퍼지 방법을 이용한 능동 방진 시스템의 개발

Development Of Active Vibration Isolation System Using Fuzzy Method

양손* · 안채헌** · 진경복*** · 임경화†

Xun Yang, Chae-Hun An, Kyoung-Bog Jin and Kyung-Hwa Rim

Key Words : Active Vibration Isolation System (능동 방진 시스템), Air-spring (공기스프링), Fuzzy Control (퍼지 제어), Takagi-Sugeno Method (Takagi-Sugeno 방법)

ABSTRACT

Vibration isolation equipments are mostly required in precise measurement and manufacturing system. Among all the vibration isolation system, air-spring is the most widely used equipment because of low resonant frequency and high damping ratio. In this study, Takagi-Sugeno fuzzy method is used 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.

요 약

최근 반도체 및 디스플레이 산업 등에서 초정밀 가공 및 측정에 방진 시스템을 많이 필요로 한다. 기존에 소개된 여러 방진 시스템 중에서 가장 많이 연구되는 공기스프링은 압축 공기를 이용하여 큰 하중을 지지할 수 있으면서 상대적으로 낮은 강성으로 낮은 고유진동수를 유지할 수 있다. 본 연구는 Takagi-Sugeno 퍼지 방법을 이용해서 능동 방진 시스템을 설계한다. 공기의 비선형 특성에 기인하는 복잡한 비선형 시스템 제어에 PID 제어기 보다 유리한 퍼지 제어기를 설계하였고, 실험과 해석을 비교하였다.

NOMENCLATURE

A effective area

C_r flow restriction constant

m_b mass flow rate of air into bottom chamber

m_p payload mass

Q_t volume flow rate of air into top chamber

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

V_b bottom chamber volume

V_t top chamber volume

x_b base displacement

ω_0 natural frequency

x_p payload displacement

† 책임저자, 한국기술교육대학교
E-mail : rim@kut.ac.kr
Tel : (041) 560-1209, Fax : (041) 560-1253

* 한국기술교육대학교 메카트로닉스공학부 대학원

** 한국기술교육대학교 메카트로닉스공학부 대학원

*** 한국기술교육대학교 메카트로닉스공학부

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. 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 three degree of freedom vibration isolation system designed using mode-based controller.

In our study, according to the non-linearity characteristics of air-spring, a fuzzy controller is designed using Takagi-Sugeno 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. 1 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 this orifice, producing a 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 are also included in this modeling.

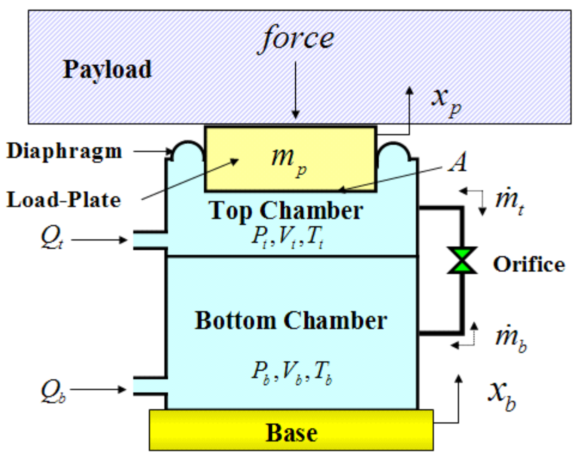


Fig. 1 Schematic diagram of air-spring

From the natural frequency of air-spring isolator equation showing as follows

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

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 system.

2.2 System structure

Four air-springs are used to make up of a 3 degree of freedom vibration isolation system shown as Fig. 2, 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 together as one. According to the large non-linear characteristics of air-spring, a feedback system with two loops is designed for active control method. 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 pressure of chambers because the top and bottom are connected by orifice. A proportional control valve is a 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.

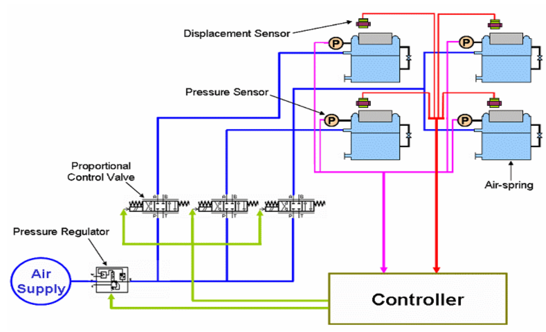


Fig. 2 Vibration isolation system structure

2.3 Fuzzy logic control

Fuzzy logic is much closer in spirit to human thinking and natural language than the traditional logical systems. ϑ Basically, it provides an effective means of capturing the approximate, inexact nature
of the real world. 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 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.

