EXPERIMENTAL STUDY OF PIEZOELECTRIC ACTUATORS AND MAGNETOSTRICTIVE ACTUATORS FOR LARGE-SCALE SMART STRUCTURES

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ABSTRACT :
Whether smart structures can be applied to large-scale structures on the earth or not, depends on performances and costs of actuators. Therefore, it is suitable that piezoelectric actuators of stack type and magnetostrictive actuators which can produce much larger forces are used. In this study, three types of piezoelectric actuators of stack type and two types of magnetostrictive actuators were tested to investigate its performances. Through static and dynamic tests, satisfactory performances of piezoelectric actuators of stack type and magnetostrictive actuators for large-scale smart structures were shown.

KEYWORDS : Smart Structure, Civil Engineering Structure, Large-Scale, Vibration Control, Piezoelectric Actuator, Magnetostrictive Actuator

1. INTRODUCTION

Smart structures equipped with embedded or bonded actuators using piezoceramics, magnetostrictive alloys, shape memory alloys and so on, have been proposed mainly for structural control of aerospace vehicles/structures such as airplanes, helicopters and large space structures in the future. If the smart structures can be applied to large-scale structures on the earth, they will provide new and advantageous methods for vibration control of buildings, bridges, machines and so on. In order to investigate such applicability, various smart structures have been studied for active and semiactive vibration control of them **[KAMADA]**, **[FUJITA]**, **[KAJIWARA]**, **[FUJITA]**. Whether the smart structures can be applied to the large-scale structures on the earth, depends on performances and costs of actuators. Therefore, it is suitable that piezoelectric actuators of stack type and magnetostrictive actuators which can produce much larger forces are used. However, there are many unknown characteristics in these actuators for the smart structures. In this study, small-sized, middle-sized and large-sized piezoelectric actuators of stack type, and middle-sized and large-sized magnetostrictive actuators were tested to investigate its performances.

2. PIEZOELECTRIC ACTUATORS

Three types of piezoelectric actuators were tested to investigate its performances. Figure 1 shows a small-sized piezoelectric actuator having an external size of 10 mm×10 mm×18 mm^H that consisted of 144 piezoceramic plates of a 10 mm×10 mm×0.115 mm^T external size, and Figure 2 shows a middle-sized piezoelectric actuator having an external size of 25 mm×25 mm×36 mm^H that consisted of 288 piezoceramic plates of a 10 mm×10 mm×0.115 mm^T external size. Figure 3 shows a large-sized actuator having an external size of 102 mm×102 mm×170 mm^H, and Figure 4 shows a configuration of the actuator. The actuator consisted of 30 piezoceramic plates of a 100 mm×100 mm×5 mm^T external size. Table 1 shows specifications of the piezoelectric actuators used for the tests. The maximum displacement and the maximum force in design of the small-sized actuator when a 100 V voltage was input were 15 μm and 3.43 kN respectively, those of the middle-sized actuator when a 100 V voltage was input were 30 μm and 21.4 kN respectively, and those of the large-sized actuator when a 5 kV voltage was input were 145 μm and 345 kN respectively.

3. MAGNETOSTRICTIVE ACTUATORS

Two types of magnetostrictive actuators were tested to investigate its performances. Figure 5 shows a middle-sized magnetostrictive actuator used for the tests, and Figure 6 shows the cross-sectional view of the actuator. The actuator consisted of a magnetostrictive rod of a 75 mm length and a 12 mm diameter surrounded by a driving coil. The rod was held by a permanent magnet to produce a bias field, and was always lengthened by the magnetic bias. Therefore the actuators could be operated by a control voltage without a bias. Figure 7 shows a large-sized actuator used for the tests, and Figure 8 shows the cross-sectional view of the actuator. The actuator consisted of ten magnetostrictive plates of a 30 mm diameter and a 75 mm thickness surrounded by a driving coil. The plates were held by a permanent magnet, and were always lengthened by the magnetic bias. Table 2 shows specifications of the magnetostrictive actuators used for the tests. The maximum displacement and the maximum force in design of the middle-sized actuator when ±2.1 A currents were input were ±35 μm and ±1.85 kN respectively, but those of the large-sized actuator were unknown.

