Development of Active Vibration Isolation Equipments Using Fuzzy Method

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ABSTRACT

Vibration isolation equipments are mostly required in precise measurement and manufacturing system. Among all the vibration isolation equipments, air-spring is the most widely used equipment because of low resonant frequency and high damping ratio. In this study, we used Takagi-Sugeno fuzzy method to design an active vibration isolation system using air-spring, and compared the fuzzy method with passive control method and PID control method. Due to the non-linearity characteristics of air-spring, fuzzy controller was verified to be the most effective both in simulation and experiment.

Key Words : Active Vibration Isolation System, Air-spring, Fuzzy Logic Control, Takagi-Sugeno Method, PID Control

------------------ NOMENCLATURE ---------------

- A effective area
- C_r flow restriction constant
- g gravitation acceleration
- m_b mass flow rate of air into bottom chamber
- m_p payload mass
- m_t mass flow rate of air into top chamber
- n polytropic exponent
- P_b bottom chamber pressure
- P_t top chamber pressure
- Q_b volume flow rate of air into bottom chamber
- Q_t volume flow rate of air into top chamber
- V_b bottom chamber volume
- V_t top chamber volume
- x_b base displacement
- x_p payload displacement
- ω_0 natural frequency

1. INTRODUCTION

Vibration isolation system is mostly required to reduce vibration due to external disturbances and internal actuators in super-precision measurement and manufacturing system for semiconductor and display industry as shown in Fig. 1 Jin Hu Song[1] and Kyu Yong Kim[2] did the research on active control using proportional valve. Erin[3] introduced air-spring modeling and did experimental analysis while Hoque[4] proposed a 3 DOF vibration isolation system designed using mode-based controller.

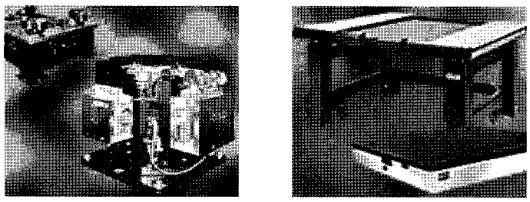

Fig. 1. Display equipment with vibration isolation table.

In our study, according to the non-linearity characteristics of air-spring, a fuzzy controller is designed using Takagi-Sugeno fuzzy method[5], and then through simulation and experiment, the results are compared with passive control method and PID control method.

2. NUMERICAL SIMULATION

2.1. Modeling of air-spring isolator

The modeling of air-spring isolator is shown in Fig. 2 which uses two air chambers connected by a small orifice[6]. As the load-plate moves up and down, air is forced to move through the orifice, producing a

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damping to be very strong for large displacement, while be weak for small displacement. This allows for fast settling of the payload, without compromising small amplitude vibration isolation performance. A payload which receives the load straightly and a diaphragm is also included in this modeling.

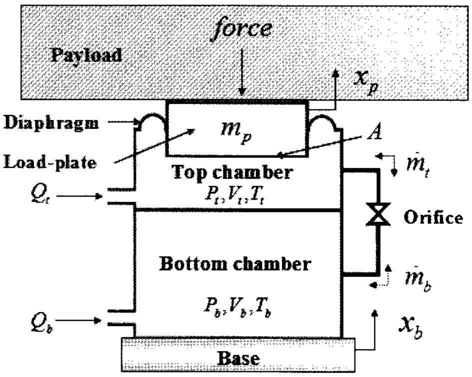


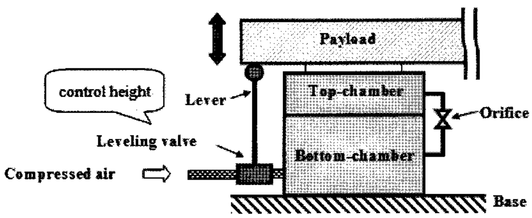
Fig. 2. Schematic diagram of air-spring.

