

Characterization of Multilayer Piezoelectric Actuators for Use in Active Isolation Mounts

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Abstract

Active mounts are desirable for isolating spacecraft science instruments from on-board vibrational sources such as motors and release mechanisms. Such active isolation mounts typically employ multilayer piezoelectric actuators to cancel these vibrational disturbances. The actuators selected for spacecraft systems must consume minimal power while exhibiting displacements of 5 to 10 μm under load. This report describes a study that compares the power consumption, displacement, and load characteristics of four commercially available multilayer piezoelectric actuators. The results of this study indicate that commercially available actuators exist that meet or exceed the design requirements used in spacecraft isolation mounts.

Introduction

Many spacecraft require vibration-suppression systems to isolate science instruments from vibrational disturbances such as mechanical motors or the release of spacecraft components on orbit. These disturbances are transmitted to the science instruments through the mounting hardware, thus affecting the accuracy of the science data that are gathered. One concept for vibration suppression uses active mounts to isolate science payloads from vibrational disturbances during science data collection (refs. 1 and 2).

In a previous study at Langley Research Center, active isolation mounts that used piezoelectric actuators were tested by using the Earth Observing System Dynamic Test Bed (ref. 3). In the Langley study, each active mount was equipped with strain-gauge sensors, which provided feedback to a controller. The controller regulated voltage to the piezoelectric actuator in response to micrometer-scale disturbances. In the Langley design, each piezoelectric actuator was required to produce displacements between 5 and 10 μm under loads up to 9 kg. When these active mounts were used, the payload pointing error was reduced by 50 to 80 percent, thus demonstrating concept feasibility.

The Langley active-isolation-mount concept employs multilayer piezoelectric ceramic actuators to reject vibrations. Multilayer actuators are produced by stacking thin layers of piezoelectric ceramics together either by adhesive bonding or by cofiring tape cast sheets (refs. 4 and 5). Depending on actuator size, multilayer stacks exhibit micrometer-scale displacements under loads up to several hundred kilograms.

When multilayer piezoelectric actuators are used in spacecraft systems, the actuators should be selected to minimize power consumption while maintaining sufficient performance to meet design requirements. This report describes the results of a study comparing the power consumption, displacement, and load characteristics of four commercially available multilayer piezoelectric actuators.

Experimental Procedure

Test Specimens

Based on the displacement and load requirements from the Langley design, multilayer actuators from four suppliers were evaluated. The supplier, part number, and dimensions of each actuator are provided in table I. Additionally, figure 1 shows a photograph of the components tested in this work.

As shown in figure 1, all actuators tested had an insulating coating except for the Physik Instrumente (PI) components, which were enclosed in cylindrical stainless-steel housings. All actuators were supplied with electrical leads for applying voltage. Three actuators from each supplier were evaluated to determine the repeatability of their properties and to enable a statistical interpretation of the data.

Power Consumption

Because the majority of spacecraft vibrations occur at low frequencies, the capacitance and the dielectric dissipation ($\tan \delta$) of each actuator component were measured from 25 to 200 Hz by using an LCR meter. The power consumed during operation at each frequency was then determined using the relation (ref. 6)

$$P_p = \pi \cdot f \cdot C \cdot U^2 \quad (1)$$

where

| | |
|-------|--|
| P_p | peak power consumed by the actuator, W |
| f | frequency of operation, Hz |
| C | capacitance at the frequency of operation, F |
| U | peak-to-peak operational voltage, V_{p-p} |

Because all displacement measurements in this study were performed by using a 100- V_{p-p} input signal, this value was used as the operational voltage U in all calculations.

Resonance Measurements

The resonance properties of each actuator were measured by using an impedance analyzer. The frequency of minimum impedance, the resonance frequency (f_r), and the frequency of maximum impedance, the antiresonance frequency (f_a), were recorded. By using these values, the effective electromechanical coupling coefficient (k_{eff}) was calculated by using the following relation (ref. 7):

$$k_{\text{eff}} = \sqrt{\left(\frac{f_a^2 - f_f^2}{f_a^2}\right)} \quad (2)$$

Displacement and Load Measurements

The displacement properties of the piezoelectric actuators were measured by using a noncontacting, fiber-optic displacement sensor. This sensor puts out a voltage proportional to the distance between the actuator surface and the sensor. Thus, as the piezoelectric stack is activated by the application of an ac voltage, the total dynamic motion of the stack is measured.

The displacement properties of the stacks were measured by using an input voltage of 100 V_{p-p} at frequencies of 0.2, 1, 10, 20, 30, and 40 Hz. To generate the input signals, a function generator was used in conjunction with a voltage amplifier. The displacement properties of the actuators were determined by displaying the input signal and fiber-optic output on an X-Y plot by using an oscilloscope. A schematic representation of a typical displacement-versus-voltage plot, also referred to as a strain loop, is shown in figure 2.

