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Simulation of the Dynamic Characteristics of a Pneumatic Circuit by OHC-Sim

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ABSTRACT

OHC-Sim is a simulation package for design of an oil-hydraulic circuit and analysis of its dynamic characteristics. To make the design and the improvement processes of an oil-hydraulic circuit more effective and systematic, OHC-Sim had been developed with the support of JFPS and has been enhanced in the research committee in JFPS. OHC-Sim is executable on personal computers in Windows® environment, and provides easy design and improvement of an oil-hydraulic circuit based on the simulated results. However, in order to enhance the use of OHC-Sim, it is desirable that the simulation of the dynamic characteristics of a pneumatic circuit becomes executable on OHC-Sim. In this study, to enhance OHC-Sim to the simulation of a pneumatic circuit, the bond-graph models for pneumatic components are discussed. And, by using the user-customized function, these bond-graph models are registered to OHC-Sim, and the simulation of dynamic characteristics of a pneumatic circuit is carried out.

KEY WORDS

OHC-Sim, Pneumatic circuit, Simulation, Dynamic characteristics, Bond-graph method

NOMENCLATURE

A : area of piston [m^2]
A_e : effective area [m^2]
C_P : specific heat at constant pressure [J/(kg・K)]
C_V : specific heat at constant volume [J/(kg・K)]
M : mass of air in a chamber [kg]
$\dot{m}$: mass flow rate [kg/s]
P : absolute pressure [Pa]
R : gas constant [J/(kg・K)]
T : absolute temperature [K]
t : time [s]
V : volume of a chamber [m^3]
v : piston velocity [m/s]
x : piston displacement [m]
κ : specific heat ratio

Subscripts

A : atmosphere
S : supply

INTRODUCTION

To make the design and the improvement processes of an oil-hydraulic circuit more effective and systematic, it is effective to predict the dynamic characteristics of the circuit beforehand by computer simulation. And then, it is necessary to derive the mathematical model for the circuit and to construct the program for computer simulation. Therefore, some exclusive simulation packages had been developed, which provide the environment where an oil-hydraulic circuit can be designed and improved easily based on the simulated dynamic characteristics without deriving mathematical models and constructing simulation program.

OHC-Sim (Oil-Hydraulic Circuit Simulation package) is one of such simulation packages, and had been developed in Japan with the support of JFPS (the Japan Fluid Power System Society, formally The Japan Hydraulics and Pneumatics Society) [1]. And it has been improved and enhanced in the research committee of JFPS [2]. OHC-Sim has a user-friendly graphical user interface in Windows® environment, and provides easy design and improvement of an oil-hydraulic circuit referring to the simulated results by personal computer. Furthermore, the first version of the user-customized function [3,4], which is based on bond-graph method [5,6], had been developed to make it possible to register the models for new oil-hydraulic components to the database of OHC-Sim. By the development of this user-customized function, it becomes possible to carry out the simulation of the dynamic characteristics of a complicated oil-hydraulic circuit or a water-hydraulic one [7] in OHC-Sim.

However, in order to enhance the use of OHC-Sim much more, it is desirable that the simulation of the dynamic characteristics of a pneumatic circuit becomes possible on OHC-Sim. To realize this, it is necessary to derive the bond-graph models for basic pneumatic components in the shape that these models can be handled with OHC-Sim. Moreover, it is required that the maintenance of the models registered in the database is easy.

Pneumatic circuits have compressible fluid-flow and thermal fields. In constructing the bond-graph model for such a circuit, true or pseudo bond-graph has so far been employed. In addition, two kinds of bonds, which represent both fluid power and thermal power, have been used, and multi-port C and multi-port R elements have been frequently used in the model as well [5,6,8]. Therefore, the resulting bond-graph models are complicated, and the maintenance of the models becomes troublesome when the models are in the database. In addition to it, when multi-port C and multi-port R elements are used in the model, it is necessary to modify the main body of OHC-Sim and simulation program BGSP for OHC-Sim so as to use them.

In this study, the bond-graph models for pneumatic components are derived by using 1-port C and 1-port R elements. In deriving the bond-graph model for compressible flow field, pseudo bond-graph, in which effort is absolute pressure and flow is mass flow rate, is employed so as to represent the continuity equation in the field easily. Furthermore, to confirm the usefulness of the proposed bond-graph models, the bond-graph models are registered to OHC-Sim by the use of the user-customized function and the simulation of dynamic characteristics of a pneumatic circuit is carried out.

