2D4-6

Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

Semi-active and Active Control of an ERF Embedded in Pneumatic Vibration Isolator

Ming-Chang Shih, Teng-Yen Wang, Ping-Chang Chen

Department of Mechanical Engineering, National Cheng-Kung University
No.1, Ta-Hsueh Road, Tainan 701, Taiwan
(E-mail:mcshih@mail.ncku.edu.tw)

ABSTRACT

In the paper, the Electrorheological fluid(ERF) is embedded in the pneumatic vibration isolator and three kinds of control systems are designed, which experimental results are also compared. The first kind of the control system is the semi-active control system, which is designed for ERF controllable damper. The second kind of the control system is the active control system, which is designed for the air servo position control of the platform of the pneumatic vibration isolator. The third kind of vibration isolator control systems is the combination of the active air servo control system and the ERF controllable damper. The experimental results are shown and compared to those of the passive pneumatic vibration isolators, the transmissibility of a vibration source to the isolation platform can be reduced by the first control system. Using the second kind of the control system, the transmissibility of the system is less than that of the first kind of the control system. Using the third control system, the transmissibility becomes the least of these control systems.

KEY WORDS

ER fluid, Active control, Semi-active control

NOMENCLATURE

d	Gap thickness
υ_0	Piston velocity
A_d	Cross-sectional are of annulus
A_p	Piston area of the isolator
A_{pe}	Piston head area of ERF damper
C_r	flow restriction constant
C_m	Equivalent viscous damping
V_t, V_b	Volume of the top and bottom chamber
P_t, P_b	Pressure of the top and bottom chamber
L	Length of inner electrode
n	Polytropic exponent
μ	Viscosity of ER fluid

1. INTRODUCTION

Vibration isolation systems are essential in ensuring a higher productivity, an improvement in quality, and an enhanced safety. Vibration isolators are commonly applied during the performance of optical experiments, during semiconductor manufacturing, and in high precision measurement instrumentation. Vibrations are generated by a wide variety of sources, including passing traffic, elevators, human activity, and nearby motorized equipment. Hence, vibration isolators are designed to isolate delicate equipment from environmental vibrations.

Vibration isolation systems can be categorized as either active or passive, depending on whether or not external power is required. Passive vibration isolation systems provide a simple yet reliable means of protecting a mechanical system from a vibration environment. However, these elements have inherent performance limitations which cannot be overcome. By contrast, vibration isolation systems comprised of the actuators can provide a significantly enhanced vibration isolation performance [1]. For achieving the reduction of the transmissibility, the active system is added to the pneumatic vibration isolator. Fowler [2] added an active damping system in parallel with the pneumatic isolation. Eric [3] developed a product that incorporates piezoelectric actuators to minimize to motion of the payload.

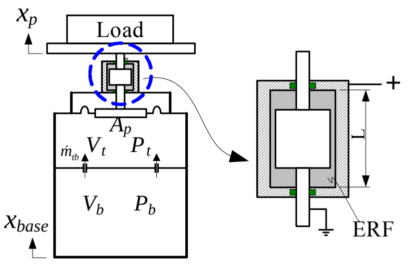
The ER fluid is a substance, which changes its rheological characteristics according to the strength of the applied electric field. This fluid has been widely applied in a variety of mechanical engineering applications, including vehicle suspensions, rotation machinery, railway vehicles, hydraulic systems, and damping-controlled dampers [4]-[7]. Conventionally, the term “ER fluid” refers to the particle-type ER fluids which exhibit Bingham characteristics [8]. Jin and Zhang [9] presented a friction-type ER damper, and applied it to dissipate the vibratory energy of robots. Kenaley and Cutkosky [10] employed ER fluid to control the stiffness of a robotic finger. In addition to particle-type ER fluids, macromolecular liquid crystals have been used to develop a homogeneous-type ER fluid which exhibits Newtonian fluid characteristics. Takesue [11] et al. utilized this particular form of ER fluid in a viscous damping arrangement for the precise positioning control of robot arms. The results of their study confirmed the effectiveness of this arrangement in improving both the precision of the positioning and the stability of the arm.

In the study, a pneumatic vibration isolator which is embedded the ER damper is designed and controlled. A semi-active control system, an active control system, and a hybrid control system are designed for the pneumatic vibration isolator embedded with ERF damper. The first control system is designed for the damping controllable damper. The second control system is designed for the air servo control of the pneumatic vibration isolator. The third control system is the air servo control and the ER damper control.