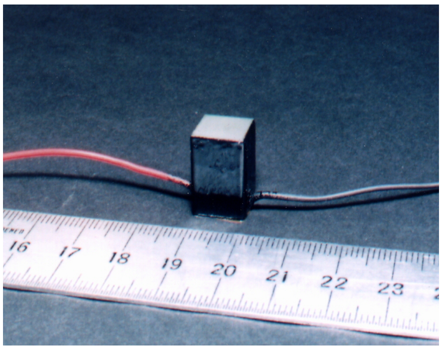


Figure 1. Small-sized piezoelectric actuator

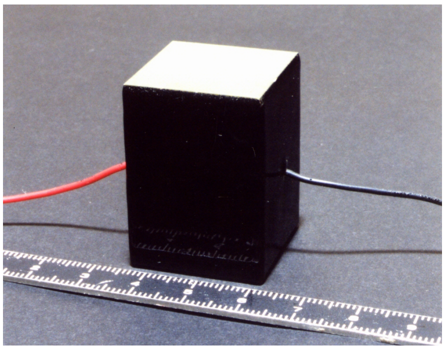


Figure 2. Middle-sized piezoelectric actuator

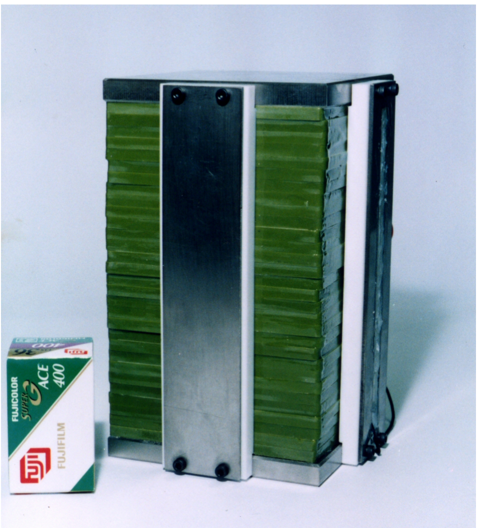


Figure 3. Large-sized piezoelectric actuator

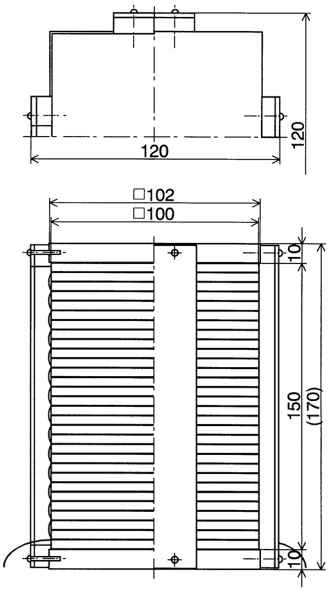


Figure 4. Configuration of large-sized piezoelectric actuator

Table 1. Specifications of piezoelectric actuators

	Small-sized	Middle-sized	Large-sized
External size	$10\times10\times18^{H}$ mm	$25\times25\times36^{H}$ mm	$102\times102\times170^{H}$ mm
Piezoceramic plate	$10\times10\times0.115^{T}$ mm	$25\times25\times0.115^{T}$ mm	$100\times100\times5^{T}$ mm
Piezoceramic material	PZT	PZT	PZT
Number of stacks	144	288	30
Rated input voltage	100 V	100 V	5 kV
Displacement	15 μm	30 μm	145 μm
Force	3.43 kN	21.4 kN	345 kN
Capacitance	6.5 μF	84 μF	2.5 μF

