공기스프링을 이용한 능동 방진 시스템의 퍼지 제어기 설계

Fuzzy Controller Design for Active Vibration Isolation System Using Air-spring

양손* · 안채헌** · 진경복*** · 임경화†

Xun Yang, Chae-Hun An, Kyong-Bok Jin and Kyung-Hwa Rim

Key Words : Active Vibration Isolation System(능동 방진시스템), Air-spring(공기스프링), Fuzzy Control(퍼지 제어), Passive Control (수동 제어)

ABSTRACT

In recent days, vibration isolation system is mostly required in precise measurement and manufacturing system to reduce vibration due to external disturbances and internal actuators. Among all the vibration isolation systems, air spring is widely used because of its low resonant frequency and high damping ratio. In this study, we first analyze the passive air-spring system using leveling valve, and then design the active vibration isolation system. Because the non-linearity of pneumatic characteristics, we try to design the fuzzy controller which is better than PID controller at complex and non-linear system, and then compare them both in experiment and simulation.

요 약

최근 반도체 및 디스플레이 산업 등에서 초정밀 가공, 측정 등이 필요함에 따라, 외란과 내부 진동을 차단하는 방진 시스템에 대한 연구가 활성화 되고 있다. 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 기존의 레벨링 밸브를 이용한 수동 방진 시스템을 분석하여 이를 개선하고 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 for precision machines, optical or semiconductor test machines, or other micro-precision measuring instruments to isolate vibration effects from external disturbances and internal actuators in recent days.[1] In this paper, according to the characteristics of air-spring, we analyze the passive control system using leveling valve, and then we use fuzzy control method instead of PID method to design a controller which is better at both settling time and natural frequency.[2]

2. Modeling of vibration isolation system

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.[10] As the load-plate moves up and down, air is forced to move through this orifice, producing a damping force on the payload.[3] This type of damping is very strong for large displacement of the load-plate, and weak for small displacement. This allows for fast setting of the payload, without compromising small amplitude vibration isolation performance. This modeling also has a payload which receives the load straightly and a diaphragm.

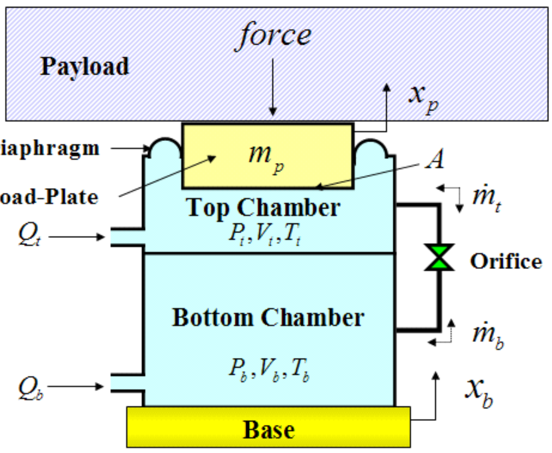


Fig. 1 Schematic diagram of air-spring

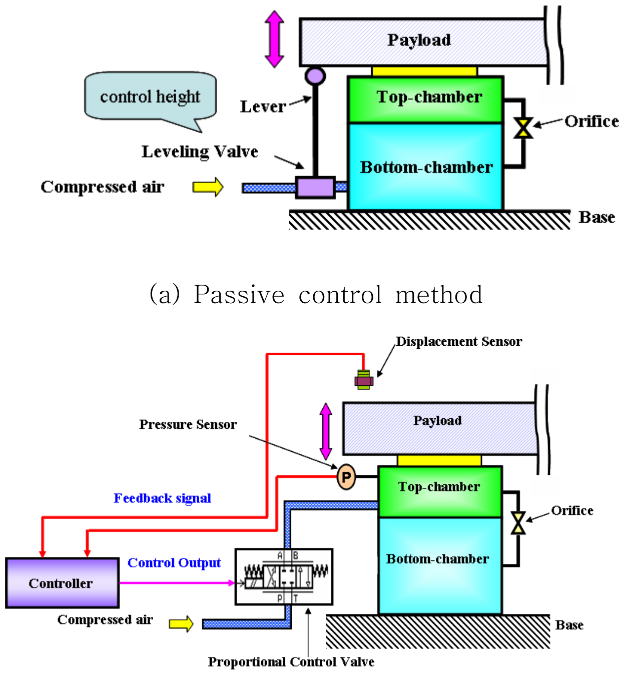
The natural frequency of air-spring isolator is given by

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

From Eq (1)[6], we can conclude that the stiffness of the spring (and hence the natural frequency of a mass supported on the spring) is dependent upon the height of the spring (volume of air), but unlike steel coil spring, its natural frequency is nearly independent of the mass of the payload. 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.