The remainder of this paper is organized as follows. Section 2 introduces the design of the pneumatic vibration isolator embedded with the ERF Damper. Section 3 presents the layout of the current experimental system, while Section 4 develops the design of the controllers and presents the experimental results. Finally, Section 5 presents conclusions.

2. DESIGN OF PNEUMATIC VIBRATION ISOLATOR EMBEDDED WITH ERF DAMPER

The scheme of the pneumatic vibration isolator embedded with the ERF damper is usually shown in figure 1. It has two chambers and flow restrictors between the top chamber and bottom chamber. The ERF damper is located between the platform and the top chamber.



(a) (b)

Figure 1 Scheme of the designed isolator

An Electrorheological fluid is a substance, which can change its rheological characteristics according to the strength of an applied electric field. The ER fluids are classified as particle-type ER fluids and homogeneous ER fluids. ER fluids of particle-type are colloidal fluids comprising solvents with dispersed particles. In the absence of an electric field, the ER fluid exhibits Newtonian fluid characteristics. However, when an electric field is applied, the fluid demonstrates the characteristics of a Bingham fluid. The other is homogeneous ER fluids developed by using low-molecule liquid crystals or macromolecular liquid crystals. For homogeneous ER fluids, the shear stress is basically proportional to the shear rate, and that its slope, i.e. its viscosity, is governed by the strength of the applied electric field. The ER fluid used in this study is a liquid crystalline polymer, a sort of homogeneous ER fluids, because the fluid has the characteristics of no sedimentation and no particle-crushing. The characteristic of the fluid is shown in Figure 2.

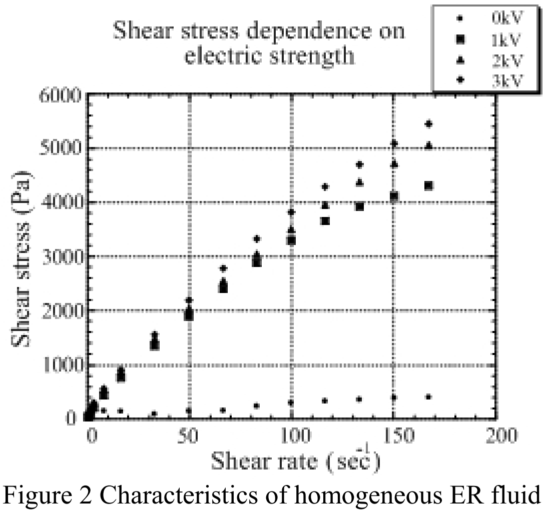


Figure 2 Characteristics of homogeneous ER fluid

Three ER vibration control modes exist, namely flow mode, shear mode, and squeeze mode. In the study, the mixed damper is composed of the flow mode and shear mode and shown in figure 1(b). The damper has the inner electrode attached to the piston head, and so it moves with the piston head. In the damper, rate-dependent damping force results from the pressure drop in the electrode gap as well as direct shear of the fluid in the gap due to the piston head motion. The mixed mode damper is considered as the approximate parallel plate analysis. The 1D axisymmetric analysis is given in [12], and the expression for the force is written as :

$$F = \frac{12\mu A_{pe}^2 L}{A_d d^2}\left(1 + \frac{A_d}{2A_p}\right)\upsilon_0 = C_m \upsilon_0 \qquad (1)$$

The mathematical models of the pneumatic vibration isolator are the same as those of a servo-pneumatic cylinder and the nonlinear models of a servo-pneumatic cylinder first proposed by Shearer [13]. These models include the enthalpy equations for the pneumatic chambers, an equation for the flow through the restrictor, and a displacement equation for the piston under load. The linear model of the pneumatic vibration isolator can be derived from the nonlinear model. Harris and Crede [14] were the first researchers to propose a linear model of the pneumatic vibration isolator. However, DeBra [15] has also developed a linear model of the pneumatic vibration isolator.