Figure 5. Middle-sized magnetostrictive actuator

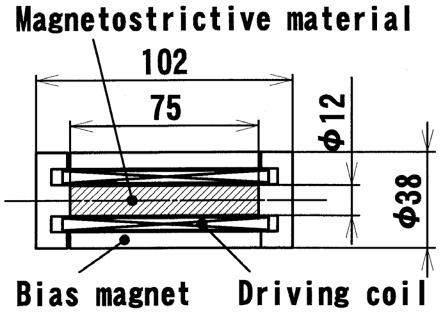


Figure 6. Cross-sectional view of middle-sized magnetostrictive actuator

Figure 7. Large-sized magnetostrictive actuator

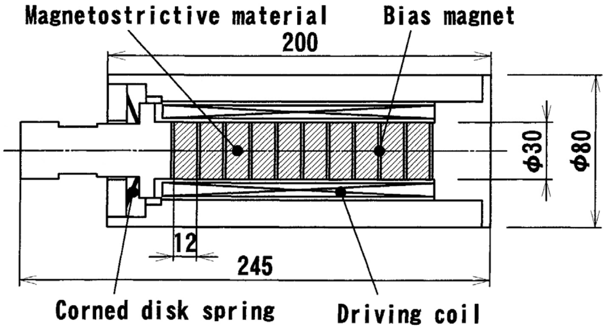


Figure 8. Cross-sectional view of large-sized magnetostrictive actuator

Table 2. Specifications of magnetostrictive actuators

	Middle-sized	Large-sized
External size	$\phi 38 \times 102^{L}$ mm	$\phi 80 \times 245^{L}$ mm
Magnetostrictive material	$\phi 12 \times 75^{L}$ mm	$\phi 30 \times 12^{T}$ mm×10
Rated input current	±2.1 A	±8.0 A
Displacement	±35 μm	----
Force	±1.85 kN	----

