Vibration control of a beam using linear magnetostrictive actuators

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ABSTRACT

Terfenol-D is one of magnetostrictive materials with the property of converting the energy in magnetic field into mechanical motion, and vice versa. We designed and fabricated a linear magnetostrictive actuator using Terfenol-D as a control device. In order to grasp the dynamic characteristics of the actuator, a series of experimental and numerical tests were performed. Induced-strain actuation displacements of the actuator measured by the test and predicted by magnetic analysis agreed well. And blocked forces according to the input currents were estimated from the testing results. Modeling method representing the exerting force of the actuator was confirmed through some testing results. We also explored the effectiveness of the linear magnetostrictive actuator as a structural control device. A series of numerical and experimental tests was carried out with simple aluminum beam only supported at each end by the actuator. After the equation of motion of the controlled system was obtained by the finite element method, a model reduction was performed to reduce the numbers of degree of freedom. A linear quadratic feedback controller was realized on a real-time digital control system to damp the first four elastic modes of the beam. Through some tests, we confirmed the possibility of the actuator for controlling beam-like structures.

Keywords: Linear magnetostrictive actuator, Terfenol-D, Blocked force, Active vibration control

1. INTRODUCTION

Smart materials are increaseingly applied to not only traditional sensors but to actuators, precision systems, adaptive or smart structures, mechatronic systems, structronic systems, and so on. The magnetostrictive actuator (MSA) is recently in the limelight using a giant magnetostrictive material or Terfenol-D. Terfenol-D can produce great forces; fast, high-precision motion; high efficiencies; and high power levels[1]. This material has other notable properties which are of practical value, these include[2]:

- a high magnetomechanical coupling, enabling the efficient conversion of magnetic to mechanical energy;
- a high load bearing capability;
- high compressional strength;
- durability under static and dynamic loading;
- low voltage operation.
- high reliability and unlimited cycle life[3]

Therefore, the researches on MSA have been recently undertaken in many application fields. During the European Commission funded project MADAVIC (Magnetostrictive Actuators for Damage Analysis and Vibration Control) six actuator prototypes have been developed[4,5]. Maier and Seesmann[6] have characterized the dynamic behavior of an MSA and developed two analytical models based on linear constitutive equations. Moreover, a control scheme for the MSA has been presented, which not only stabilized the mathematical model of the magnetostrictive rod, but also led to an excellent tracking behavior[7]. Zhang, et al[8] have developed giant magnetostrictive actuators for active vibration control, performed some experiments, and achieved better vibration attenuation results.

In this research a linear magnetostrictive actuator using Terfenol-D has been designed and fabricated as a control device. A series of experimental and numerical tests have been performed to grasp the dynamic characteristics of the actuator. Induced-strain actuator displacement of the linear MSA has been measured by the test and predicted by magnetic analysis. And blocked force according to the input currents has been estimated from the testing results. The effectiveness of the linear MSA as a structural control device has been also explored. A series of numerical and

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experimental tests have been carried out with simple aluminum beam only supported at each end by the actuator. A linear quadratic feedback controller has been realized on a real-time digital control system to damp the first four elastic modes of the beam. Through some tests, the possibility of the linear MSA for structural control has been confirmed.

2. A Linear Magnetostrictive Actuator

Terfenol-D is an alloy of terbium, dysprosium, and iron metals. In technical terms, Terfenol-D is a solid-state transducer capable of converting very high energy levels from one form to another. In the case of electrical-to-mechanical conversion, the magnetostriction of the material generates strains 20 times greater than traditional magnetostrictives, and 2-5 times greater than traditional piezoceramics.

In this research the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ Terfenol-D produced by ETREMA Products, Inc.[9] is used. Physical properties of the Terfenol-D are summarized in Table 1. A linear MSA is conceptually designed as shown in Figure 1. The linear MSA consists of a Terfenol-D rod inside an electric coil for generating magnetic field and enclosed into an annular permanent magnet for magnetic bias. The Terfenol-D rod, the coil, and the magnet are assembled between two steel-washers (end plates). A commercial magnetostrictive rod with 25*mm* in diameter and 100*mm* long is selected.

