Computer aided hydraulic circuit design system using bondgraph symbols

Selection and Estimation of Pipeline Models

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ABSTRACT

Selection and estimation of Bondgraph models in simulation process for a developed expert system are discussed. Simple Bondgraph models for hydraulic pipelines are presented and dimensionless transfer matrices for the pipeline models are derived and compared with the distributed parameter models including Bessel functions in frequency domains. A correlation coefficient in frequency domains between the distributed parameter modes and the simple Bondgraph models is introduced into the quantitative estimation of the pipeline models for an index. By introducing the correlation coefficient, selection and estimation of pipeline models make it easy for nonprofessional persons to perform the process to be repeatedly executed as modifying components of a hydraulic circuit.

KEYWORDS

Bondgraph, Computer simulation, Distributed parameter model, Expert system, Hydraulic pipeline

NOMENCLATURE

\( c \) = speed of sound in pipeline  
\( j \) = complex variable  
\( K^*_i \) = dimensionless parameter \((=Lr/cr^2)\)  
\( J_0, J_1 \) = Bessel functions of the 1st kind  
\( L \) = length of pipeline  
\( P_i, P_o \) = inlet and outlet pressure  
\( Q_i, Q_o \) = inlet and outlet flowrate  
\( R_b \) = correlation coefficient  
\( r \) = radius of pipeline  
\( s \) = Laplace operator  
\( Z_c^* \) = characteristic impedance  
\( \Gamma^* \) = propagation operator  
\( \nu \) = kinematic viscosity of oil  
\( \rho \) = density of fluid  
\( \omega^* \) = dimensionless angular frequency \((=\omega r^2/\nu)\)

INTRODUCTION

Computer simulations are widely used in hydraulic circuit design. The availability of dynamic simulation packages; BGSP[5], HASP[6], BATHfp[7], CATSIM[8], DSH[9], HOPSAN[10], OHCS[4], etc., have provided the area of fluid power control with powerful tools to assist in the design and analysis of highly efficient. The process of designing hydraulic circuits, as shown in Figure 1, may be divided into four stages[4]; circuit design; components selection; analysis of the circuits; and inspection of completed drawings. In these four stages, the static and dy-
Dynamic analysis of the hydraulic circuits has been investigated in a traditional numerical simulation program. The stages of components selection and inspection of drawing are entrusted to specialists. Computer simulation plays an important role in evaluating and predicting the dynamic characteristics of hydraulic systems. However, how to select and estimate appropriate simulation models for practical hydraulic components are also important processes in designing hydraulic circuits for engineering tasks. The simulation process is generally characterized as the process to be repeatedly executed as modifying simulation models for practical hydraulic components until a senior designer is satisfied with the result. The designer depends upon his intuition or experience for the selection of models. In particular, dynamic characteristics of hydraulic pipeline have a significant influence on the system performance, so the model selection for the pipeline is the most important problem for professional or nonprofessional persons.

The authors[12][13] have developed a computer aided hydraulic circuit design system with artificial intelligence, in which hydraulic circuits using Bondgraph symbols are automatically drawn. In this report, a method of selection and estimation for pipeline models for the developed expert system are proposed and discussed.

DEVELOPED EXPERT SYSTEM

The expert system developed by the authors[12][13] uses a knowledge representation known as frames. A frame is a group of attributes which describes a given object. Figure 2 shows a organization of the developed hydraulic circuit design system. The system consists of a knowledge base which are framed by hierarchy structures of the hydraulic circuit representation using Bondgraph and an inference engine using Lisp functions.

The knowledge base provides an object-oriented database which contains the specifications of the hydraulic components and procedures of Bondgraph model selection and formation. Figure 3 shows a frames-based knowledge base for pipeline models. The use of frames assumes that the knowledge is represented in blocks of data. Each block of data in a frame has the capability of housing specific values about the data, rule or declaration, and procedural information. Each frame is linked together. This linkage gives rise to inheritance. An advantage in using frames is related information, i.e. rules for model selections, can be used repeatedly without the development of repetitive blocks of knowledge data.