2.2 Passive and active control method

Vibration isolation control method can be divided into two kinds, passive control method and active control method, according to the existence of energy source. A passive system does not need any external power. It consists of a resilient member (stiffness) and an energy dissipater (damping) and it can be easily designed and available at low cost. On the other hand, an active system is comprised of a servomechanism with sensors, signal processors, and actuators, thus giving better isolation effects than a passive system.[5]



(a) Passive control method

(b) Active control method

Fig. 2 Schematic diagram of air-spring control system

(1) Passive control method for air-spring

Fig. 2 (a) is the schematic diagram of air-spring vibration control system using passive control method. The pressure in the isolator is controlled by a height control valve which senses the height of the payload, and the height control valve always brings the payload back to the same operating height. But, because this method is dependent on the mechanical characteristics of the leveling valve, this method has some limitation such as large non-linearity of air-spring and be sensitive to disturbances that will cause various natural frequencies. In case of the four actuators of the vibration isolation not moving together because of no sensors to harmonize their motion, it will cause coupling problem for this system.

(2) Active control method for air-spring

Fig. 2 (b) is the schematic diagram of air-spring vibration control system using active control method. In our study, according to the larger non-linear characteristics of ai-spring, we design a feedback system with two loops, as shown in Fig. 2 (b). First, we use the displacement sensor to measure the displacement of payload as the outside feedback loop, and design a controller for this part. Second, we use the pressure sensor to measure the pressure of top chamber as the inside feedback loop, and the difference between output of PID controller and pressure output is used as input for the second controller. After designing control method for each feedback and through the proportional control valve we could control the pressure of chambers because the top and bottom are connected by the orifice.

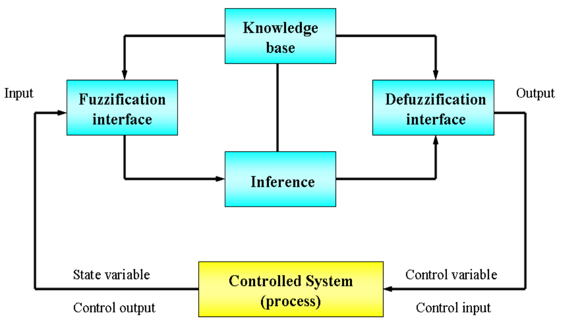


Fig. 3 Configuration of fuzzy logic control

2.3 Fuzzy logic control

Fuzzy logic is much closer in spirit to human thinking and natural language than the traditional logical systems, 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 advantage of fuzzy logic control can be summarized as follows. First, the control strategy is represented by multiple fuzzy rules, and thus it is easy to represent complex systems and non-linear systems[8]. Second, the control strategy is modeled by linguistic terms and thus it is easy to represent the human knowledge. Lastly, fuzzy control is a kind of robust control that more than one control rule can be used[9].

Linguistic variables, such as small, medium, and big are used to represent the domain knowledge, with their membership values lying between 0 and 1. Basically, a fuzzy logic controller has the following components, and you can see the relation in Fig. 3.[7]

Although fuzzy logic control is widely used at complex system and non-linear system, but it is difficult to make the fuzzy control rules because it is dependent on expert experience and engineering knowledge. And if you use too many fuzzy logic controllers, it will need expensive high capability signal processors. So in our study, in order to weaken the non-linearity effect of air-spring, we use the fuzzy logic control at the pressure feedback loop controller according to displacement output and pressure output calls error, and the

Table 1 Rule base for the fuzzy logic controllers

e \ $\dot{e}$	NB	NM	NS	ZO	PS	PM	PB
NB	ZO	ZO	NS	NM	NM	NB	NB
NM	ZO	ZO	NS	NM	NM	NB	NB
NS	PM	PM	ZO	NS	NM	NB	NB
ZO	PB	PB	PM	ZO	NM	NB	NB
PS	PB	PB	PM	PS	ZO	NM	NM
PM	PB	PB	PM	PM	PS	ZO	ZO
PB	PB	PB	PM	PM	PS	ZO	ZO

derivative of error as the input variables while the input voltage of proportional control valve is its output. And Matlab simulink with fuzzy toolbox is used. Table 1 shows the rule base for our fuzzy logic controllers. NB, NM, NS, ZO, PB, PM, PS represent negative big, negative medium, negative small, zero, positive big, positive medium and positive small, respectively.

We make the air-spring modeling in AMESim software shown as Fig. 4 and then use the Matlab S-Funciton to simulate the pressure control part of the system. We both use the PID controller and Fuzzy controller in this part, then compare the results with no-control system which is shown in Fig. 5. We can see that although the fuzzy controller has big steady error which is not very important in air-spring system, it could get better settling time.