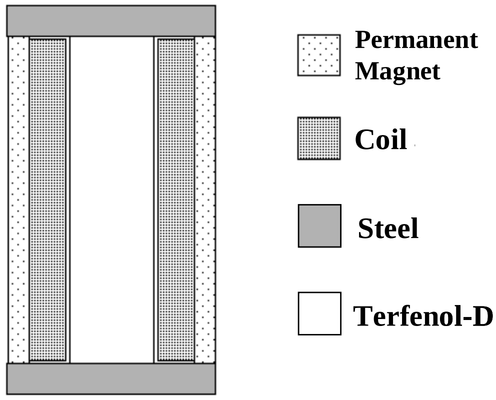


Figure 1: Conceptual Design of Linear MSA

Table 1: Physical Properties of the Terfenol-D[9]

Item	Property	Item	Property
Mechanical Property	- Young's modulus: 25 ~ 35 GPa - Compressive strength: 700 MPa - Tensile strength: 28 MPa - Sound speed: 1640 ~ 1940 m/s	Electrical Property	- Resistivity: 58 μΩcm - Curie temperature: 380℃
Magnetostrictive Property	- Maximum strain: 1000 ~ 2000 ppm - Strain estimated linear: 800 ~ 1200 ppm - Energy density: 14 ~ 25 kJ/m^2	Magnetomechanical Property	- Relative permeability: 3 ~ 10 - Coupling factor: 0.75

In order to design the MSA in detail, some parameters such as prestress level, magnetic bias, coil size, and so on must be determined. The magnetostriction S of Terfenol-D is a function of mechanical compressive prestress T_p, magnetic field intensity H, and temperature t[10]. The room-temperature magnetostriction of the Terfenol-D rod is experimentally obtained as a function of magnetic field intensity for different prestress levels as shown in Figure 2. Maximum magnetostriction occurs at prestress level of 7*MPa* and its curve has a nearly linear section. So, prestress level of 7*MPa* is determined. This value is realized using a specific spring with stiffness of 324*kN/m*. Regardless of magnetic field polarity, Terfenol-D can provide only positive strain. To obtain both positive and negative strains, magnetic bias H_b is required. This bias effect may be provided by a permanent magnet, thus minimizing the need for electrical bias current and so reducing power requirements. The bias magnetization level of about 20*kA/m* is properly considered from Figure 2. A solenoid coil wound around the rod to expand or contract in response, leading to proportional, positive, and repeatable expansion in either positive

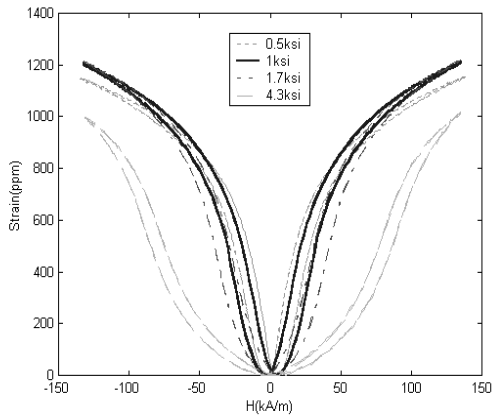


Figure 2: S-H Curve

or negative magnetic field direction. A nonlinear magnetic field analysis using a finite element method is carried out to decide the coil turns, thickness of the permanent magnet and end plates, and so on. Through these investigations, it is decided that the ferrite permanent magnet has a thickness of 11*mm*, coil 1.0*mm* in diameter and 700 turns at working current of 5.0*A*, and steel plates 8mm in thickness. Based on the analysis results the linear MSA is fabricated as shown in Figure 3.

3. DYNAMIC CHARACTERISTICS OF THE MSA

The displacement characteristics of the fabricated linear MSA are investigated through experimental tests. Figure 4 shows experimental set-up for measuring the induced-strain actuator displacement, u_{ISA}. The MSA is fully fixed on the rigid structure and a non-contact gap sensor is mounted to measure the tip displacement as shown in Figure 4. While alternating current (AC) with intervals of 5*Hz* is applied, the displacement responses are measured. Through Figure 5 showing the results, it is confirmed that the u_{ISA} to the input current has nearly linear characteristics with slope of 9.17$\mu m/A$ regardless of current frequency.