The mathematical model of the pneumatic vibration isolator embedded with the ERF damper comprises thermodynamic equations for the upper and lower chambers, a displacement equation for the piston under load, the air flows through the restrictor between the upper and lower chambers and the damping force of the ER damper. Air compressibility characteristics cause the associated mathematical models to be nonlinear, which significantly complicates the system analysis process. However, the Taylor series expansion can be used to linearize the model. After linearization, the transfer function of the pneumatic vibration isolation embedded with the ER fluid can be written as:

$$G_{PE}(s) = \frac{X_p(s)}{X_{base}(s)} = \qquad (2)$$

$$\frac{c_m s^2 / m_p + [\omega_n^2 + c_m / m_p(1+\alpha)]s + a\omega_n^2}{s^3 + [a(1+\alpha) + c_m / m_p]s^2 + [\omega_n^2 + ac_m / m_p(1+\alpha)]s + a\omega_n^2}$$

Where $a = nP_0 C_r / V_b, \omega_n^2 = nP_0 A_p^2 / m_p V_{t0}, \alpha = V_b / V_{t0}$

In equation (2), C_m is the damping coefficient of ERF damper and has the influence on the transmissibility of the pneumatic vibration isolator embedded with the ERF damper. When the ERF damper is not embedded in the pneumatic vibration isolator, hence, the damping coefficient of ERF damper is zero, and the transfer function of the pneumatic vibration isolator can be written as:

$$G_P(s) = \frac{x_p(s)}{x_{base}(s)} = \frac{\omega_n^2 s + a\omega_n^2}{s^3 + a(1+\alpha)s^2 + \omega_n^2 s + a\omega_n^w} \qquad (3)$$

The simulation result of the pneumatic vibration isolator embedded with and without the ERF damper is shown in figure 3. It is shown that the transmissibility of the system could be reduced with the increased electric field near the nature frequency.

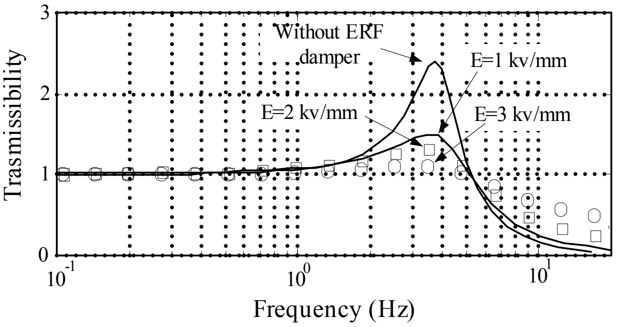


Figure 3 Simulation of the pneumatic vibration isolator embedded with the ERF damper at different electric filed

3. LAYOUT OF EXPERIMENTAL EQUIPMENT

Figure 4 shows the experimental arrangement employed to measure the transmissibility of the system. The pneumatic vibration isolator embedded with the ERF damper is located on a flat base connected to a hydraulic servo- cylinder, which serves as a small vibration source. The chambers of the pneumatic vibration isolator are pressurized with air and support a load. Position sensors are attached to the load and to the base of the pneumatic vibration isolator. The ER power supply generates the electric field on the ERF damper and the pneumatic servo valve regulates the air flows in/out the upper chamber. For the passive system, the displacements of the load and the base are measured by the two position sensors, which then transmit the displacement signals to the computer. For the semi-active control system, the electric field is applied to the ERF damper embedded in the pneumatic vibration isolator. For the active control system, the computer acts as a controller and sends the control signals to the pneumatic servo valve to regulate the air flows in/out the upper chamber in order to reduce vibration. For the hybrid control system, the air servo control and the applied electric field act on the isolator.

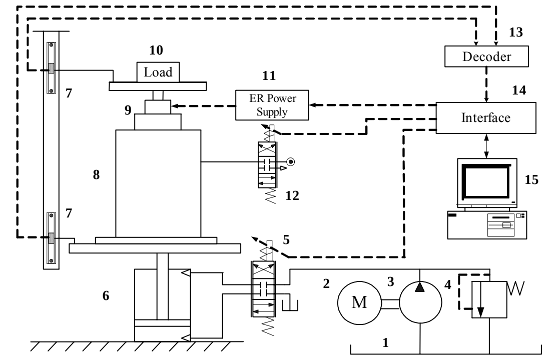


Figure 4 Layout of the experimental equipment

4. CONTROLLER DESIGN AND EXPERIMENTAL RESULTS

4-1 Open-loop control of ERF damper

Figure 5 shows the block diagram of the electric field applied to the pneumatic vibration isolator embedded with the ERF damper. From equation (1), the damping force of the ERF damper increases with the increased applied electric field. The experimental results of the pneumatic vibration isolator embedded with ERF damper are shown in Figure 6. It is observed that the transmissibility near the natural frequency decreases as the strength of the applied electric field increases, but the transmissibility is not improved when the frequencies are lower and higher than the nature frequency. So the semi-active control for the ERF damper is used to improve the performance.

