JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
**45**, 1, pp. 171-177, Warsaw 2007

# FUZZY-PID CONTROL METHOD FOR TWO-STAGE VIBRATION ISOLATION SYSTEM

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The arithmetic of PID control is simple and the stability of it is good. However, the dynamic characteristics of PID control are poor. The fuzzy logic control method is flexible and adaptive. It does not rely on a mathematical model of the system and can deal with the nonlinearity of parameters and uncertain problems. However, the stability of fuzzy logic control is poor. In this paper, fuzzy logic control combined with PID control is applied to a two-stage vibration isolation system to improve the vibration isolation effectiveness. Simulation results show that the method is effective.

*Key words:* two-stage vibration isolation system, fuzzy-PID control, simulation

## 1. Introduction

Vibration and noise on ships is getting strong with the machinery getting high-speed, light and burdened. Damage caused by noise is serious and the significance of noise control is obvious. Firstly, noise control can improve the concealment capability and survivability of ships. Secondly, noise control can improve the detectability of sonars. Finally, noise control can ameliorate working conditions and enhance the efficiency of communication.

Previous researches showed that the descend slope of the transmission rate curve after a resonance peak of a single-stage vibration isolation system is 12 dB/oct when taking no account of elasticity of equipment, the middle block, the base and damping of the system. The same for a two-stage vibration isolation system is 24 dB/oct. The two-stage vibration isolation system is superior to a single-stage one by a higher frequency domain and it is widely used in ships that need noise elimination. However, the natural frequency of a two-stage passive vibration isolation system can not be designed to be very low, while considering the stability of the system. The vibration isolation effectiveness in the low-frequency domain is limited. An active vibration isolation system should be studied to improve the vibration isolation effectiveness (Shi *et al.*, 1990; Zhu and He, 1990).

At present, the active damping technology for vibration control, vibration absorbers and vibration isolation is intesively studied. The active vibration isolation method is being studied with the development of passive control theory and technology. It needs external energy. Active vibration isolation systems generally consist of feedback control which can track and control dynamic characteristics of the system. A active vibration isolation system developed in this paper can isolate low-frequency vibration.

The arithmetic of PID control is simple and its stability is good. However, the dynamical characteristic of it is poor. The fuzzy logic control method is a type of intelligent language control. It adopts manual control rules or rules established upon experts' experience and simulates logically consequent processes of human brain. It does not rely on the model of the system and can deal with the nonlinearity of parameters and uncertain problems. The fuzzy logic control method is flexible and adaptive, however, its stability is insufficient. In this paper, a fuzzy-PID controller is formed combining strong points of the two methods. Hence, the fuzzy-PID controller is applied to a two-stage vibration isolation system to improve its vibration isolation effectiveness (Sun *et al.*, 2002).

## 2. The model of active vibration isolation system

### 2.1. The principle of the system

The principle of the system is shown in Fig. 1. A machine $m_1$ is supported by two elastic elements in series. The machine is connected to the middle mass block $m_2$ by an oil cylinder. One end of the cylinder is fixed to the machine and the other end to the middle mass block. The inputs of the controller are the displacement $x_2$ and velocity $\dot{x}_2$ of the middle mass block, while the output is the control force $r$. In working conditions, when $m_1$ is excited by $f$, the middle mass block can be kept still under the force $r$. The second elastic element does not carry dynamic loads, so the acceleration of the base is zero. Simulation results show that the vibration isolation effectiveness of fuzzy-PID control is superior to that of fuzzy control and PID control separately (Li and Fu, 1997).

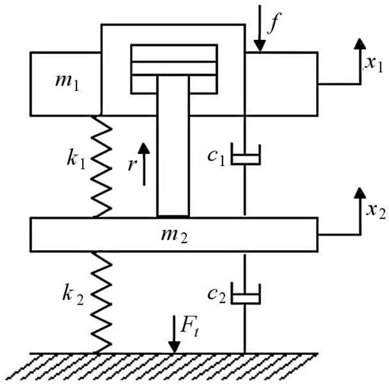


Fig. 1. The principle of the system

### 2.2. The mathematical model of the system

The equation of motion of the system shown in Fig. 1 is

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_1 & -c_1 \\ -c_1 & c_1+c_2 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1+k_2 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} r-f \\ -r \end{Bmatrix} \tag{2.1}$$