Figure 3: Fabricated MSA

Since the maximum force of the MSA is realized when the actuator is fully blocked, the force characteristics of the MSA may be expressed by blocked force[11]. In order to measure the blocked force directly, the stiffness of external blocking fixture must be infinite. However, the fixture can't have the infinite stiffness. So, the blocked force of the MSA should be indirectly predicted from dynamic testing results. As shown in Figure 6, the MSA is fixed using steel fixtures at both ends. A gap sensor and a piezoelectric-type force transducer are installed to measure the responses. The MSA can be modeled using internal stiffness of the MSA, k_a, external stiffness of the fixture, k_e, and displacement u. Because the k_e is not infinite, u exists in the range of $0 < u < u_{ISA}$. When the current is input from 0 A to 3 A, force F_a and displacement u of the MSA are measured. Figure 7 shows the force results under alternating current up to 50*Hz*. It is confirmed that they have nearly linear characteristics with respect to input current and flat with respect to frequency.

The blocked force of the MSA can be mathematically defined by

$$F_b = k_a \cdot u_{ISA} \quad (1)$$

where k_b is the blocked force, which can't be measured. However, the blocked force may be predicted from measured responses as a following equation.

$$F_b = F_a + k_a \cdot u \quad (2)$$

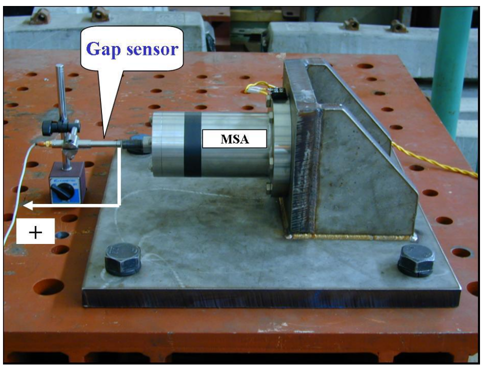


Figure 4: Displacement Measurement

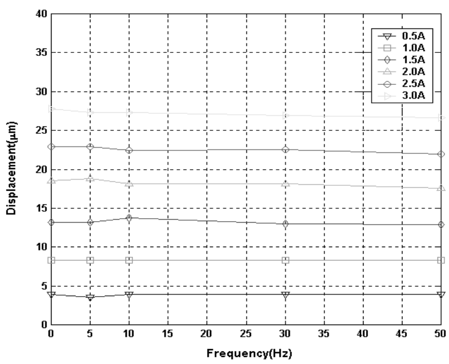


Figure 5: Induced-Strain Actuator Displacement under AC

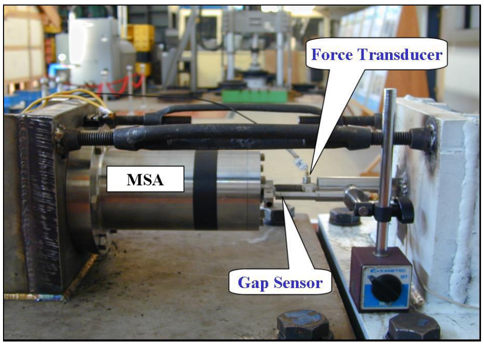


Figure 6: Force Measurement

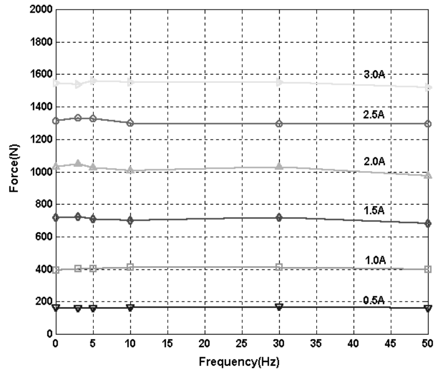


Figure 7: Force Response under AC

where $k_a = A_T E_T / l_T$ = 149.21*MN/m*. In order to verify the accuracy of Equation (2), the predicted blocked force is compared with calculated force from Equation (1). Figure 8 shows the result. Since the two blocked forces are agreed well, the blocked force of the MSA is accurately predicted from Equation (2). On the other hand, force F_a can be expressed by