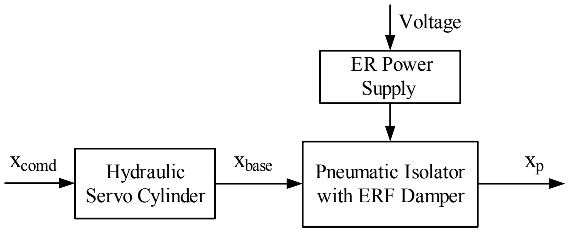


Figure 5 Block diagram of the pneumatic vibration isolator with open-loop controlled ERF damper

4-2 Semi-active control

The block diagram of the semi-active control is shown in figure 7. The input command, r, is the reference displacement of the load supported by the pneumatic vibration isolator, while the output, x_p, is the current displacement of the platform of the pneumatic vibration isolator. The vibrations to the pneumatic vibration isolator is x_{base}. In this case, the reference displacement is set to zero. The error is written as:

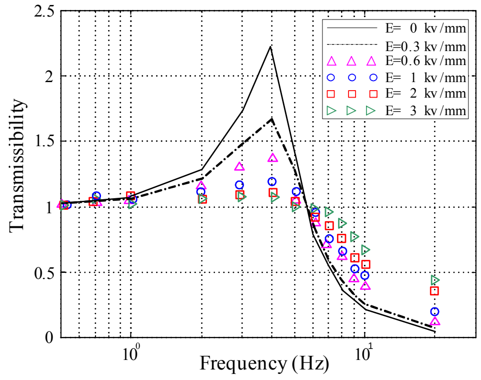


Figure 6 Transmissibility of different preset electric field

$$e = r - x_p = -x_p \tag{4}$$

The transmissibility is defined as:

$$T = \frac{x_p}{x_{base}} = \frac{-e}{x_{base}} \tag{5}$$

From equation (5), the switch condition of the electric field can be given as:

$$\begin{cases} T \le 1, E = 0 \\ T > 1, E \ne 0 \end{cases} \tag{6}$$

When the transmissibility is smaller than 1 or equal to 1($T \le 1$), the electric field is not applied to the ER damper. When the transmissibility is larger than 1, the electric field acts on the ER damper.

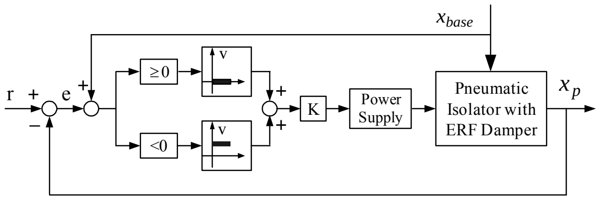


Figure 7 Block diagram of semi-active control system

4-3 Active Control

An active vibration isolation system is designed which employs an active controller to regulate the operation of a pneumatic servo valve. The active control system regulates the flow of air into, and out of, the upper chamber of the pneumatic vibration isolator such that the load is protected from vibration. Figure 8 presents a block diagram of the developed active control system. The fuzzy control can be described as follows.

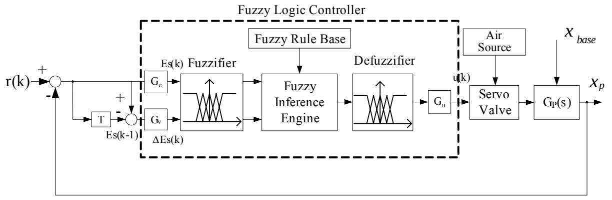


Figure 8 Block diagram of active control system

The fuzzy controller comprises four basic elements, namely a fuzzifier, a fuzzy inference engine, a defuzzifier, and a fuzzy rule base [16],[17]. E_s and ΔE_s represent the input signals to the fuzzy logic controller, and u represents the output of the fuzzy controller. The input command and the plant output are crisp values but non-fuzzy variables, and must therefore be fuzzified by the fuzzifier, which performs a mapping from the crisp points to the corresponding fuzzy set. A fuzzy set is denoted by a linguistic term such as "positive error" or "negative error", and is characterized by a membership function. The fuzzifier of the fuzzy logic control system is a nonsingleton (triangular) fuzzifier. The fuzzy rule base of the fuzzy controller comprises a set of IF-THEN rules, which are typically expressed in the form of a fuzzy conditional statement, i.e.