The equation of the system state is

$$\dot{\boldsymbol{X}} = \mathbf{A}\boldsymbol{X} + \mathbf{B}\boldsymbol{u} \tag{2.2}$$

where the state variable in (2.2) is

$$\boldsymbol{X} = [x_1, x_2, \dot{x}_1, \dot{x}_2]^\top \qquad \boldsymbol{u} = \begin{Bmatrix} r-f \\ r \end{Bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\dfrac{k_1}{m_1} & \dfrac{k_1}{m_1} & -\dfrac{c_1}{m_1} & \dfrac{c_1}{m_1} \\ \dfrac{k_1}{m_2} & -\dfrac{k_1+k_2}{m_2} & \dfrac{c_1}{m_2} & -\dfrac{c_1+c_2}{m_2} \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \dfrac{1}{m_1} & 0 \\ 0 & -\dfrac{1}{m_2} \end{bmatrix}$$

The displacement and velocity of the middle mass block are taken as the outputs

$$y_1 = \dot{x}_2 \qquad y_2 = x_2 \qquad \boldsymbol{Y} = \{y_1, y_2\}^\top$$

The output equation is

$$\boldsymbol{Y} = \mathbf{C}\boldsymbol{X} + \mathbf{D}\boldsymbol{u} \tag{2.3}$$

where

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix} \qquad \mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

## 3. Design of the fuzzy-PID controller

The fuzzy-PID controller is made up of a PID controller and a fuzzy controller. Because the stability of PID control is good and the dynamical characteristic of fuzzy logic control is good, a special controller is formed. When the error $e$ is small, the fuzzy controller does not work. When the middle mass block is far away from the equilibrium position and the error $e$ is large, both fuzzy and PID controllers will work. The PID control is assumed to be familiar to us, while the and fuzzy controller will be explained in detail.

The input and output variables of the controller are described by seven fuzzy values, that is, NL, NM, NS, ZE, PS, PM, PL. The range of the inputs is consistent with the biggest response of the middle mass block. The range of the output is $[-1000, 1000]$ N for the two-stage vibration isolation system brought forward below. The membership function is selected to be of Gaussian type, that is

$$\mu_{A_j^i}(x_j) = \exp\Big[-\frac{(x_j - x_j^i)^2}{\sigma_j^i}\Big] \tag{3.1}$$

where $\mu_{A_j^i}(x_j)$ is the membership function of $x_j$ $(j = 1, 2)$, $A_j^i$ is the fuzzy collection of the variable $j$ in the rule $i$ $(i = 1, \ldots, 49)$, $x_j^i$ is the centre of the membership function, $\sigma_j^i$ is the decentralization of the membership function (Sun *et al.*, 2002; Xu *et al.*, 2000).

The rules of fuzzy control and the method of consequence are regular. The rules of fuzzy control are listed in Table 1. The consequence methods used in the fuzzy logic control system are the following: the method is either minimum or maximum, the implication is minimum, aggregation maximum and the defuzzification is centroid.

Tabela 1. Rules of fuzzy logic

| $\dot{e}$ | $e$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | NL | NM | NS | ZE | PS | PM | PL |
| NL | PL | PL | PM | PS | PS | PS | ZE |
| NM | PL | PM | PS | ZE | PS | ZE | NS |
| NS | PM | PS | ZE | ZE | ZE | NS | NM |
| ZE | PM | PS | ZE | ZE | ZE | NS | NM |
| PS | PM | PS | ZE | ZE | ZE | NS | NM |
| PM | PS | ZE | NS | ZE | NS | NM | NL |
| PL | ZE | NS | NS | NS | NM | NL | NL |

## 4. Simulation and analysis

The two-stage vibration isolation system has two natural frequencies in ideal conditions. The vibration isolation effectiveness in the frequency domain between the two natural frequencies is poor. The distribution of masses and stiffness of the system should be adjusted so that the interval between the two natural frequencies is as small as possible. The parameters of the experimental equipment are as follows (Xu *et al.*, 2000), $m_1 = 105.42\,\mathrm{kg}$, $m_2 = 59\,\mathrm{kg}$, $k_1 = 5.7 \cdot 10^5\,\mathrm{N/m}$, $k_2 = 1.9 \cdot 10^6\,\mathrm{N/m}$, $c_1 = 0.1$, $c_2 = 0.1$. The two natural frequencies of this system are 10.1 Hz and 33.1 Hz.

The experimental equipment is simulated using the MATLAB/Simulink package. The simulation modules of the fuzzy-PID control method for the two-stage vibration isolation system are shown in Fig. 2 (Xue and Chen, 2002).