$$F_a = k_e \cdot u \quad (3)$$

Substitute Equations (1) and (3) into Equation (2), the displacement of the MSA can be obtained like

$$u = \frac{u_{ISA}}{1 + k_e / k_a} \quad (4)$$

And substitute Equation (4) into Equation (3), the force of the MSA can be obtained such as

$$F_a = k_e \cdot \frac{u_{ISA}}{1 + k_e / k_a} \quad (5)$$

The force estimated from Equation (5) is compared with the measured data in Figure 9. The figure shows the comparison of the dynamic forces with flexible support with respect to input current and frequency. Although there is a little error, the results can be acceptable. Thus, the displacement and force of the fabricated MSA can be predicted using Equations (4) and (5).

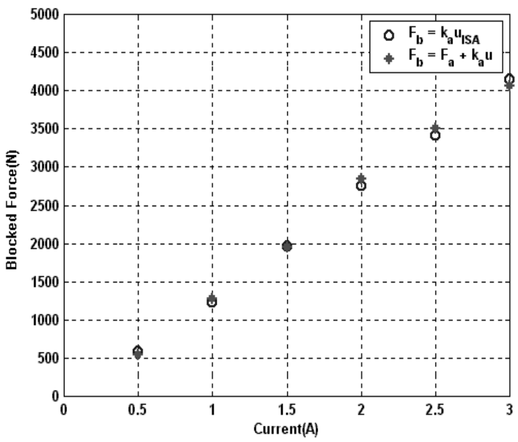


Figure 8: Comparison of the Blocked Forces

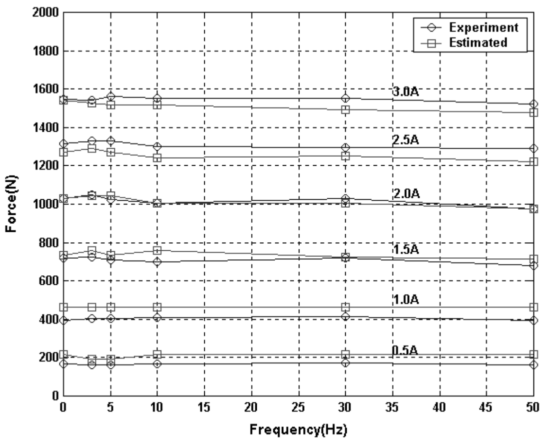


Figure 9: Experiment vs. Estimation on Force

4. APPLICATION ON ACTIVE VIBRATION CONTROL

The developed MSA is applied to vibration control as control devices. In order to check effectiveness and possibility of the linear MSA out, the experiment and numerical simulation regarding the active vibration control are carried out on a simple beam. An aluminum beam is simply supported at each end by the MSA as shown in Figure 10. The beam is 1000*mm*(*L*) long, 25*mm*(*b*) wide, and 10*mm*(*h*) high. The specific jig is used to realize simply supporting condition at ends. In case the MSA is connected with a flexible structure modeled with a lumped mass and a spring, the system may be equivalently modeled as shown in Figure 11. In Figure 11, m and k_e denote mass and stiffness of the structure connected with the MSA. The generated force from the MSA is

$$F_a = k_a \cdot (u_{ISA} - u) \quad (6)$$

and equation of motion on the structure is

$$F_a = m\ddot{u} + k_a u \quad (7)$$

From Equations (6) and (7), the following equation is obtained

$$m\ddot{u} + (k_e + k_a)u = k_a u_{ISA} \quad (8)$$

Since u_{ISA} and k_a of the MSA are known parameters, the dynamic responses of the structure are calculated based on Equation (8).