The natural frequency of air-spring isolator is given by

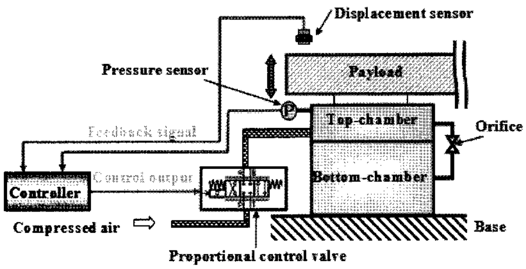
$$\omega_0 = \sqrt{\frac{nAg}{V}} \tag{1}$$

From Equation (1), we can conclude that the stiffness of the air-spring is dependent upon the height of the spring, but unlike steel coil spring, its natural frequency is nearly independent of the mass of the payload[7]. Consequently, if the load is changed but the pressure is adjusted to bring the payload back to the same operating height, then the natural frequency remains constant, which is highly desirable for vibration isolation table.

Fig. 3(b) is the schematic diagram of air-spring vibration control system using active control method. According to the large non-linear characteristics of air-spring, a feedback system with two loops is designed. Eddy current displacement sensor is used to measure the displacement of payload while pressure sensor is used to measure the pressure of the top chamber. All the feedback signals are introduced into the controller and then the output signal is imported to the proportional control valve to control the pressure of chambers because the top and bottom are connected by orifice. A proportional control valve is a



(a) Passive control system



(b) Active control system

Fig. 3. Schematic diagram of air-spring control system.

signal proportional to import and export volume of the pneumatic valves. It can be given for the importation of electrical signal proportional to the control pressure, flow and direction.

2.2. Fuzzy logic control

Fuzzy logic is much closer in spirit to human thinking and natural language than the traditional logical systems[8]. Basically, it provides an effective means of capturing the approximate, inexact nature of the real word. Therefore, the essential part of the fuzzy logic control (FLC) is a set of linguistic control strategy based on expert knowledge into an automatic control strategy. The relationship of all the components is shown in Fig. 4.

The Takagi-Sugeno (T-S) fuzzy model is a system described by fuzzy If-Then rules which can give local linear representation of the nonlinear system by decomposing the whole input space into several partial fuzzy spaces and representing each output space with a linear equation. For the reason that it employs linear model in the consequent part, conventional linear system theory can be applied for the system analysis and synthesis accordingly. And hence, the T-S fuzzy models are becoming powerful engineering tools for modeling and control of complex dynamic systems.

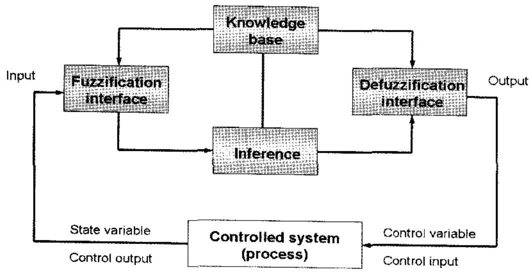


Fig. 4. Configuration of fuzzy control.

According to the system characteristics we make the fuzzy control rules that constitute 9 (3x3) rules shown in Table 1. Linguistic variables, such as Small, Medium, and Big are used to represent the domain knowledge. The final output of the system is the weighted average of all rule outputs, computed as

$$u = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \tag{2}$$

Table 1. Rule base using Sugeno method.

e \ $\dot{e}$	N	Z	P
N	N	N	P
Z	N	Z	P
P	N	P	P

Although fuzzy logic control is widely used for complex system and non-linear system, it is difficult to make the fuzzy control rules because it is dependent on expert experiences and engineering knowledge. And if you use too many fuzzy logic controllers, it will need expensive high capability signal processors. So in our study, PID controller is used to control the displacement feedback part, while due to the large non-linear characteristics of air, fuzzy controller using Sugeno method is used to control the pressure feedback part. In Fig. 5, you could see the one degree