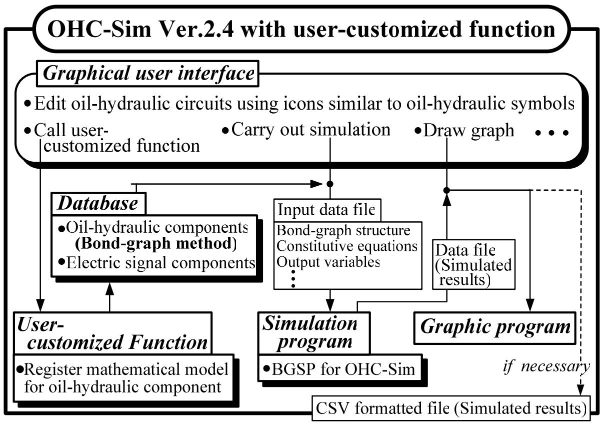


Figure 1 Basic structure of OHC-Sim

OUTLINE OF OHC-Sim

The basic structure of OHC-Sim is shown in Figure 1. OHC-Sim is an exclusive simulation package for design of an oil-hydraulic circuit and analysis of its dynamic characteristics, and it is executable on personal computers in all Windows® environments. In OHC-Sim, an oil-hydraulic circuit can be constructed on the display with ease by using graphical user interface and connecting oil-hydraulic component icons similar to oil-hydraulic symbols as shown in Figure 2. In this figure, SU1~SU4 are the components called sensor. This component is used to pick up the physical quantity such as pressure, discharge or displacement. And, by copy and paste of the sensor, the physical quantity sensed by the sensor can be utilized to represent a feedback loop or a pilot line. The mathematical models for components are registered in the database of OHC-Sim, and these models are represented by bond-graph method. Based on these models, the mathematical model for the oil-hydraulic circuit on the display is automatically created, and the simulation of the dynamic characteristics of the circuit is carried out. As simulation program, BGSP for OHC-Sim is employed. BGSP [9] is a simulation program based on bond-graph method, had been developed in Japan, and has obtained a number of fruitful results [10]. The simulated results can be confirmed easily and quickly on the display. In addition, OHC-Sim has a user-customized function. By using this function, users can register the mathematical models for their own oil-hydraulic components to the database. By

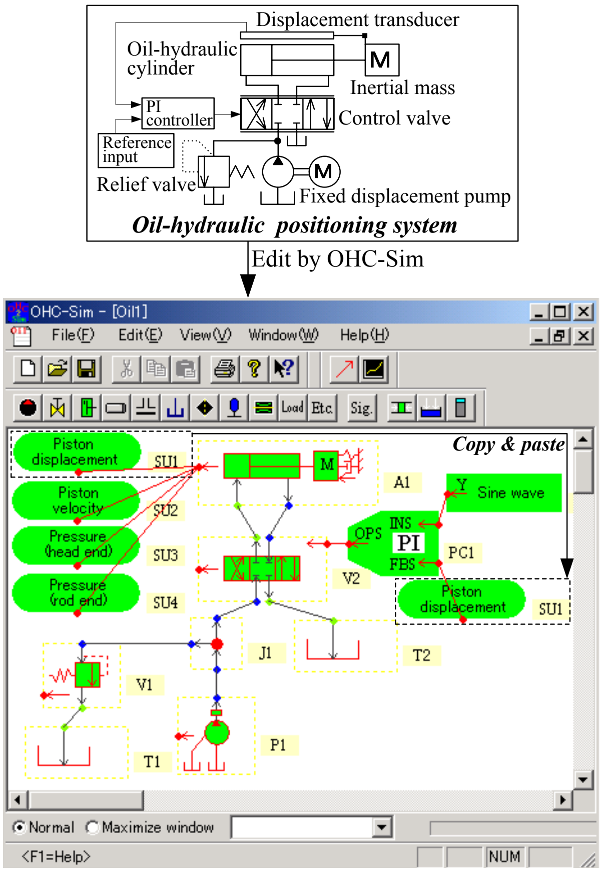


Figure 2 Edit of oil-hydraulic circuit by OHC-Sim

the development of this user-customized function, it becomes possible to carry out the simulation of the dynamic characteristics of a complicated oil-hydraulic circuit or a water-hydraulic one in OHC-Sim.

BOND-GRAPH MODEL FOR BASIC PNEUMATIC COMPONENT

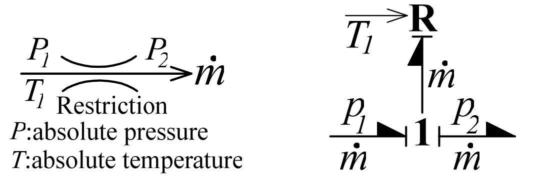
In this section, each bond-graph model for restriction and chamber of a pneumatic cylinder is derived. In constructing the bond-graph model for compressible flow field, pseudo bond-graph is employed, in which effort is absolute pressure and flow is mass flow rate. In mechanical field, true bond-graph is used, in which effort is force and flow is velocity.