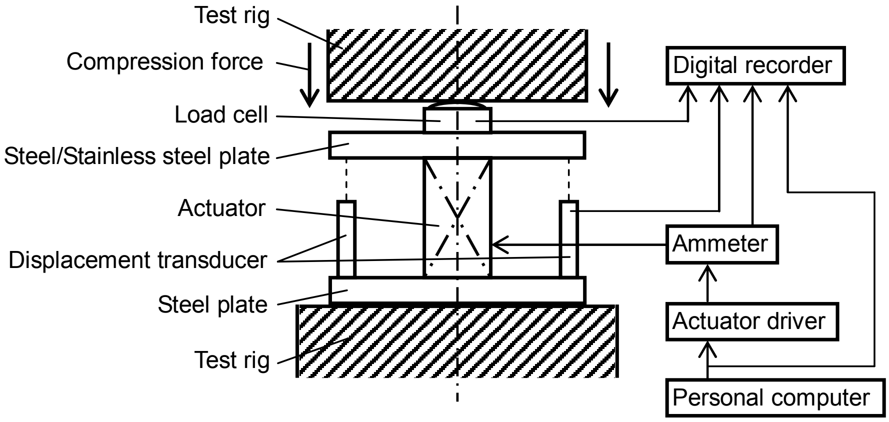


Figure 9. Schematic drawing of test apparatus

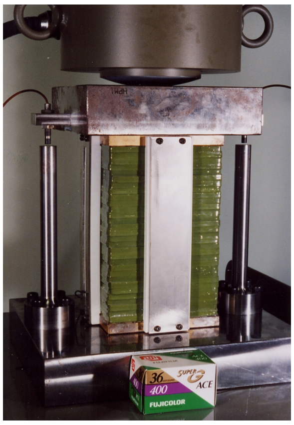


Figure 10. Large-sized piezoelectric actuator under tests

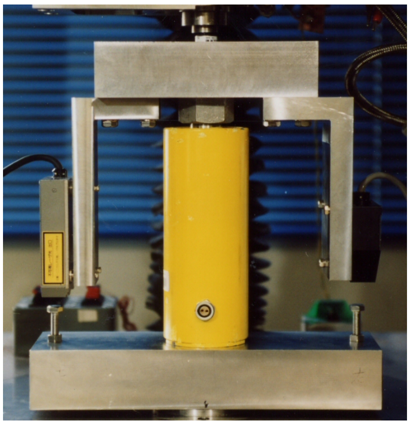


Figure 11. Large-sized magnetostrictive actuator under tests

4. TEST APPARATUS

Figure 9 shows a schematic drawing of a test apparatus for the piezoelectric and magnetostrictive actuators. The actuator was sandwiched between the top and the bottom plates, and was set in the test rig via a load cell. Compression forces to the actuator could be loaded by the test rig. Driving signals generated by a personal computer were input to the actuator via an actuator driver. Displacements of the actuator could be obtained by the mean values of displacements between the top and the bottom plates measured with two displacement transducers attached to the bottom plate, forces of the actuator could be measured with the load cell, and currents in the electric circuit could be measured with an ammeter inserted into the circuit. Figure 10 and Figure 11 show the large-scale piezoelectric actuator and the large-scale magnetostrictive actuator set in the test apparatus respectively. Although steel plates were used for the top and the bottom plates when the piezoelectric actuators were tested, stainless steel plates were used instead of the steel plates when the magnetostrictive actuators were tested.

5. TEST RESULTS

5.1. Test Results of Piezoelectric actuators

Figs. 12 and 13 show relationship between the force and the displacement of the small-sized and the middle-sized actuators under no initial compressive load respectively. The maximum displacement under no initial load and the maximum force under zero displacement condition of the small-sized actuator when a 100 V voltage was input were 14.0 μm and 4.83 kN respectively, and those of the middle-sized actuator when a 100 V voltage was input were 29.7 μm and 21.2 kN respectively. Figure 14 shows relationship between the force and the displacement of the large-sized actuator under an initial compressive load of 196 kN (a pressure of 19.6 MPa). The maximum displacement under the initial load was 94 μm, and the maximum force under zero displacement condition was 270 kN, when a 3.0 kV voltage was input, which was the highest voltage in this test. Although these results are passable, it is expected that the performance will be improved if insulation between electrodes of the piezoceramic plates becomes more perfect and a higher voltage can be applied. The maximum displacements per unit length of piezoelectric actuators were about 0.6-0.8$\times 10^{-3}$, and the maximum forces per unit cross-section area of the piezoelectric ones were about 26-48 N/mm^2. From results as shown in Figs. 12, 13 and 14, Young's modulus of the actuator in each input voltage was identified. Figs. 15, 16 and 17 show relationship between the Young's modulus and the input voltage of each actuator respectively. The Young's moduli of the small-sized and the middle-sized actuator were about 60 GPa and 45GPa respectively, and were comparable to that of the aluminum. Those of the large-sized actuator were about 40-50 GPa.

Figs. 18-20 show relationship between the displacement and the frequency when sinusoidal voltages were input. The displacements of the small-sized and the middle-sized actuators were constant in the frequency range of 1-50 Hz, and those of the large-sized actuators were constant in the frequency range of 0.1-1 Hz. The piezoelectric actuators had enough responses for the large-scale smart structures on the earth.

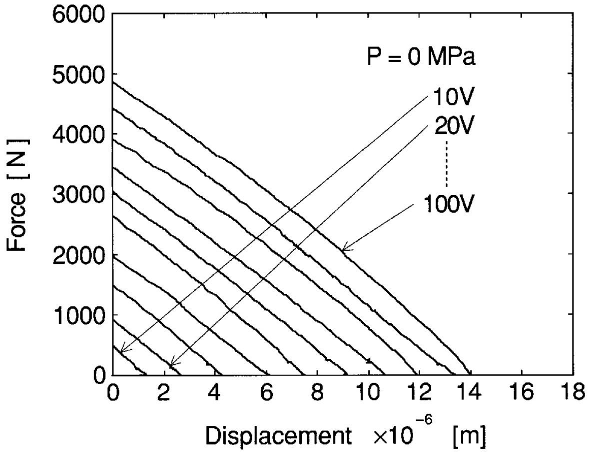


Figure 12. Relationship between force and displacement (Small-sized actuator)

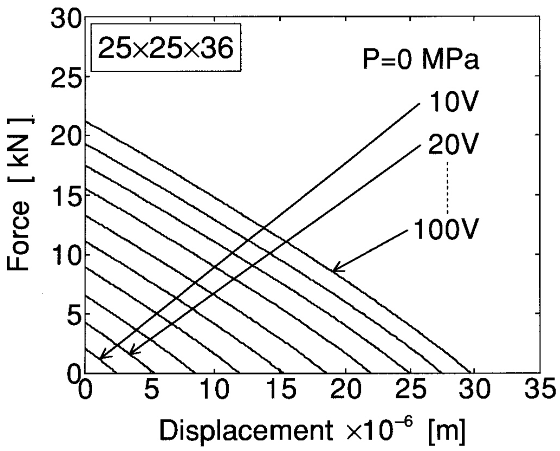


Figure 13. Relationship between force and displacement (Middle-sized actuator)