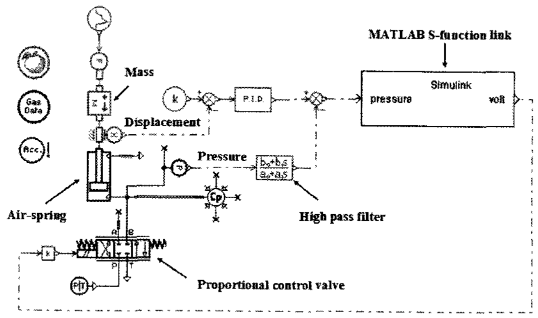


Fig. 5. Air-spring control system using AMESim.

freedom air-spring control system using AMESim. A high pass filter is designed here to cut off low frequency. MATLAB S-Function is used to design the fuzzy controller. The simulation result of this system is shown in Fig. 6. From the figure we could see that the fuzzy controller has more effective result than PID controller and no control.

2.3. Active vibration isolation system

2.3.1 Vibration isolation system modeling

Four air-springs are used to make up of a vibration isolation system. A moving mass which is 10% of the whole mass is used to give impulse. The whole 3 degree of freedom system modeling is shown in Fig. 7, which including z-dir, roll(θ_x) and pitch(θ_y). Four actuators are used to drive the corresponding air-springs, but because this system is a 3 degree of freedom system, two actuators are joined to moving

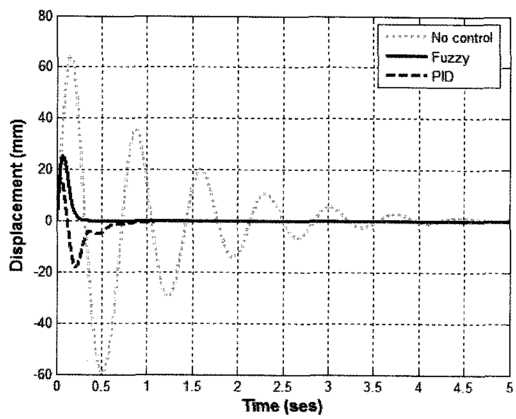


Fig. 6. Comparison among no control, PID and fuzzy control results of air-spring system with impulse response.

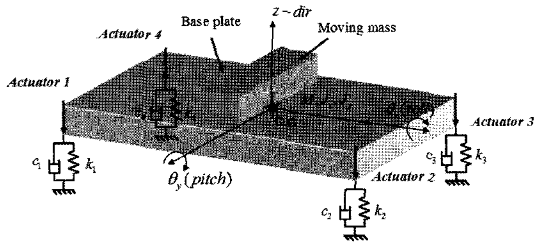


Fig. 7. Vibration isolation system modeling.

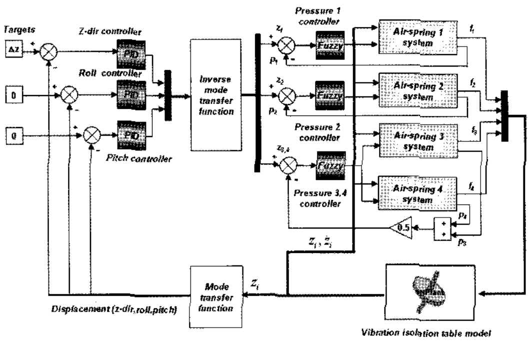


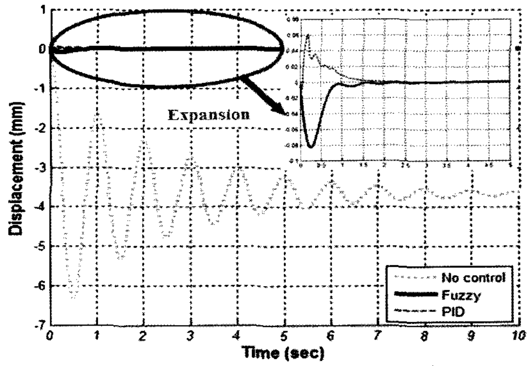
Fig. 8. Mode-based control system.

together as one.