Restriction

At a restriction shown in Fig. 3, the continuity equation yields

$$\dot{m}_1 = \dot{m}_2 = \dot{m} \tag{1}$$

where $\dot{m}_i$ (i=1,2) is the mass flow rate through cross sections 1 and 2 in Fig. 3, respectively.



(a)Restriction (b)Bond-graph model

Figure 3 Bond-graph model of restriction

The mass flow rate through the restriction can be expressed by Eq. (2) and (3).

$$0 \le \frac{P_2}{P_1} < 0.528$$

$$\dot{m} = A_e P_1 \sqrt{\frac{\kappa}{RT_1}\left\{\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}\right\}} \tag{2}$$

$$0.528 \le \frac{P_2}{P_1} \le 1$$

$$\dot{m} = A_e P_1 \sqrt{\frac{2\kappa}{\kappa-1}\frac{1}{RT_1}\left\{\left(\frac{P_2}{P_1}\right)^{\frac{2}{\kappa}} - \left(\frac{P_2}{P_1}\right)^{\frac{\kappa+1}{\kappa}}\right\}} \tag{3}$$

As can be seen from Eq.(1), flow $\dot{m}$ is equal at the restriction. And, from Eqs. (2) and (3), flow $\dot{m}$ is expressed as a function of effort P_1 and P_2. Therefore, the restriction can be represented by 1-junction and an R-element as shown in Fig.3 (b). In order to calculate mass flow rate $\dot{m}$ based on Eqs. (2) and (3), temperature T_1 is necessary. Therefore, temperature T_1 is inputted to R-element through the active bond which is denoted by full arrow and transmits a signal.

Chamber of pneumatic cylinder

In a head-end chamber of a pneumatic cylinder shown in Fig. 4, the heat transfer through a wall is assumed to be adiabatic to make the bond-graph structure simple. Then, the first law of thermodynamics yields

$$\frac{dU}{dt} = \dot{H} - P\frac{dV}{dt} \tag{4}$$

where U is the internal energy of air in the chamber of the pneumatic cylinder and $\dot{H}$ is the enthalpy flux through the control surface.

Internal energy U and enthalpy flux $\dot{H}$ are expressed as

$$U = C_V \rho V T \tag{5}$$

$$\dot{H} = C_P \dot{m}\, T^* \tag{6}$$

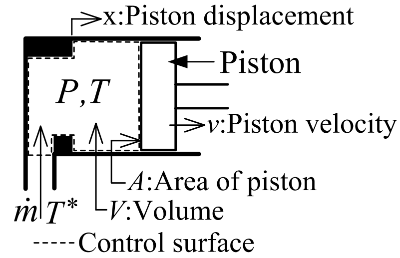


Figure 4 Head-end chamber of pneumatic cylinder

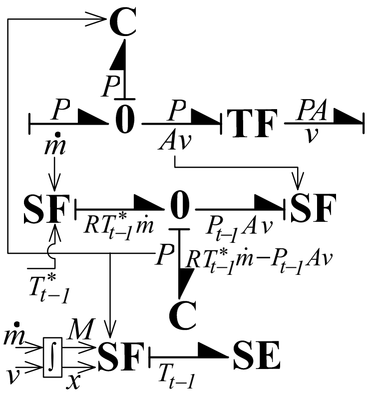


Figure 5 Bond-graph model for head-end chamber of pneumatic cylinder

where ρ is the density of air in the chamber and T^* is the temperature of air through the control surface.
Substituting Eqs. (5)-(9) into Eq. (4), we obtain Eq.(10).

$$C_P - C_V = R \tag{7}$$

$$C_V = \frac{R}{\kappa - 1} \tag{8}$$

$$\frac{dV}{dt} = Av \tag{9}$$

$$\frac{dP}{dt} = \frac{\kappa}{V}\left(R\dot{m}\,T^* - PAv\right) \tag{10}$$

Assuming that T^* and P in the right-hand side of Eq. (10) can be replaced with the values at one time step before the time, we get Eq. (11).

$$P = \frac{\kappa}{V_{H0} + Ax}\int\left(RT^*_{t-1}\,\dot{m} - P_{t-1}\,Av\right)dt + P_{H0} \tag{11}$$

where V_{H0} is the head-end chamber dead volume and P_{H0} is the initial pressure at the chamber.
As can be seen from Eq.(11), effort P can be determined by integrating flow $\dot{m}$ and v. And effort P is equal in the head-end chamber of the pneumatic cylinder. Hence,