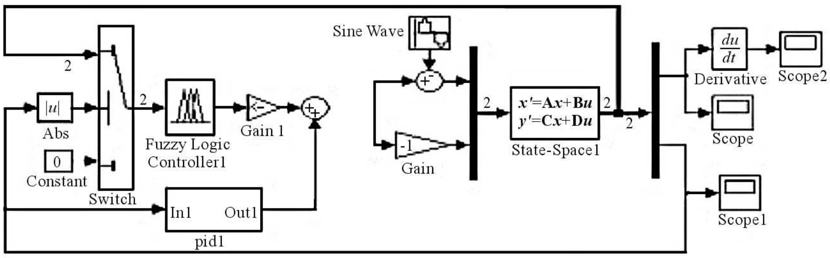


Fig. 2. Simulation of the fuzzy-PID control method

The vibration levels of the middle mass block before and after control are shown in Fig. 3. The acceleration response of the middle mass block for a sinusoidal excitation of 8 Hz are shown in Fig. 4.

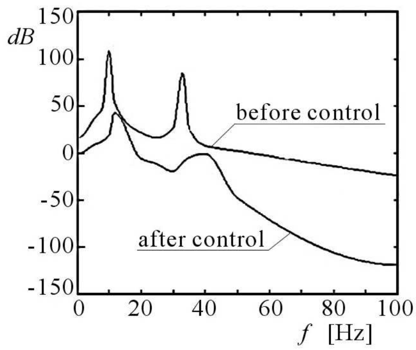


Fig. 3. Comparison of the acceleration level of the middle mass block

It can be seen in Fig. 3 that the vibration level of the middle mass block in full frequency domain is reduced, when the fuzzy-PID controller is used. The

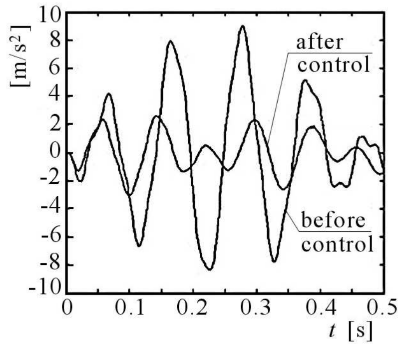


Fig. 4. Comparison of the acceleration response of the middle mass block

deficiency of vibration isolation effectiveness of the traditional passive two-stage vibration isolation system in the low frequency domain is eliminated. It can be also seen in Fig. 4 that the amplitude of the middle mass block is greatly reduced, and the stability of the system is improved. It can be induced that the fuzzy-PID controller can work well when the system is under multi-frequency excitation. Since the vibration of the middle mass block is reduced, the force transmitted to the base is greatly reduced and the concealment capability of ships is improved.

## 5. Conclusions and hints

The arithmetic of PID is simple and its stability is good. Fuzzy control is flexible and adaptive. It does not rely on a mathematical model of the system and can deal with nonlinear phenomena and uncertainty. The actual two-stage vibration isolation system is nonlinear and its precise mathematical model can not be built up. This paper makes use of the strong points of the two methods and formulates the design of a fuzzy-PID controller. Simulation results show that the method is effective.

The simple fuzzy controller has its weak points. The design of the fuzzy-PID controller does not rely on the mathematical model of the system, but it relies deeply on the experience and knowledge of experts and operators. When there is a shortage in the control experience, the final control effect is not as good as expected. Furthermore, the control rules of the fuzzy controller are not easy to be studied and adjusted. Contrarily, neural networks are easy to be studied and adjusted. Therefore, neural networks can be used to adjust control rules of the fuzzy controller online. Thus the adaptive capability of the fuzzy-PID controller may be obviously improved. This is the direction of further research.

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### Połączenie sterowania rozmytego z regulatorem PID w dwustopniowym układzie wibroizolacji


Streszczenie

Arytmetyka regulatora PID jest prosta, a jego stabilność dobra. Jednakże charakterystyki dynamiczne PID już tak korzystne nie są. Z drugiej strony, metody sterowania oparte na logice rozmytej są elastyczne i cechuje je duża zdolność adaptacyjna. Nie polegają one na ścisłym modelu matematycznym danego układu i dobrze sobie radzą z nieliniowościami parametrów i słabo zdefiniowanymi zagadnieniami. Niestety stabilność sterowania z logiką rozmytą jest niedostateczna. W pracy zaprezentowano rodzaj kombinacji metody logiki rozmytej z regulatorem PID zastosowanej do dwustopniowego układu izolacji drgań. Przeprowadzone symulacje pokazały efektywność takiego podejścia.


*Manuscript received August 3, 2006; accepted for print August 18, 2006*