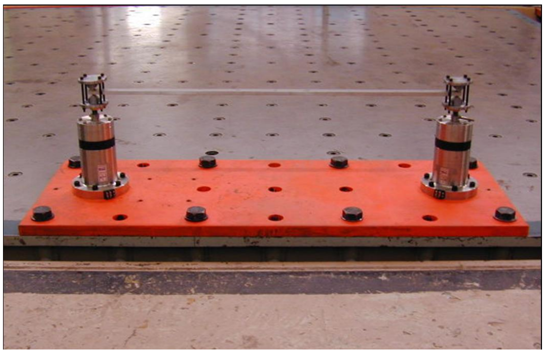


Figure 10: Overview of the Experimental Set-up

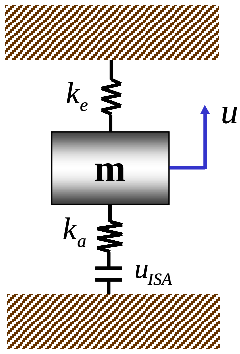


Figure 11: Equivalent Mathematical Model

For the numerical simulation and experiment of the active control system, the equation of motion of the test structure is firstly obtained. The test structure in Figure 10 is modeled using 10 beam elements as shown in Figure 12. The boundary condition at each end is expressed by stiffness of the MSA. Using static condensation method the equation of motion is formulated. Displacements in rotational direction are removed. A homemade current amplifier with dual channels is used to supply the working current to the MSA. The dynamics of the amplifier is included for considering the time delay effect in the control logic. It is modeled by

$$\frac{I}{V} = \frac{b}{s + a} \quad (9)$$

where a = 439.82, b = 917.47. Because of finite stiffness of the MSA at each end, the small displacement response can be occurred at each end. The first four modal parameters (natural frequency and damping ratio) of the test structure are summarized in Table 2. The natural frequencies obtained from both the experiment and the finite element analysis have closely same values. Damping ratio is estimated from the experiment data. In case both u_1 and u_2 have same direction, the symmetric modes are only excited. If opposite direction, the asymmetric modes are only excited. Figure 13 shows the transfer function at w_5 point when only a MSA is activated ($u_1 = u$, $u_2 = 0$ or $u_2 = u$, $u_1 = 0$). The mathematical model is accurately predicted the magnitude of the transfer function at each natural frequency. Since the results based on Table 2 and Figure 13 are very good, the system matrices of the test structure are extracted well.

Next, the total system including the beam, the MSA and current amplifier is mathematically modeled to design the control logic. The MSA has linear dynamic characteristics and produces 9.17μm per current as addressed in Sections 2 and 3. The first four natural modes of the beam are considered to design the control logic. The reduced system matrices are obtained using balanced model reduction method[12]. Finally the controller is designed based on the well-known LQG method, and one acceleration signal at w_5 point is only fedback. The performance of the designed control logic is tested through numerical simulation. When random excitation is loaded at w_7 point, the displacement and acceleration responses at w_5 point are calculated with and without control. The results are plot in Figure 14. The displacement in RMS (root-mean-squared) value is reduced to about 1/3 level, and RMS acceleration to about 1/4 level. The modal responses at each natural frequecny are examined, however, the graphical results are not including in this paper.

Table 2: Natural Frequencies and Damping Ratios of the Beam

Mode	Natural Frequency (Hz)		Damping Ratio (%)
	Experiment	FEA	Experiment
1	25.6	24.8	0.50
2	98.1	98.7	0.30
3	220.0	220.4	0.14
4	387.4	387.6	0.11

