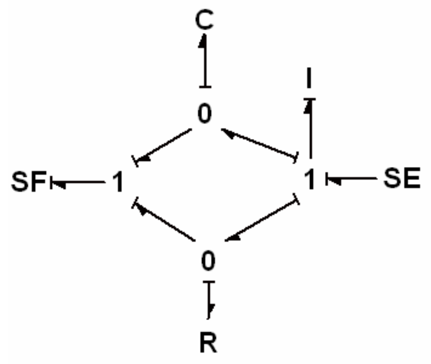


Fig. 4 Spring-Mass-Damper Model with Bondgraph

The final equations to be solved, which are derived from the Bondgraph method, are equal to the ordinary differential equation which is expressed by the following equation.

$$m\ddot{x} + c\dot{x} + kx = f \qquad (5)$$

Dynamic characteristics of the mechanical system can be calculated successfully by Eq. (5) with Runge-Kutta method. In the future study, however, coupled analysis program will expand relations of the dynamic characteristics of the system such as the oil-hydraulic systems after the coupled analysis with the fluid system will be completed. Therefore, mechanical system was modeled by the Bondgraph method which is easily applicable to many systems such as fluid and mechanical systems.

COUPLED ANALYSIS

Coupling Way

Fig. 5 shows a flow chart of the coupled analysis method with an electromagnetic system and a mechanical system. This flow chart is explained as follows;

First, the vector potential is calculated using Eq. (2). Next, the electromagnetic force working on the conductor which is derived from Eq. (4) is calculated. The calculated force is substituted into the mechanical system as an external force, which is equal to an effort variable of SE element in Fig. 4 and the dynamic characteristics of the mechanical system is calculated. After that, the displacement of the conductor, which corresponds to the displacement of I element in Fig. 4, is calculated from the numerical results in the Bondgraph method. The calculation grids for the electromagnetic field are restructured because the conductor moves in the distance equal to this displacement. Finally, the vector potential is calculated using Eq. (2). Iterating these steps, the analysis coupled with the electromagnetic system and the mechanical system could be carried out in the calculation of the dynamic characteristics of the spool valve.

Analysis Model

Fig. 6 shows the side view of the analysis model. The top view of the analysis model is the same as Fig. 1 (a). The unit of Fig. 6 is millimeter. The hatched areas indicate the conductor and the movable conductor. The outline area indicates the coil area and the otherwise is the air area. The size of the stationary conductor which is surrounded by the coil is 100*100*200. The size of the movable conductor which locates above the stationary conductor is 100*100*20. This movable conductor is constrained by the spring and the damper.

Analysis Condition

The movable conductor locates initially at the position which is shown in Fig. 6. The gap between the movable conductor and the stationary conductor is 20 [mm]. The movable conductor is fixed at this location until this analysis becomes steady. After this steady state is assumed to be the initial condition, the movable conductor can freely move.

The purpose of this analysis is to investigate the behavior of this movable conductor. The analyses were carried out under three kinds of conditions with different spring and damper coefficients. These conditions are shown in Table 3.

Table 3 Analysis Conditions

Parameters	Amount of Parameters
Time Step	1.0E-4 [s]
Current of Coil	3000 [AT]
Relative Magnetic Permeability of the Conductor	1000 [-]
Conductivity of the Conductor	1.03E+07 [S/m]
Number of Grid	51*51*81
Mass of the Conductor	1.56[kg]
Spring Coefficient	Case 1: 200[N/m]
	Case 2: 400[N/m]
	Case 3: 200[N/m]
Damper Coefficient	Case 1: 1.0[Ns/m]
	Case 2: 1.0[Ns/m]
	Case 3: 5.0[Ns/m]

Result and Discussion

Fig. 7 shows the displacement change of the movable conductor. The abscissa axis shows the time [s] and the ordinate axis shows the displacement [cm] of its conductor from the initial location. The solid line represents the result of Case 1, alternate long and short dash line the result of Case 2 and the dashed line the result of Case 3, respectively.