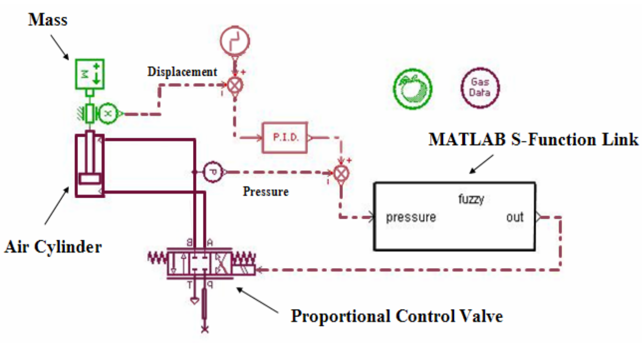


Fig. 4 Block diagram of 1 DOF air-spring control system using AMESim

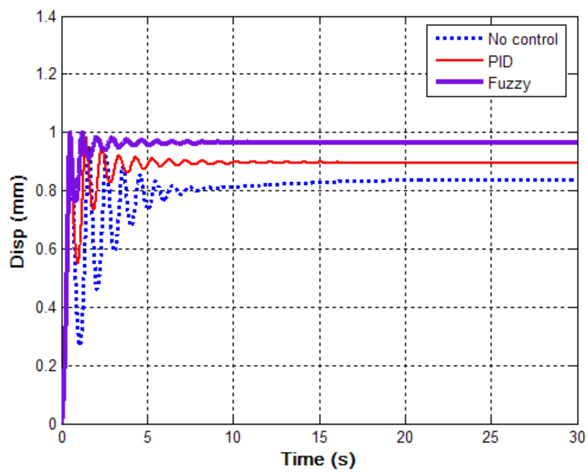


Fig. 5 Comparison among no-control, PID control and fuzzy control results using AMESim

2.4 Active vibration isolation system

(1) The modeling of active vibration isolation system

In order to simulate the action of vibration isolation system, we use the rigid body analysis Visual Nastran software to make a 3 degree of freedom modeling including z-dir, roll(Θ_x) and pitch(Θ_y), which is shown in Fig. 6. We use four actuator to drive the corresponding air-spring, but because this is a 3 degree of freedom system, then we should make two actuators move together as one.

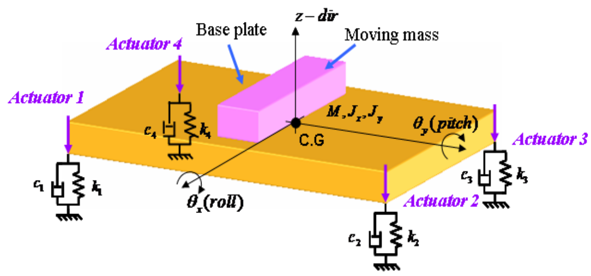


Fig. 6 Active vibration isolation system model

(2) Active control system

According to the active vibration isolation system model, we use the interface between Visual Nastran and Matlab to make the control system. With four air springs involved, there are several vertical vibration modes of the table on the support system. But we consider the motions including vertical motion, pitch and roll. We should make the mode-based control system shown as Fig. 7 according to the motion equations of three degree of freedom[4]. We first use the PID controllers to control the displacement of each degree of freedom, and then both use the PID

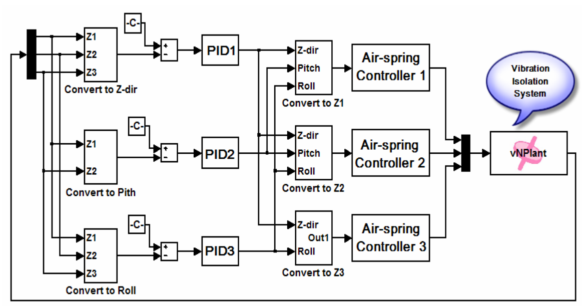


Fig. 7 Block diagram of mode-based control system

controller and fuzzy controllers the same as 1 DOF system to control the pressure which shown in the figure as air-spring controller. Let the moving mass which is 10% of the whole mass moving quickly, then we could simulate the active vibration isolation system and get the results that is shown in Fig. 8.