In some cases, the drive condition employed yielded a displacement-versus-voltage plot that exhibited a *butterfly* strain loop. In these instances, a dc offset voltage was used to negate this strain behavior, thereby permitting a direct comparison of the properties under evaluation.

The displacement properties of the actuator stacks were measured under three load conditions: namely zero load (free displacement), 4.5 kg, and 9 kg. To characterize the actuation properties of the stacks under load, a test fixture was employed that translates a static load vertically through a linear bearing. Because the surface of the actuator was covered by the load-bearing shaft, the fiber-optic sensor monitored the dynamic motion of the platform supporting the load above the piezoelectric actuators (fig. 3).

Results

Power Consumption

The capacitance data for the four stacks ranged from 0.45 μF to greater than 7 μF at 100 Hz. The PI and the

Morgan Matroc actuators exhibited the lowest capacitance values, measuring 0.45 μF and 1.8 μF , respectively. The highest capacitance values of the actuators tested were in excess of 7 μF for the Tokin and the Piezo Systems, Inc. (PSI) components. The Morgan Matroc actuators demonstrated the lowest dielectric dissipation ($\tan \delta$), with a value of 0.017 at 100 Hz. The other actuators exhibited dissipation values ranging from 0.022 to 0.024. Both the capacitance and the dissipation data were found to be independent of frequency from 25 to 200 Hz. Graphs showing the average capacitance and $\tan \delta$ values for the four actuators as a function of frequency are shown in figures 4 and 5, respectively.

The low capacitance of the PI actuators resulted in the consumption of significantly less power when compared with the other components tested. Only 1.4 W of peak power was required to operate these actuators at 100 Hz, compared to 5.7 W for the Morgan Matroc actuators and approximately 23 W for the PSI and the Tokin actuators. A graph comparing the peak power consumed as a function of frequency for the four actuators is provided in figure 6. Additionally, a summary of the dielectric properties and power consumption characteristics of the actuators at 100 Hz is shown in table II.

Resonance Properties

The PI actuators also exhibited the lowest resonance frequency (37.5 kHz) of the four actuators tested. All other actuators possessed resonance frequencies greater than 57 kHz, with the Morgan Matroc specimens showing the highest values at approximately 62 kHz. As an example of these data, a typical impedance-versus-frequency plot for a PSI component, with the resonance and antiresonance frequencies indicated, is shown in figure 7.

In addition to the low-resonance frequency values, the PI components exhibited the lowest electromechanical coupling coefficient k_{eff} with a value of 0.45. The PSI and the Tokin stacks exhibited the highest k_{eff} values of the actuators tested, 0.80. The Morgan Matroc specimens possessed values of 0.57. The frequencies of resonance and antiresonance and the average values for k_{eff} for the four actuators are summarized in table III.

Displacement and Load Properties

Three of the piezoelectric stacks evaluated in this study exhibited a butterfly strain behavior when operated at 100 V_{p-p} (i.e., ± 50 V). However, when a 20-Vdc offset was applied to the 100-V_{p-p} input signal (i.e., 70/-30 V), all three materials displayed symmetrical displacement-versus-voltage characteristics. The elimination of this asymmetric strain behavior allowed direct comparison of displacement properties. An example of

the nonideal strain behavior and the elimination of this behavior through the use of a dc offset are shown in figures 8 and 9, respectively.

Using drive conditions which produce symmetric displacement-versus-voltage plots, three of the piezoelectric stacks exhibited free displacement values ranging from 10 to 15 μm at 0.2 Hz. The fourth stack, supplied by Morgan Matroc, possessed an average displacement of 7.4 μm at 0.2 Hz. Throughout this work, slight increases in free displacement were observed for all four stacks as the operational frequency was increased. However, the increase in displacement varied among the actuators tested, and no trend as a function of frequency could be established. As examples of this behavior, the average displacement of the Morgan Matroc and the PI stacks, as a function of frequency, is shown in figure 10.

When tested under increasing load, the displacement of all four piezoelectric stacks was reduced. The motion of the PI stacks was found to decrease most significantly with the displacement at 1 Hz reduced from 14.9 μm at no load to 5.3 μm when operated under a 9-kg load. Conversely, the Morgan Matroc stacks were found to be least affected by the addition of a 9-kg load. The average motion of these stacks was reduced from 8.4 to 8.0 μm at 1 Hz. The average displacement as a function of load for all four stacks is compared in figures 11 and 12. These two graphs show the decrease in piezoelectric motion when operated under 0-, 4.5-, and 9-kg loads at frequencies of 0.2 Hz and 1 Hz, respectively. The PSI and the Tokin actuators exhibited the highest displacements at the maximum load condition of 9 kg.

The displacement properties of the PSI and the Tokin stacks were not measured over the 20- to 40-Hz frequency range. These stacks were not characterized at these frequencies because the power required to activate the stacks at these frequencies exceeded the 5-W output capacity of the voltage amplifier used to activate these materials. The power required to operate these stacks was predicted by the results of the power consumption calculations described previously.