The Lisp functions for the inference engine used by the authors are written by the HyperLispEX[11] which runs on MS-DOS for personal computers. These functions are written in Japanese,
HYDRAULIC PIPELINE MODEL

Distributed parameter model

A distributed parameter model of a uniform rigid fluid pipeline with laminar flow and considering unsteady velocity distribution over the cross section, as shown in Figure 4, can be expressed in the following two-port dimensionless matrix form in frequency domain [1]:

\[
\begin{pmatrix}
P_a^*(s^*) \\ Q_a^*(s^*)
\end{pmatrix} = \begin{pmatrix}
\cosh \Gamma^*(s^*) & Z_c^* \sinh \Gamma^*(s^*) \\
\frac{1}{Z_c^*(s^*)} \sinh \Gamma^*(s^*) & \cosh \Gamma^*(s^*)
\end{pmatrix}
\begin{pmatrix}
P_d^*(s^*) \\ Q_d^*(s^*)
\end{pmatrix}
\]  
(1)

where \( \Gamma^*(s^*) \) and \( Z_c^*(s^*) \) are the dimensionless propagation operator and the dimensionless characteristic impedance for the pipeline respectively, and defined as follows:

\[
\Gamma^*(s^*) = K_i^* s^* \left( 1 - \frac{2J_1(j\sqrt{s^*})}{j\sqrt{s^*} J_0(j\sqrt{s^*})} \right)^{-1/2} 
\]  
(2)

\[
Z_c^*(s^*) = \left( 1 - \frac{2J_1(j\sqrt{s^*})}{j\sqrt{s^*} J_0(j\sqrt{s^*})} \right)^{-3/2} 
\]  
(3)

The distributed parameter model of the hydraulic pipeline given in Eq.(1)-(4) has given sufficiently accurate responses in both frequency and time domains demonstrated by various authors [1]-[3]. But the solution of these equations contains Bessel functions, so it needs troublesome calculations in time domains.

Bondgraph models

Bondgraph [15] is one of the most useful graphic representation for modeling the fluid power systems, because Bondgraph symbols represent a system from the viewpoint of energy flow. And moreover, numerical computing using a lumped parameter model such as Bondgraph are easily carried out in time domains.

Margolis and Yang [16], Lebrun [17] developed the modal Bondgraph representations using a modal approximation technique for fluid transmission lines, but the modal Bondgraph model is complexity for nonprofessional persons. Therefore, the hydraulic circuits using the modal Bondgraph symbol have been constructed by the senior designer.

From the viewpoint of an efficient design, it is desirable that the selected model is as simple as possible. Nine kinds of simple Bondgraph models (Model No.1-No.9n as shown in Table 1 [14]) for hydraulic pipelines are assumed by coupled Bondgraph
of the pipeline models for an index. A degree of agreement between the selected model and the exact model are estimated by the value of the correlation coefficient $R_b$ as follows:

$$R_b = \frac{\sum_{i=0}^{n} |x_e(\omega_i)| \cdot |x_b(\omega_i)|}{\sqrt{\sum_{i=0}^{n} |x_e(\omega_i)|^2 \cdot \sum_{i=0}^{n} |x_b(\omega_i)|^2}}$$

where the two variables $x_e(\omega_i) (= \alpha_e(\omega_i) + j\beta_e(\omega_i))$ and $x_b(\omega_i) (= \alpha_b(\omega_i) + j\beta_b(\omega_i))$ are complex representations for the frequency transfer functions of the exact model and the Bondgraph models within the range of discrete angular frequencies $\omega_i$ ($\omega_0 \leq \omega_i \leq \omega_n$) respectively. The inner product representation $(x_e, x_b)$ in Eq.(5) is defined as follows:

$$(x_e(\omega_i), x_b(\omega_i)) = \alpha_e(\omega_i)\alpha_b(\omega_i) + \beta_e(\omega_i)\beta_b(\omega_i)$$

As the value of the correlation coefficient $R_b$ is closer to unity, the selected Bondgraph model is more agreement with the exact model within the specific frequency range. If the specified allowance of the correlation coefficient is determined in advance, the simulation system make the decision of an appropriate model according to the information of the value of the correlation coefficient and can select the appropriate model automatically. The developed expert system on the process of model selection suggests users an appropriate Bondgraph model corresponding to the value of the correlation coefficient.

**Examples of estimation**

Simulation results for examples of a hydraulic circuit illustrates the validity of the proposed index.