According to the system characteristics we make the fuzzy control rules that constitute 9 (3×3) 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 in the weighted average of all rule outputs, computed as

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

and from Fig. 3 we could see the surface of output.

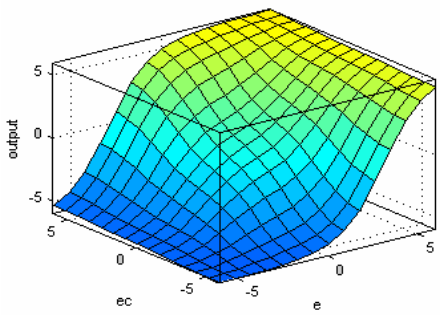


Fig. 3 Surface of output using Sugeno method

Table 1 Rule base using Sugeno method

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

2.4 Simulation results

(1) One degree of freedom system

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 Takagi-Sugeno method based on above is used to control the pressure feedback part. In Fig. 4, you could see the one degree 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. After giving an impulse to the payload, the simulation result of this system could be got shown as Fig. 5. From the figure we could see that the fuzzy controller has more effective result than PID controller and no control.

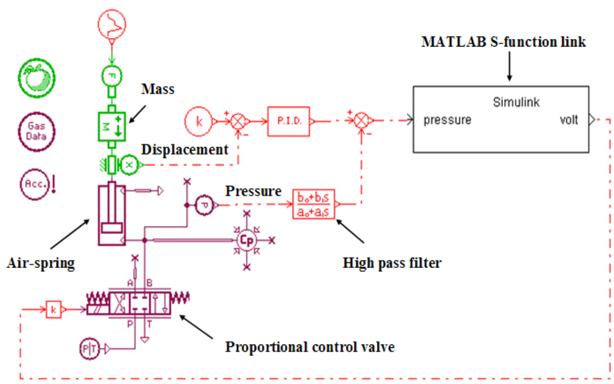


Fig. 4 Air-spring control system using AMESim

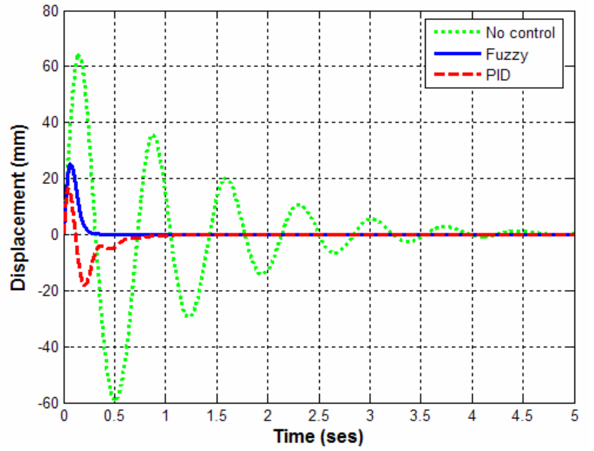


Fig. 5 Comparison among no control, PID and fuzzy control results of air-spring system with impulse response

(2) Three degree of freedom system

In order to simulate the action of vibration system, a three degree of freedom system modeling is made using the rigid body analysis Visual Nastran software, then through the interface among MATLAB and AMESim, the whole control system could be made up shown as Fig. 6. Two air-springs are designed as one in order to constitute three degree of freedom system.

The same with the one degree system, PID controller is used to control the displacement feedback part while fuzzy controller using Sugeno method 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. 7.