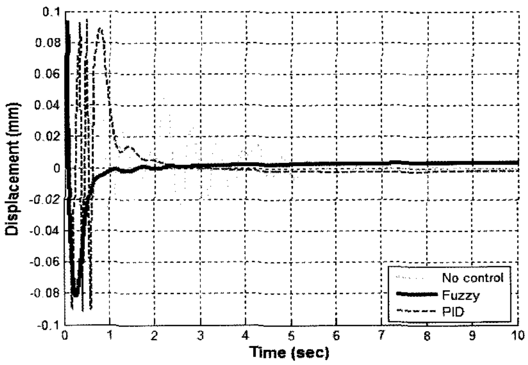
2.3.2. Active control system

In order to simulate the action of vibration system, a 3 degree of freedom system modeling is made using the rigid body analysis Visual Nastran software, then through the interface among MATLAB and AMESim, we could make up the whole control system. With four air-springs involved, there are several vertical vibration modes of the table on the support system. But we just consider the motions including vertical motion, pitch and roll. So the mode-based control system is shown in Fig. 8.

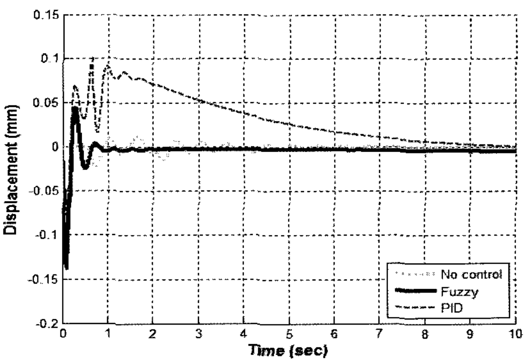
The same with the one degree system, PID controller is used to control the displacement feedback part while fuzzy controller to control the pressure feedback part. After giving an impulse, the response results, including z-dir, roll and pitch, among no control, PID control and fuzzy control could be seen in Fig. 9.



(a) Z-dir



(b) Roll



(c) Pitch

Fig. 9. Comparison of impulse response result.

3. EXPERIMENT

According to the designed system, vibration isolation is consisted using experiment setups shown in Fig. 10, including four air-springs and isolation table, while moving mass is 10% of the whole mass. DSP card is used to transfer the date to computer, while all the controllers are designed using MATLAB software. After giving an impulse to the vibration isolation table on z-dir, the impulse response and power

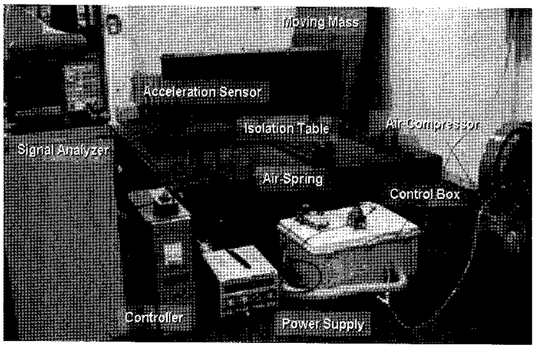
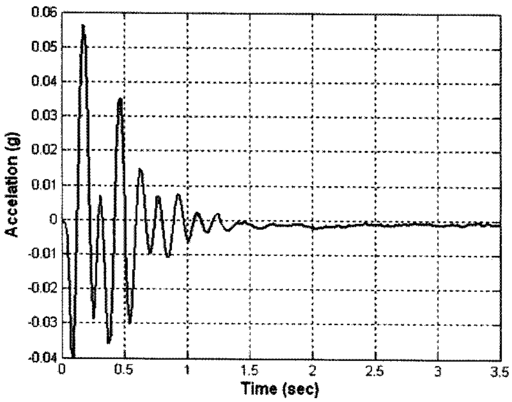
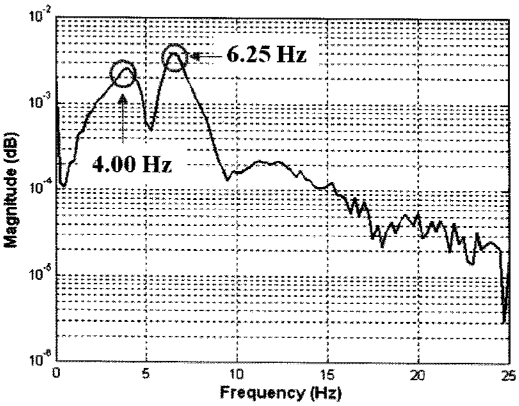