A pipeline terminated by a blocked downstream end is firstly taken as an example. The frequency transfer function of the exact model for the pipeline is defined by the ratio of the pressure signal at the downstream side $P_d(\omega^*)$ to the pressure signal at the upstream side $P_u(\omega^*)$ as follows:

$$\frac{P_d(\omega^*)}{P_u(\omega^*)} = \frac{1}{\cosh \Gamma^*(\omega^*)}$$

where $\Gamma^*(\omega^*) = \sqrt{\frac{k}{\rho}}$.
Figure 5 Frequency characteristics of pipeline

Table 3 Correlation coefficient in Figure 5

<table>
<thead>
<tr>
<th>Freq. range, $\omega^*$</th>
<th>Model 8</th>
<th>Model 92</th>
<th>Model 93</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 — 100</td>
<td>0.993</td>
<td>0.999</td>
<td>0.992</td>
</tr>
<tr>
<td>10 — 300</td>
<td>0.076</td>
<td>0.129</td>
<td>0.502</td>
</tr>
<tr>
<td>10 — 800</td>
<td>0.075</td>
<td>0.109</td>
<td>0.304</td>
</tr>
</tbody>
</table>

Figure 5 shows the pressure responses of the blocked pipeline. In Figure 5, the blocked pipeline has a length of 2 m, a radius of 3 mm, a kinematic viscosity of 0.4 cm$^2$/s and a wave speed of 1300 m/s, respectively. The value of dimensionless parameter $K^*_i$ is $6.84 \times 10^{-3}$. In this case, unity hundred dimensionless angular frequency ($\omega^* = 100$) corresponds to 70 Hz in a real frequency. The solid line and the broken lines in Figure 5 represent the solution of the exact model and the Bondgraph models respectively. The correlation coefficients calculated by Eq.(5) within the range of the angular frequencies which are divided into ten in unity decade are listed in Table 3. Examination of these frequency characteristics has a tendency that the larger the number of the Bondgraph model becomes, the closer the resonant frequencies of the Bondgraph model get to the exact model. This tendency agrees with the order of the values of the correlation coefficients in Table 3.

The validity of the correlation coefficients for the index can be demonstrated more clearly to predict the responses of a hydraulic circuit model in time domain. The responses of the hydraulic circuit model blocked by the cylinder with a mass and a spring at the downstream side and connected to a constant pressure source at the upstream side of the pipeline, as shown in Figure 6, has been experimentally investigated by Muto, et al.[18]. The dimensions of the pipeline, fluid properties and the relevant system parameters used in the experimental study are presented in Table 4. The correlation coefficients calculated within the real frequency range of 0.1 Hz to 30 Hz are tabulated in Table 5. Figure 7 shows step responses of the cylinder stroke $x$ and downstream pressure $P_2$ comparing the experimental results[18] with the predicted responses using Model 6 and Model 95 in time domain. The responses of Model 95 are more agreement than those of Model 6 with the experimental results. Similar results are obtained during investigation of Model 92. These results also agree with the order of the correlation coefficients in Table 5.

The procedure of the estimation using the correlation coefficient for the index is introduced into our developed expert system. By introducing the index, the selection and estimation of the pipeline models make it easy for nonprofessional persons to perform the hydraulic circuit design process.
**Table 5** Correlation coefficient for pipeline

<table>
<thead>
<tr>
<th>Model No.</th>
<th>$R_b$</th>
<th>Model No.</th>
<th>$R_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 4</td>
<td>0.668</td>
<td>Model 92</td>
<td>0.938</td>
</tr>
<tr>
<td>Model 6</td>
<td>0.746</td>
<td>Model 93</td>
<td>0.978</td>
</tr>
<tr>
<td>Model 8</td>
<td>0.698</td>
<td>Model 94</td>
<td>0.988</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Model 95</td>
<td>0.989</td>
</tr>
</tbody>
</table>

**Figure 7** Step response of hydraulic circuit

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**CONCLUSIONS**

Selection and estimation of the simple Bondgraph models in simulation process are discussed. The correlation coefficient in frequency domains between the exact model and the Bondgraph models in introduced into the quantitative estimation of the pipeline for the index. The index is able to decrease the amount of time for hydraulic circuit designers.

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**REFERENCES**