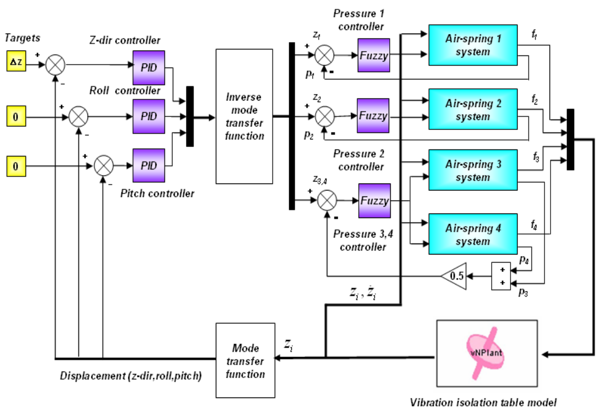
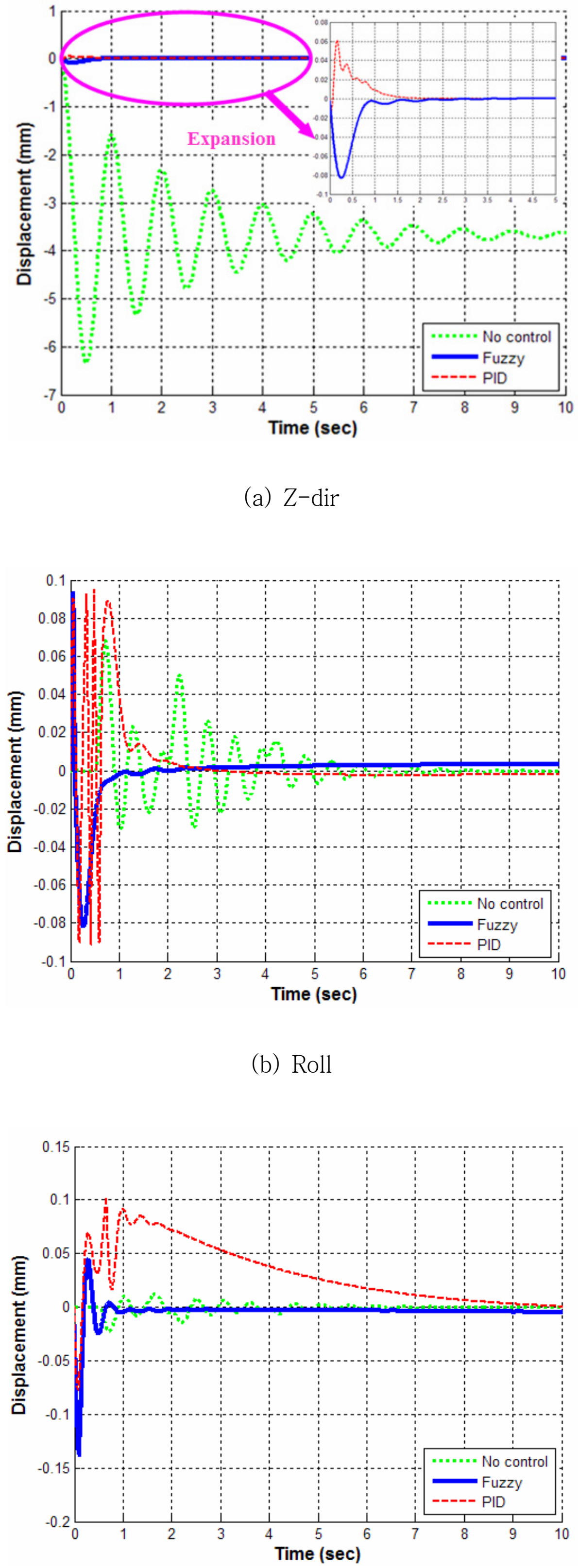


Fig. 6 Mode-based control system



(a) Z-dir

(b) Roll

(c) Pitch

Fig. 7 Comparison of impulse response result

3. Experiment results

According to the system design, vibration isolation system is consisted using experiment setups shown in Fig. 8. After giving an impulse to the vibration isolation table on z-dir, the impulse response and power spectrum of the system could be measured through acceleration sensor and signal analyzer. The passive control and active control results are shown in Fig. 9 and Fig. 10 respectively, while comparison result of vibration isolation system is shown in Table 2. The developed vibration isolation system using fuzzy controller is found to be very effective in view of natural frequency and settling time.