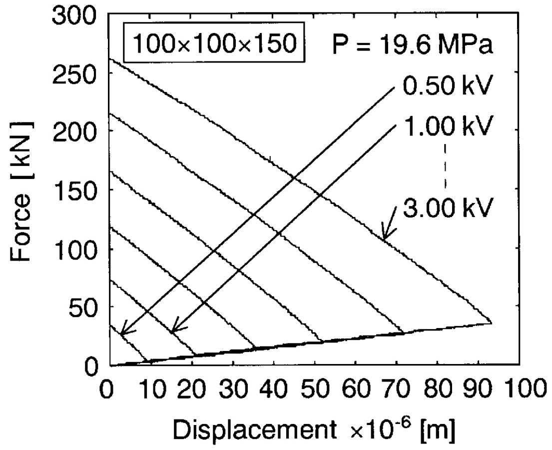


Figure 14. Relationship between force and displacement (Large-sized actuator)

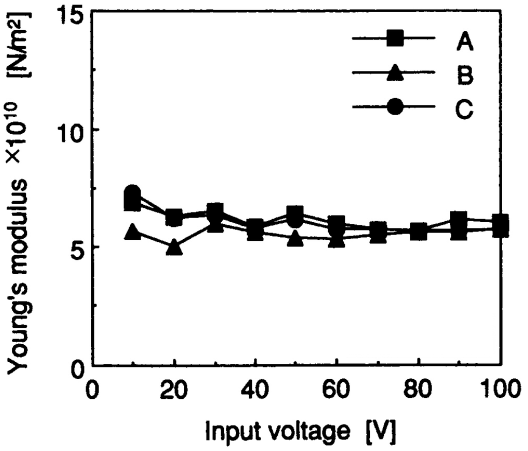


Figure 15. Relationship between Young's Modulus and input voltage (Small-sized actuator)

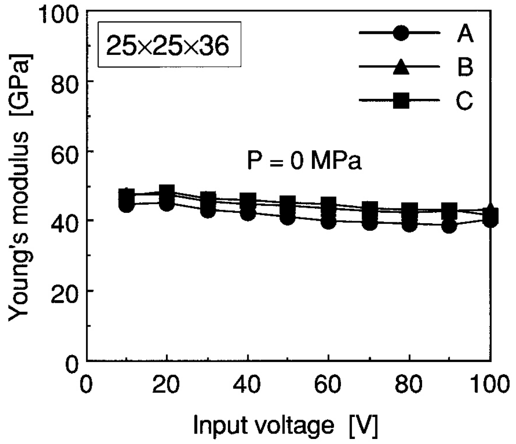


Figure 16. Relationship between Young's Modulus and input voltage (Middle-sized actuator)

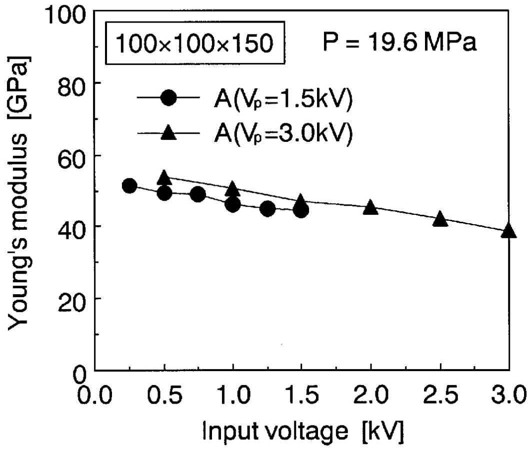


Figure 17. Relationship between Young's Modulus and input voltage (Large-sized actuator)