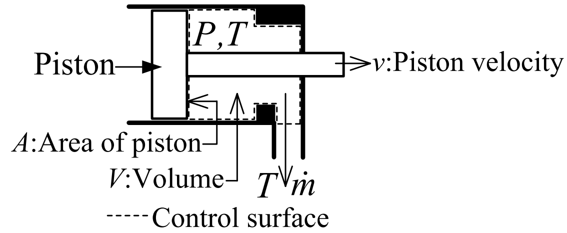


Figure 6 Rod-end chamber of pneumatic cylinder

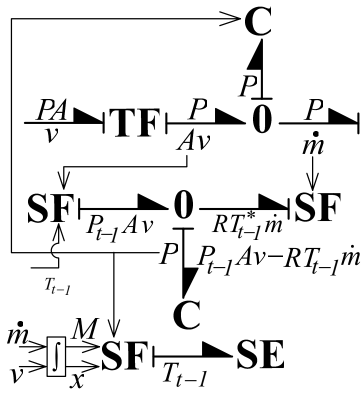


Figure 7 Bond-graph model for rod-end chamber of pneumatic cylinder

the head-end chamber of pneumatic cylinder shown in Fig.4 can be modeled by a C-element and 0-junction as shown in Fig. 5. However, in order to calculate effort P from Eq. (11), two SF-elements and a C-element is employed. And then, this C-element is used as a mere integrator. Furthermore, to calculate the temperature of air in the head-end chamber of pneumatic cylinder from Eq. (12), an SF-element and an SE-element are employed as a mere calculator. And then, the flow of the bond between these elements represents the temperature of air in the head-end chamber of pneumatic cylinder at one time step before the time.

$$T = \frac{PV}{MR} \quad , \quad T_{t-1} = T \tag{12}$$

Similarly, the pressure at the rod-end chamber of a pneumatic cylinder shown in Fig. 6 can be determined by Eq. (13).

$$P = \frac{\kappa}{V_{R0} - Ax}\int\left(-RT_{t-1}\,\dot{m} + P_{t-1}\,Av\right)dt + P_{R0} \tag{13}$$

where V_{R0} is the volume of the rod-end chamber when piston displacement x is equal to 0.
As seen from Eq.(13), effort P can be calculated by