R_i: IF E_s *is* A_i AND ΔE_s *is* B_i, THEN u *is* C_i

where A_i, B_i and C_i are fuzzy sets characterized by membership functions $\mu_A(E_s)$, $\mu_B(\Delta E_s)$ and $\mu_C(u)$ respectively.

If there are *n* fuzzy sets for each of the variables E_s, ΔE_s and u, then the total number of fuzzy rules will be given by n^2. This fuzzy rule set can be combined into a single rule by means of the following operator: $R = R_1 \cup R_2 \cup \cdots \cup R_{n^2}$.

To compute the subsequent output u, the present study adopts a max-min inference method as the fuzzy inference engine, i.e.

$$\mu_G(u) = \max\{\min[\mu_{A_i}(E_s), \mu_{B_i}(\Delta E_s), \mu_{R_i}(E_s, \Delta E_s, u)]\} \quad (7)$$

Applying the max-min inference technique yields a fuzzy output value. Hence, it is necessary to employ a defuzzifier to transform this fuzzy quantity into the corresponding crisp value. This study adopts the center-of-gravity method as the defuzzifier function, i.e.

$$u = \frac{\sum_{i=1}^{n^2} u_i \cdot \mu_G(u_i)}{\sum_{i=1}^{n^2} \mu_G(u_i)} \quad (8)$$

Equation (8) yields a crisp output command from the fuzzy logic controller. If the output command is positive, air is flowed into the upper chamber of the pneumatic vibration isolator. Conversely, if the output command is negative, air is discharged from the chamber.

The present study employs the fuzzy sets 'zero (ZE)', 'positive big (PB)', 'positive small (PS)', 'negative big (NB)' and 'negative small (NS)'. Figure 9 depicts the triangular membership functions for each fuzzy set. It is observed that these functions are symmetric with respect to the vertical axis as a result of the symmetric nature of the operating of the servo valves. Table 1 displays the fuzzy control decision table adopted in the current study.

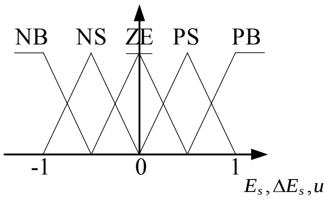


Figure 9 Membership function

ΔE_s \ E_s (u)	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

Table 1 Fuzzy rule

4-4 Hybrid control

The hybrid control system includes the air servo control and the damping control of the pneumatic vibration isolator embedded in the ER damper. When the transmissibility is larger than 1, the electric field is applied to the ER damper to reduce the transmissibility, and the air servo control controls the flow of air into, and out of, the upper chamber to reduce the transmissibility. When the transmissibility is smaller than 1, only the air servo control acts on the pneumatic vibration isolator embedded in the ER damper. The block diagram of the hybrid control system is presented in figure 10.

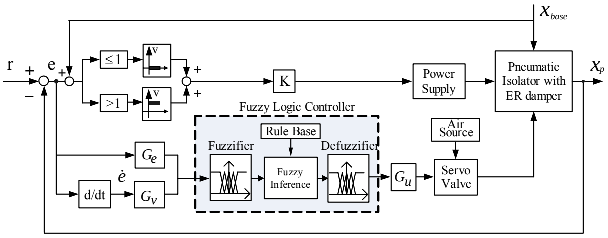


Figure 10 Block diagram of hybrid control system

4-5 Experimental results

The system supply pressure is taken to be 5 bar, while the sampling time is specified to be 20ms. Figure 11 shows the experimental results of the transmissibility of the pneumatic vibration isolation systems. It can be seen that compared with the passive system, the transmissibility is reduced near its natural frequency by using the semi-active control. Using the active control, the transmissibility is smaller than 1 at the frequency lower than nature frequency. Using the hybrid control system, the transmissibility of the vibration source to the payload is improved more effectively.