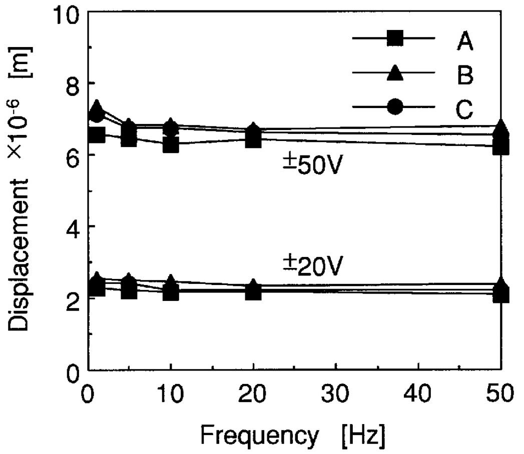


Figure 18. Relationship between displacement and frequency (Small-sized actuator)

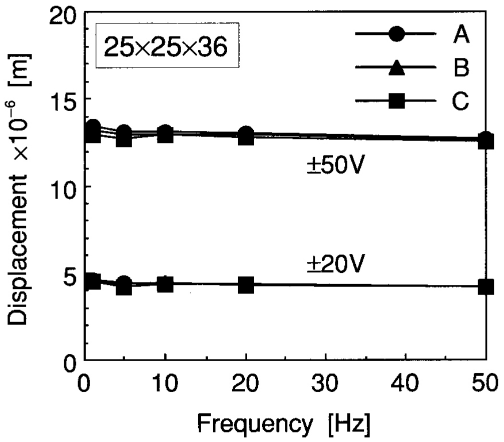


Figure 19. Relationship between displacement and frequency (Middle-sized actuator)

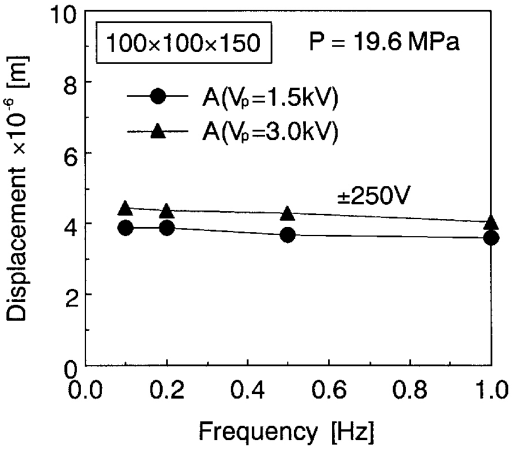


Figure 20. Relationship between displacement and frequency (Large-sized actuator)

5.2. Test Results of Magnetostrictive actuators

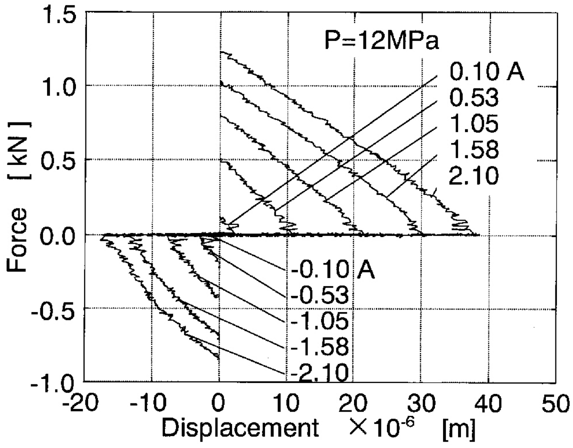
Figs. 21 and 22 show relationship between the force and the displacement of the middle-sized and the large-sized actuators under an initial compressive load of 12 MPa respectively. When ±2.1 A currents were input, the middle-sized actuator produced the maximum forces of 1.21 kN in the pushing direction and of 0.83 kN in the pulling direction, and the maximum displacements of 37.5 μm in the pushing direction and of 16.6 μm in the pulling direction respectively. The large-sized actuator produced the maximum forces of 10.6 kN in the pushing direction and of 5.57 kN in the pulling direction, and the maximum displacements of 63.0 μm in the pushing direction and of 40.0 μm in the pulling direction respectively, when ±8.0 A currents were input. The maximum displacements per unit length of magnetostrictive actuators were about $0.4\text{-}0.5 \times 10^{-3}$, and the maximum forces per unit cross-section area of the piezoelectric ones were about 1.8-3.1 N/mm^2.