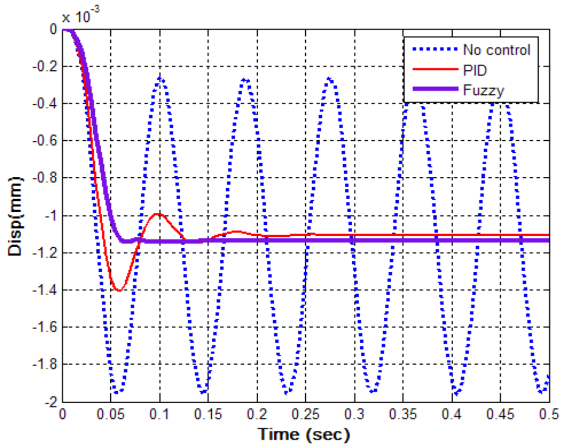


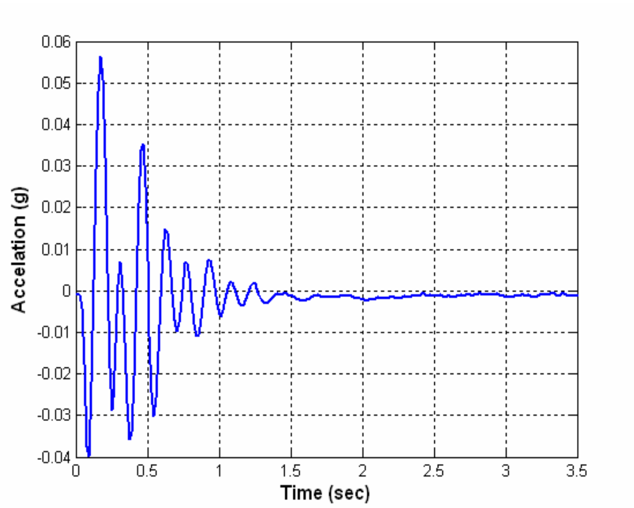
Fig. 8 Comparison among no-control, PID control and fuzzy control results with moving mass

3. Experiment results

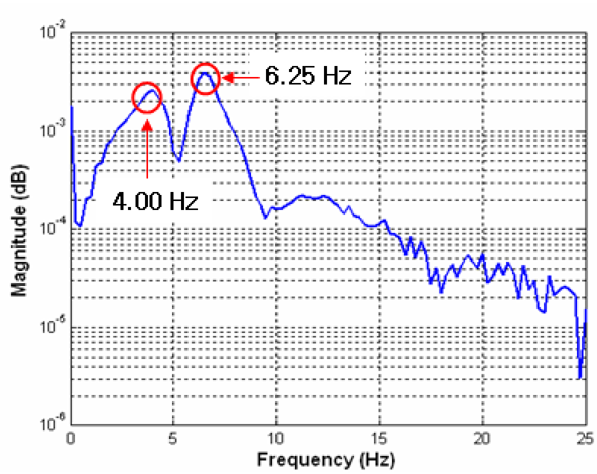
For each controller, after giving an impulse to the vibration isolation on z-dir, we could get the impulse responses and power spectrum of the system. Table 2 shows comparison results of vibration isolation table[11], and Fig. 9 shows the response of passive control system, Fig. 10 shows the response of fuzzy control system. You could see that fuzzy controller has the best isolation capability.

Table 2 Results of vibration isolation table

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

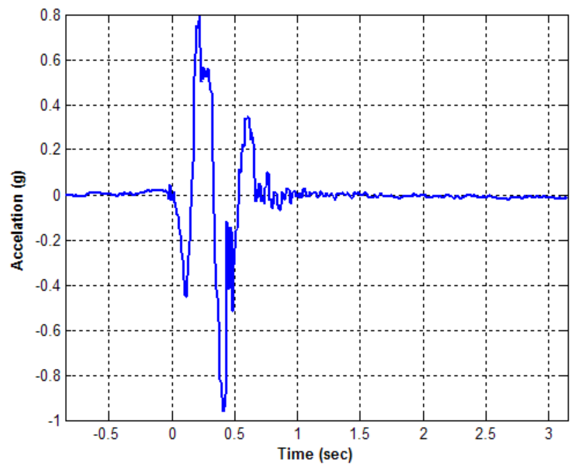


(a) Impulse Response (z-dir)

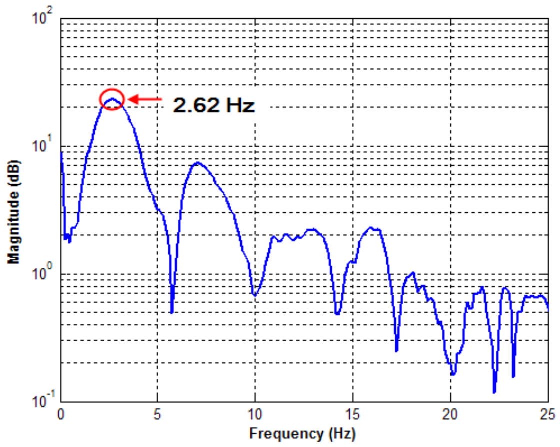


(b) Power spectrum (z-dir)

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



(a) Impulse Response (z-dir)



(b) Power spectrum (z-dir)

Fig. 10 Response of vibration isolation table using fuzzy control method

4. Conclusions

In this paper, we analyze the characteristics of air-spring and then according to the result of passive control method, we design the active controller for the vibration isolation system. Due to the non-linearity of pneumatic characteristics, we design the fuzzy controller for this system, and prove that it could get good results both at simulation and experiment.

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