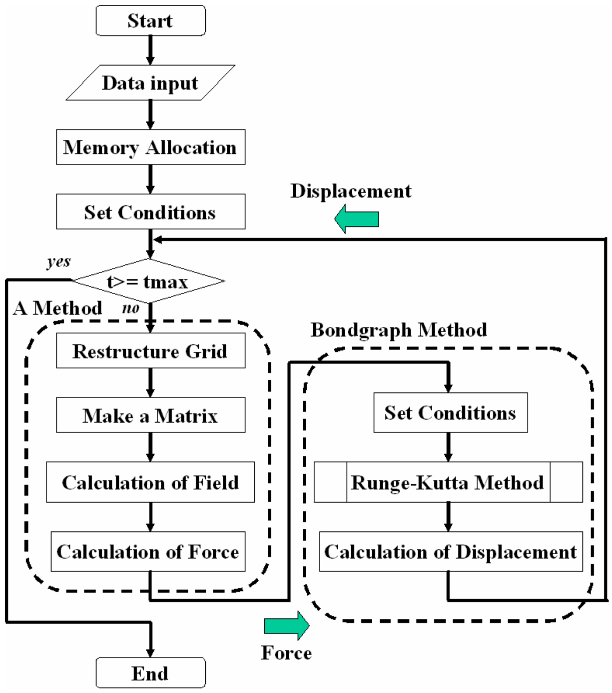


Fig. 5 Flow Chart of Coupled Analysis

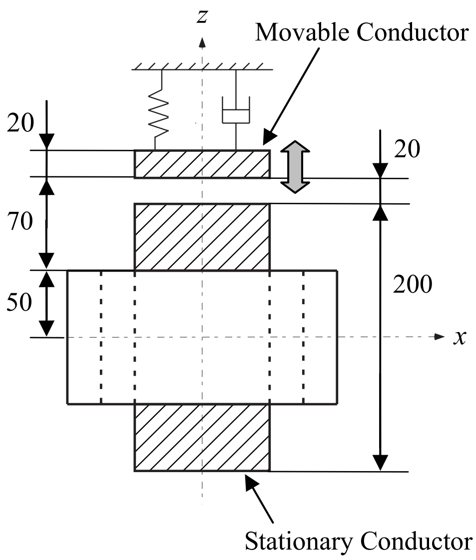


Fig. 6 Test Model for Coupled Analysis

Comparing results in Cases 1 and 2, the displacement in Case 2 is larger than that in Case 1. Because the spring coefficient in Case 2 is twice bigger than that in Case 1, the force in Case 2 which acts in the opposite direction by the spring force is stronger than that in Case 1. Additionally, comparing result of Cases 1 and 3, the both frequency is the same because the spring coefficient is the same. And the behavior of the movable conductor in Case 3 is more stable than that in Case 1 because the damper coefficient in Case 3 is larger than that in Case 1. So, it is considered that this result is reasonable.

Frequency of the movable conductor is around 4.0 or 4.5 [Hz] approximately in all cases. However, theoretical frequency of the conductor in Case 1 and Case 3, which is derived from the natural frequency of the mechanical system, is 1.8 [Hz] and that in Case 2 is 2.5 [Hz] without the influence of eddy current. The eddy current which is generated and changes time-dependently at the conductor causes this frequency increase.

Generally it can be considered that the eddy current causes frequency decrease of the movable conductor, although there is a referenced paper(2) that the natural frequency with eddy current becomes higher than that without eddy current. This feature would change according to the calculating conditions. It will become possible to explain the reason qualitatively after many parameter studies.

Fig. 8 shows the force working in *z* direction on the movable conductor. The abscissa axis shows the time [s] and the ordinate axis shows the electromagnetic force [N] working on the movable conductor. The negative and positive values indicate the repulsive force and the attractive force, respectively. The solid line represents the result in Case 1, the alternate long and short dash line the result in Case 2 and the dashed line the result in Case 3, respectively.

In this figure, the frequency of the force is around 4.0 or 4.5 [Hz] approximately in all cases. The frequency of the force in Fig. 8 corresponds to the frequency of the displacement in Fig. 7. In the analysis without the eddy current the frequency of the mechanical system changes according to the spring coefficient. However, in the coupled analysis, the frequency between in two cases with different spring coefficient was approximately same. This means that the effect of the eddy current was larger than that of the mechanical spring in this study.

When the movable conductor approaches the stationary one, the attractive force is decreased in all cases. Especially in Cases 1 and 3, the repulsive force was generated at the first vibration. On the other hand, when this movable conductor moves away from the stationary one, the attractive force was increased.

On the displacement of the movable conductor, its maximum displacement at the first vibration from the initial condition was 1.9 [cm] without influence of the eddy current and 0.7 [cm] with influence of the eddy current. The displacement was decreased by effect of the eddy current.

CONCLUSIONS

In order to establish the calculation method weakly coupled with mechanical and electromagnetic systems, the program has been own-developed and the dynamic characteristics has been performed on the test model.

The calculation result and experimental result agree well under the static condition without considering the eddy current. In the dynamic calculations, the reasonable fact was obtained that the displacement of the movable conductor was diminished by the eddy current.

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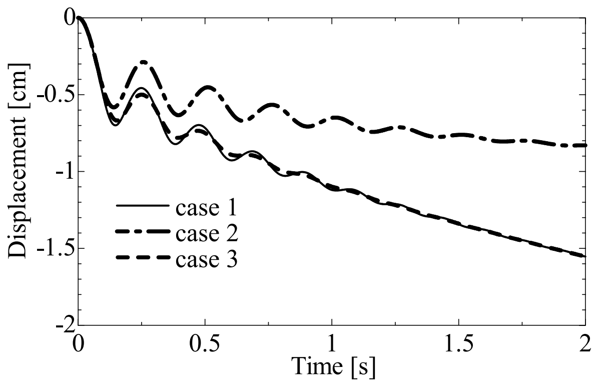

Fig. 7 Displacement of a Movable Conductor

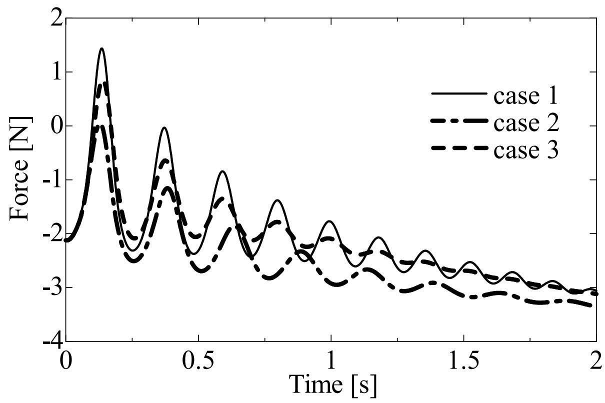

Fig. 8 Force Working on a Movable Conductor