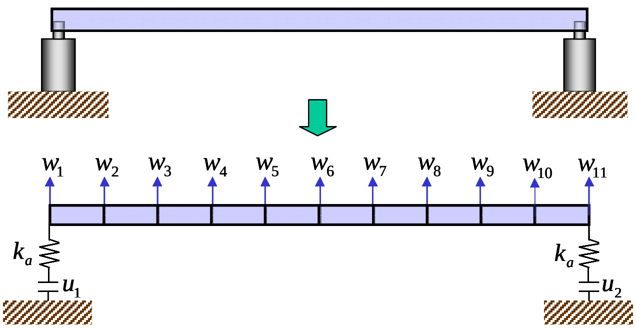


Figure 12: Model of a Beam and MSAs

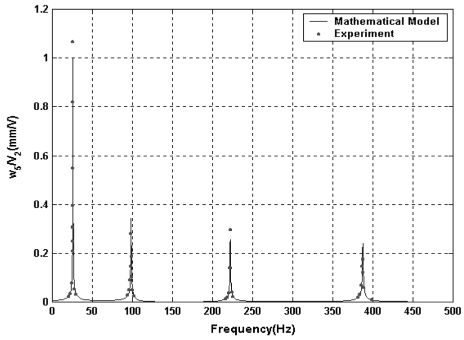
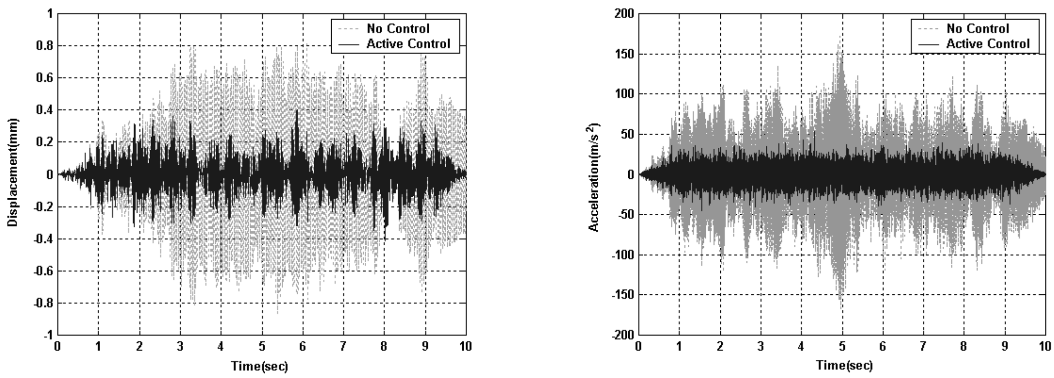


Figure 13: Transfer Function



(a) Displacement (b) Acceleration

Figure 14 Displacement and Acceleration Responses under Random Excitation

Since it is confirmed that the MSA and designed control logic have good control performance, the experimental tests are carried out. The tests are comprised of an impact test and a sinusoidal test. The impact test is conducted using an impact hammer. After the w_7 point of the beam is excited, the responses at w_5 point are measured. In time domain, the measured acceleration response is plot in Figure 15. The impacted response is sharply reduced by the active control. In frequency domain, the transfer function on acceleration is shown in Figure 16. The acceleration level is suppressed about

15dB at 1st mode, 12dB at 2nd mode, 13dB at 3rd mode, and 20dB at 4th mode. In the sinusoidal test, one MSA is used as an exciter. The other is used as a control device. The beam is excited with constant frequency, which is each natural frequency of the beam. Of course, the responses at w_5 point are measured. Figure 17 shows the measured displacement and acceleration responses at first natural frequency with and without control. To evaluate the control performance quantitatively, the reduction ratios obtained by active control are plot using bar chart with respect to mode index in Figure 18. The control system including the MSA and control logic can suppress the vibration level of the beam over 80%.

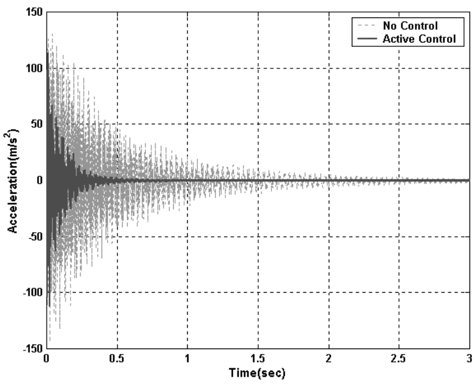


Figure 15: Acceleration Response (Experiment)