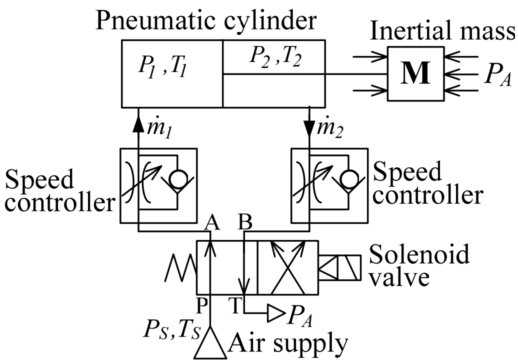


Figure 8 Pneumatic circuit

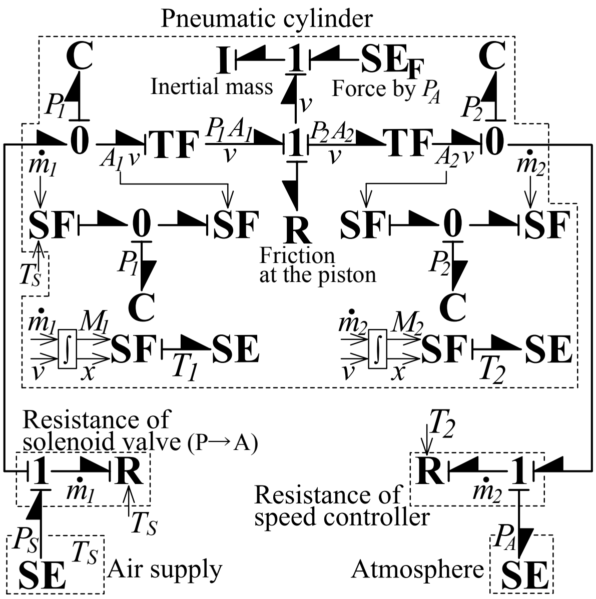


Figure 9 Bond-graph model for pneumatic circuit

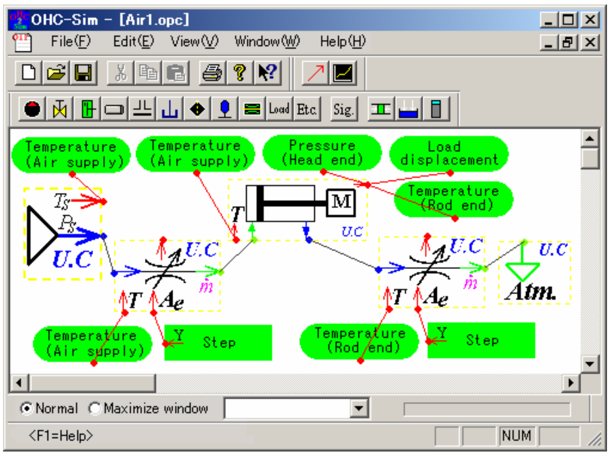


Figure 10 Edit of pneumatic circuit in OHC-Sim

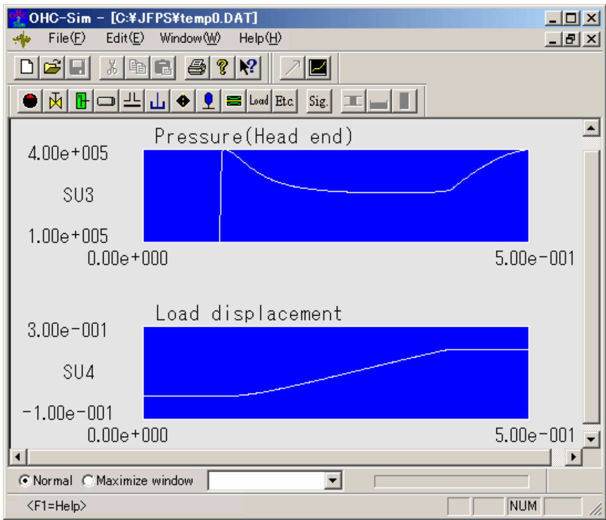


Figure 11 Simulated results

integrating flow $\dot{m}$ and v. And effort P is equal in the rod-end chamber of the pneumatic cylinder. Therefore, the rod-end chamber of pneumatic cylinder can be represented as shown in Fig. 7. Then, it should be noted that the temperature of air in the rod-end chamber is used in calculating the pressure of air in the chamber by Eq. (13).

SIMULATION OF DYNAMIC CHARACTERISTICS OF PNEUMATIC CIRCUIT BY OHC-Sim

In oeder to show the usefulness of the above-mentioned bond-graph models, the simulation of the dynamic characteristics of the pneumatic circuit shown in Fig. 8 was carried out. The bond-graph model for the circuit is shown in Fig. 9. Since the pressure and the temperature of air at the air supply are considered to be constant, the air supply can be modeled by an SE-element. When the flow through the solenoid valve or the speed controller located at the rod end of the pneumatic cylinder is assumed to be similar to that through the restriction shown in Fig.3, each valve can be regarded as an R-element. Then, the resistance of the speed controller includes the resistance between B-port and T-port of the solenoid valve. The pressure and the temperature of the atmosphere are constant. Therefore, the atmosphere can be represented by an SE-element.

The bond-graph model shown in Fig. 9 for each pneumatic component was registered to OHC-Sim by using the user-customized function. Figure 10 shows the pneumatic circuit constructed in OHC-Sim. To calculate the mass flow rate through the solenoid valve or the speed controller and the pressure at the head-end chamber of the pneumatic cylinder, the temperature at the upstream component is necessary. Therefore, the temperature is inputted to these components by copy and paste of the sensor sensing the temperature at the air supply or the rod-end chamber of the pneumatic cylinder.

Figure 11 shows the simulated results of the dynamic characteristics of the pneumatic circuit in the case where the P-port is connected to the A-port of the solenoid valve at time 0.1s. As a result, it is shown that the simulation of the dynamic characteristics of a pneumatic circuit becomes possible on OHC-Sim by using the proposed bond-graph models.

CONCLUSIONS

The bond-graph models for pneumatic components were derived, which were composed of 1-port C element and 1-port R-element. Furthermore, in order to investigate the usefulness of the proposed bond-graph models, these models were registered to OHC-Sim by using the user-customized function, and the simulation of dynamic characteristics of a pneumatic circuit was carried out. Consequently, it was shown that the simulation of the dynamic characteristics of a pneumatic circuit became possible on OHC-Sim by adopting the proposed bond-graph models without modifying OHC-Sim. It is a great merit that the modification of OHC-Sim is not necessary when the proposed bond-graph models are employed in the modeling of pneumatic components. Next step will be to confirm the validity of the simulated results on OHC-Sim by comparing the simulated results with the experimental ones in various pneumatic circuits.

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