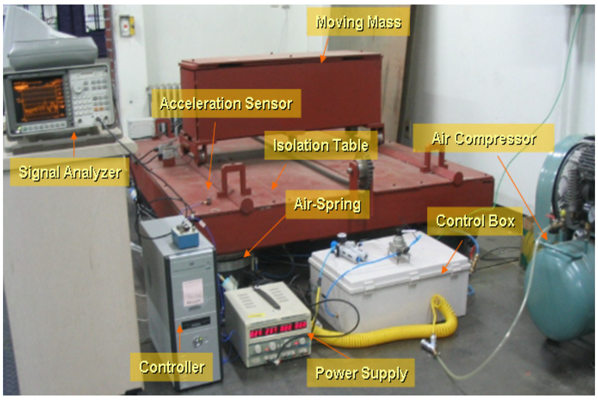
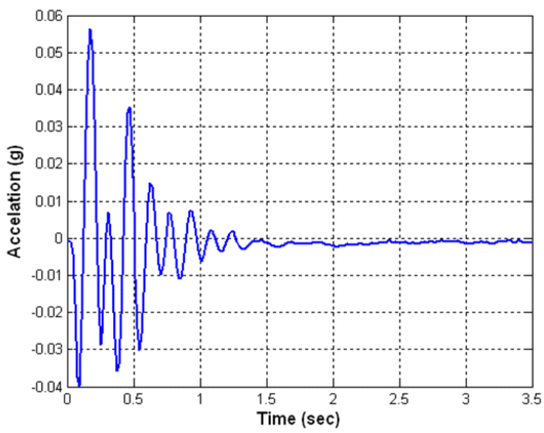
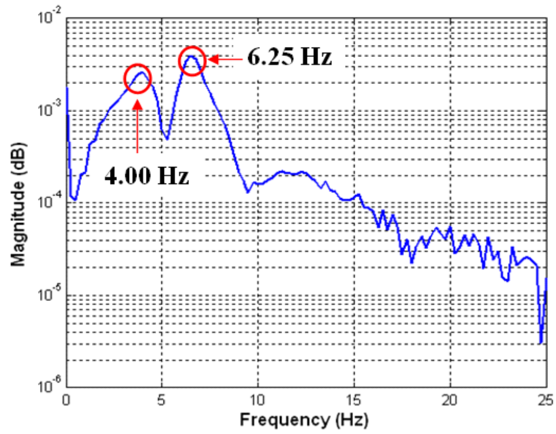


Fig. 8 Experiment setups

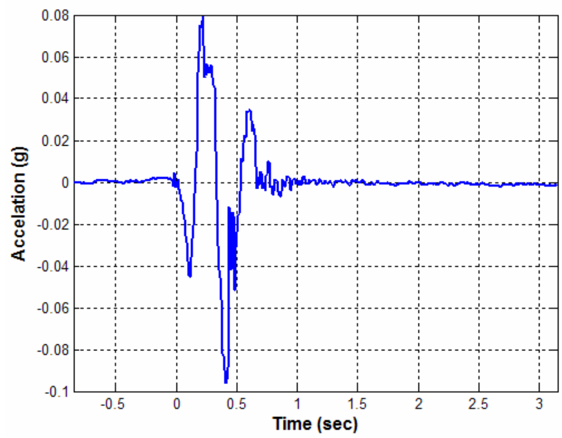


(a) Impulse response

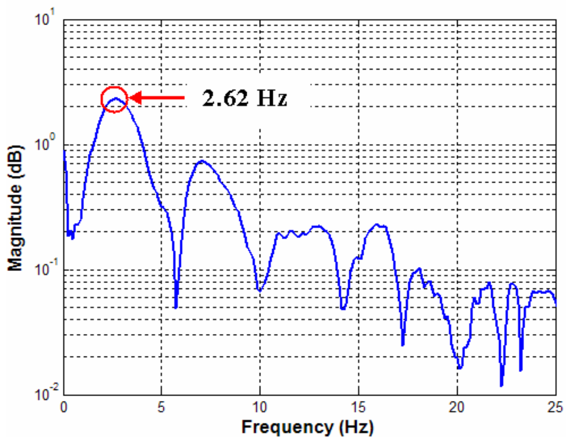


(b) Power spectrum

Fig. 9 Response of vibration isolation table using passive control method



(a) Impulse response



(b) Power spectrum

Fig. 9 Response of vibration isolation table using passive control method

Table 2 Results of vibration isolation table

Control method	Natural frequency (Hz)	Natural frequency effect (%)	Settling time (sec)	Settling time 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

4. Conclusions

In this paper through our study, a fuzzy controller using Takagi-Sugeno method is designed for active vibration isolation system. From the numerical results we could see, the developed control method using fuzzy controller could be verified to be better than other controller both for one degree of freedom and three degree of freedom system. So does the experiment, fuzzy controller could got more effective result.

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