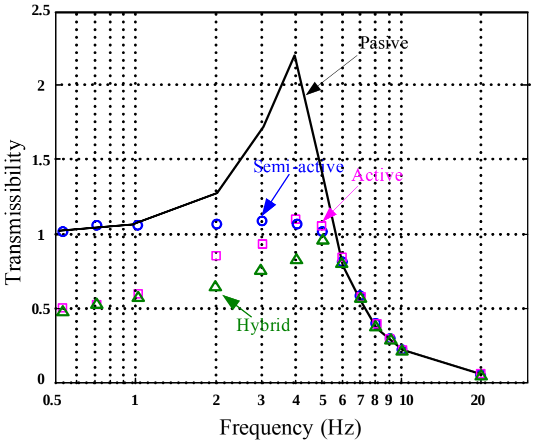


Figure 11 Transmissibility of different control systems of pneumatic vibration isolator embedded with ERF damper

5. CONCLUSION

This paper has presented the design of pneumatic vibration isolator embedded in the ER damper and the control systems. The experimental results were carried out and came to the following conclusions:

(1) Compare with the case of passive vibration isolator, when using the semi-active control system, the transmissibility is improved near the nature frequency.
(2) Using the active pneumatic control system, the transmissibility is smaller than that of the semi-active control system, when the frequency is lower than the nature frequency.
(3) Using the hybrid control system, the performance of the vibration source to the payload is better than the semi-active control system and the active control system.

ACKNOWLEDGMENT

This research is supported by Nation Science Council (NSC, Taiwan) project “91-2212-E-006-070”.

REFERENCES

[1] Su, H., Ralhrja, S. and Sankar, T. S., Vibration isolation characteristics of an active electromagnetic force generator and the influence of generator dynamics, Transactions of the American Society of Mechanical Engineers, Journal of vibration and acoustics, 1990, **112**, pp.8-15.

[2] Flowler, Leslie, Buchner, Stephen, Ryaboy and Vyacheslav, Self-contained active damping system for pneumatic isolation tables, Proceedings of SPIE - The International Society for Optical Engineering, 2000, **3991**, pp.261-272.

[3] Anderson, E. H. and Houghton, B., ELITE-3 active vibration isolation workstation, Proceedings of SPIE - The International Society for Optical Engineering, 2001, **4332**, pp.183-196.

[4] Winslow, W.M., Induced fibration of suspensions J. Appl. Phys., 1949, **20**, pp.1137-1140.

[5] Wang, K.W., Kim, Y.S. and Shea, D.B., Structural vibration control via electrorheological-fluid-based actuators with adaptive viscous and frictional damping, J. Sound Vib., 1994, **177**, pp.227-237.

[6] Nguyen, Q.D. and Boger, D.V., Measuring the flow properties of yield stress fluids, Ann. Rev. Fluid Mech., 1992, **24**, pp.47-88.

[7] Powell, J., An application of nonlinear phenomenological model to the oscillatory behavior of ER materials, J. Rheol., 1995, **39**, pp.1075-1094.

[8] Uejima, H., Dielectric mechanism and rheological properties of electro-fluids, Japan J. Appl. Phys., 1972, **11**, pp319-326.

[9] Li, J., Jin D., and Zhang X., An electrorheological fluid damper for robots, in Proc. 1995 IEEE Int. Conf. Robotics and Automation, 1995, **3**, pp. 2631-2636.

[10] Kenaley, G.L. and Cutkosky, M.R., Electrorheological fluid-based robotic fingers with tactile sensing, In Proc. IEEE Int. Conf. Robotics and Automation, 1989, pp. 132-136.

[11] Takesue, N., Zhang, G., Furusho, J. and Sakaguchi, M., Precise position control of robot arms using a homogeneous ER fluid, In Proc. IEEE Int. Conf. Robotics and Automation, 1998, **3**, pp. 2470-2475.

[12] Kamath, G. M., Hurt, M. K. and Werely, N. M. Analysis and testing of Bingham plastic behavior in semi-active electtrorheological fluid dampers, Smart mater. Struct., 1996, **5-5**, pp. 576-590.

[13] Shearer, J.L., Study of pneumatic processes in continuous control of motion with compressed air, Transactions of ASME, 1956, **78**, pp.233-242.

[14] Harris, C.M. and Crede, C.E. (1961), Shock and Vibration Handbook, McGraw-Hill, New York.

[15] Debra, D.B., Vibration isolation of precision machine tools and instruments, CIRPAnnals, 1992, **41-2**, pp.711-718

[16] Zadeh, L. A., Fuzzy sets, Information and Control, 1965, **8**, pp.338-353.

[17] Lee, C.C., Fuzzy logic in control systems: fuzzy controller part I, IEEE Trans. SMC, 1990, **20-2**, pp.419~435.