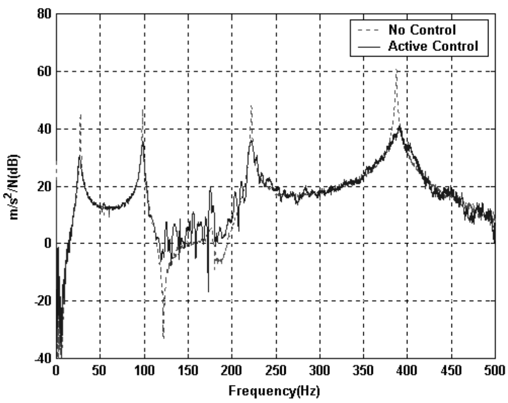
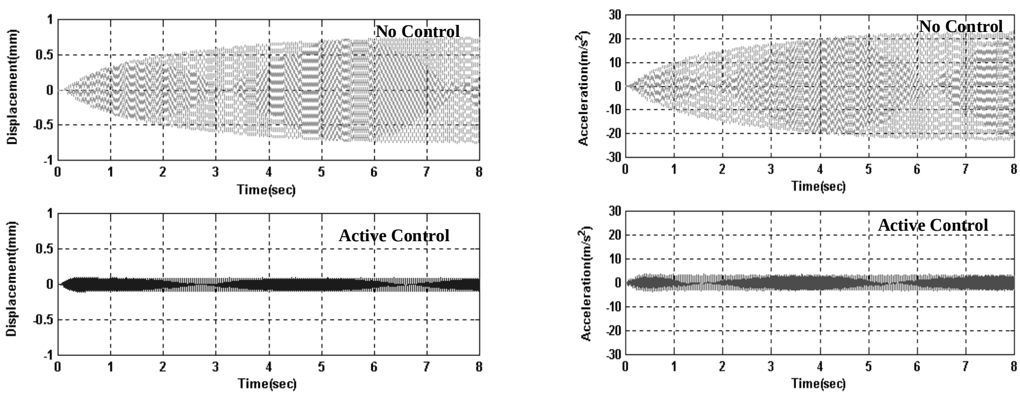


Figure 16: Transfer Function under Impact Test (Experiment)



(a) Displacement (b) Acceleration

Figure 17: Displacement Response at the First Natural Frequency (Experiment)

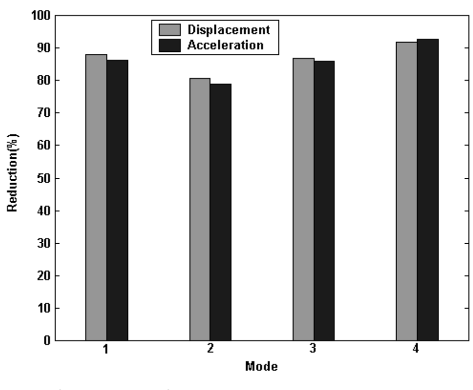


Figure 18: Control Performance of the MSA under Sinusoidal Excitation (Experiment)

5. CONCLUDING REMARKS

A linear magnetostrictive actuator using Terfenol-D rod, which has 25mm in diameter and 100mm long was designed and fabricated as a control device. The MSA consists of a Terfenol-D rod inside an electric coil for generating magnetic field and enclosed into an annular permanent magnet for magnetic bias. The Terfenol-D rod, the coil, and the magnet are assembled between two steel-washers. The induced-stain actuator displacement can be obtained to about 27μm and the blocked force up to about 4000N in the linear range. A series of experimental tests were performed to grasp the dynamic characteristics of the actuator, and then they were compared with theoretically obtained results. Induced-strain actuator displacements of the actuator measured by the test and predicted by magnetic analysis agreed well. Since it can't be measure directly, the blocked force was estimated from the measurable parameters. The MSA was proved to have good linearity. Modeling method representing the exerting force of the actuator was confirmed through some testing results. The effectiveness of the MSA was explored as a control device. A series of numerical and experimental tests was carried out with simple aluminum beam simply-supported at each end by the actuator. After the equation of motion of the controlled system was obtained by the finite element method, a model reduction was performed to reduce the numbers of degree of freedom. A linear quadratic feedback controller was realized on a real-time digital control system to damp the first four elastic modes of the beam. Through some tests, it is confirmed that the linear magnetostrictive actuator has good control performance and great possibility as a control device.

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