Fig. 10. Experiment setups.



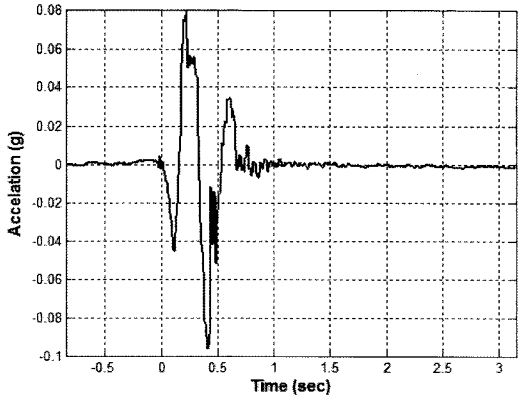
(a) Impulse response (z-dir)



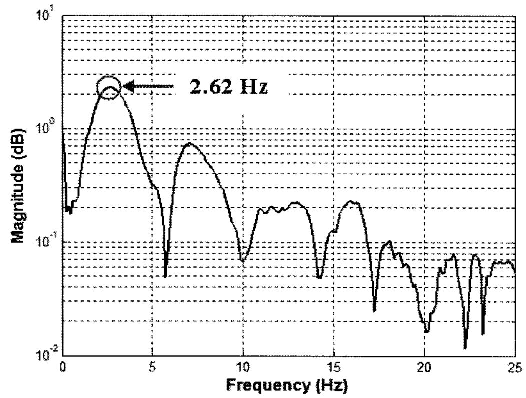
(b) Power spectrum (z-dir)

Fig. 11. Response of vibration isolation system using passive control method.

spectrum of the system could be measured through acceleration sensor and signal analyzer. The passive control and active control results are shown in Fig. 11 and Fig. 12 respectively. We could see that passive control method causes coupling vibration problem while fuzzy controller is more effective in view of natural frequency and settling time.



(a) Impulse response (z-dir)



(b) Power spectrum (z-dir)

Fig. 12. Response of vibration isolation system using fuzzy control method.

4. RESULTS AND DISCUSSIONS

The comparison result of vibration isolation system is shown in Table 2. From the table we could see that the natural frequency of passive control method remains high even though it costs less, while PID controller could only remain good result either on natural frequency or settling time according tuning gain. But fuzzy controller could get effective result both on natural frequency and settling time. Otherwise, fuzzy rules should be modified aftertime in order to get much better result at the same time.

Table 2. Vibration isolation system result.

Control Method	Natural frequency		Settling time	
	(Hz)	effect (%)	(Hz)	effect (%)
Passive control	4.00	0.0	1.7	0.0
PID control (gain tuning 1)	2.38	-40.5	2.0	+17.6
PID control (gain tuning 2)	3.10	-25.5	0.9	-47.5
Fuzzy control	2.62	-34.5	0.9	-47.5

5. CONCLUSIONS

In this paper, we have developed a vibration isolation system for display equipments, with good vibration isolation efficiency and effective position balance. Through numerical and experimental results, the developed control method using fuzzy controller has been verified to be the better effective.

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