Figs. 23-24 show relationship between the displacement and the frequency when sinusoidal currents were input. The displacements of the middle-sized and the large-sized actuators were constant in the frequency range of 1-20 Hz, and they had enough responses for the large-scale smart structures on the earth.

6. CONCLUSIONS

Whether the smart structures can be applied to the large-scale structures on the earth or not, depends on the performances and the costs of the actuators. In this study, the piezoelectric actuators of stack type and the magnetostrictive actuators were tested to investigate its performances. The main results are summarized as follows:

1. The piezoelectric actuators and the magnetostrictive ones had enough responses for the large-scale smart structures on the earth.
2. The maximum displacements per unit length of both actuators were about $0.4\text{-}0.8 \times 10^{-3}$.
3. Although the maximum forces per unit cross-section area of the magnetostrictive actuators were about 1.8-3.1 N/mm^2, those of the piezoelectric ones were 26-48 N/mm^2, and were much larger.
4. It is suitable that piezoelectric actuators are used when much larger forces are necessary such as active vibration control of buildings and bridges.
5. For active microvibration control of precision machines, the magnetostrictive actuators are suitable ones than the piezoelectric actuators, because the magnetostrictive actuators are far stronger than the piezoelectric actuators which are slightly brittle ceramics.



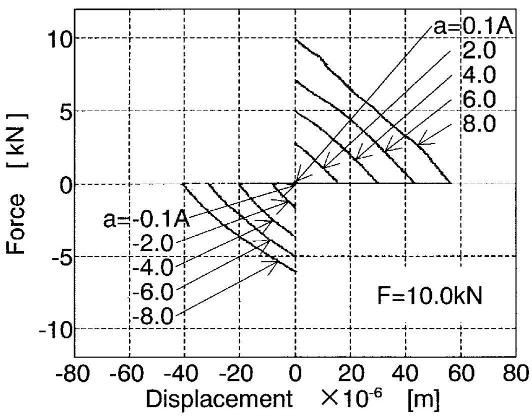
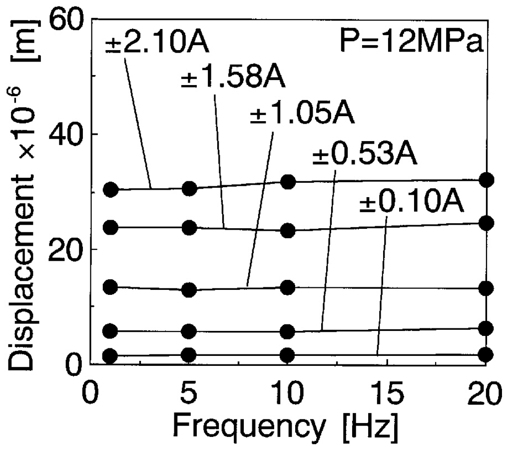


Figure 21. Relationship between force and displacement (Middle-sized actuator)

Figure 22. Relationship between force and displacement (Large-sized actuator)



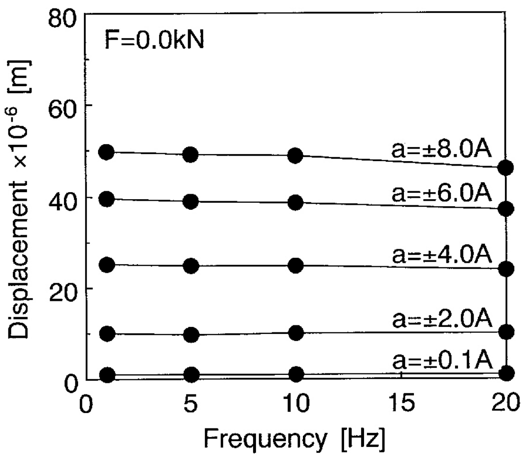


Figure 23. Relationship between displacement and frequency (Middle-sized actuator)

Figure 24. Relationship between displacement and frequency (Large-sized actuator)

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