Discussion

In this work, the free displacement, the displacement under load, the power consumption, and the electromechanical coupling coefficients of four piezoelectric actuator stacks were evaluated. The results of this study indicate that all the actuators tested meet the displacement requirement of 5 to 10 μm under a 9-kg load for the Langley Research Center active isolation mounts.

Throughout this study, the PI stacks were found to exhibit lower k_{eff} and displacement-under-load charac-

teristics than the other materials evaluated. The lower properties of these stacks may be partially attributable to the metal housings surrounding these piezoelectric actuators. In this design, the motion of the piezoelectric element is restricted by the surrounding case, thus limiting its motion under load when compared with the other stacks evaluated in this study. Additionally, these devices were found to exhibit lower resonant frequencies and k_{eff} values than the other actuators. This result may also be attributed to the presence of the steel housing.

The displacement properties of the three other stacks were less affected by static loading. The primary difference among the three remaining stacks is the power consumed during operation. Although exhibiting less displacement under load, the PI stack consumed only 1.4 W of power at 100 Hz. The lower power consumption and performance under load are both attributable to the smaller cross-sectional area of the PI actuators. The small cross-sectional area reduces the power required by decreasing the capacitive load of the stack, but it also reduces the force output of the device. Therefore, the free-displacement results were comparable to the other actuators evaluated, but the displacement under a 9-kg load was significantly less than that of the other materials.

Two of the actuators, the PSI and the Tokin stacks, could not be measured above 20 Hz because the power required to operate the stacks at these frequencies was in excess of the output capability of the voltage amplifier used to activate the piezoelectric components. The remaining actuator evaluated in this study, provided by Morgan Matroc, exhibited an average free displacement of approximately 8 μm . These stacks exhibited only a slight reduction in displacement under load while requiring 5.7 W of power for operation at 100 Hz. This power requirement is the second lowest of the materials evaluated in this report and is significantly less than the 23 W required to operate the PSI and the Tokin actuators.

In selecting a piezoelectric stack for application in an active system, the free displacement and the displacement-under-load performance of these materials must be fully evaluated. As observed in this report, the displacement properties of all four piezoelectric stacks were found to be independent of operational frequency. For isolation over a range of vibrational frequencies, this result suggests that a position sensor must be incorporated into the active system in order to accurately control the actuator motion.

Additionally, the power necessary to operate the piezoelectric actuator at a given frequency must also be considered. The power required to drive a piezoelectric actuator under given operational conditions may be determined using equation (1). This equation provides a

means of determining whether or not a candidate actuator possesses suitable properties for use in spacecraft systems where only limited power may be available.

Conclusions

The results of this study indicate that commercially available piezoelectric actuators exist that meet or exceed the displacement and load requirements for spacecraft active isolation mounts. Based on the need to minimize power consumption, the Physik Instrumente (PI) actuators proved highly satisfactory for the Langley Research Center active-isolation-mount design. Although they exhibit lower displacement under load than the other actuators tested, the PI actuators do meet the design criteria for this specific application. These actuators exhibited displacements of 5.3 μm under the maximum load condition of 9 kg.

The design requirements used in this study are based on specific vibration levels and instrument parameters. As the size and mass of spacecraft components change, the design requirements for future active isolation mounts will change as well. Therefore, actuators exhibiting greater displacements or load-bearing capabilities may be needed for future systems.

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Table I. Suppliers, Part Numbers, and Dimensions of Piezoelectric Actuators Evaluated

| Supplier | Part number | Dimensions |
|--------------------------------------|--------------|---------------------------|
| Morgan Matroc | PZT-5H | 10 mm × 10 mm × 20 mm |
| Physik Instrumente (PI) ^a | P-810.10 | 6 mm (dia) × 20 mm |
| Piezo Systems, Inc. (PSI) | TS18H5-202 | 9.9 mm × 9.9 mm × 18.3 mm |
| Token | NLA-10×10×18 | 10 mm × 10 mm × 18 mm |

^aActuator packaged inside a stainless-steel housing.

Table II. Capacitance, Dielectric Dissipation ($\tan \delta$), and Peak Power Consumption at 100 Hz for Four Actuators Tested

| Source | Capacitance, μF | $\tan \delta$ | Peak power, W |
|---------------|----------------------------|---------------|---------------|
| Morgan Matroc | 1.82 | 0.017 | 5.7 |
| PI | 0.45 | 0.024 | 1.4 |
| PSI | 7.42 | 0.023 | 23.3 |
| Token | 7.40 | 0.022 | 23.2 |

Table III. Resonance (f_r), Antiresonance (f_a), and Effective Electromechanical Coupling Coefficients (k_{eff}) for Multilayer Actuators Evaluated

| Source | f_r , kHz | f_a , kHz | k_{eff} |
|---------------|-------------|-------------|------------------|
| Morgan Matroc | 61.7 | 75 | 0.57 |
| PI | 37.5 | 42.1 | 0.45 |
| PSI | 57.1 | 95.5 | 0.80 |
| Token | 57.6 | 96.5 | 0.80 |

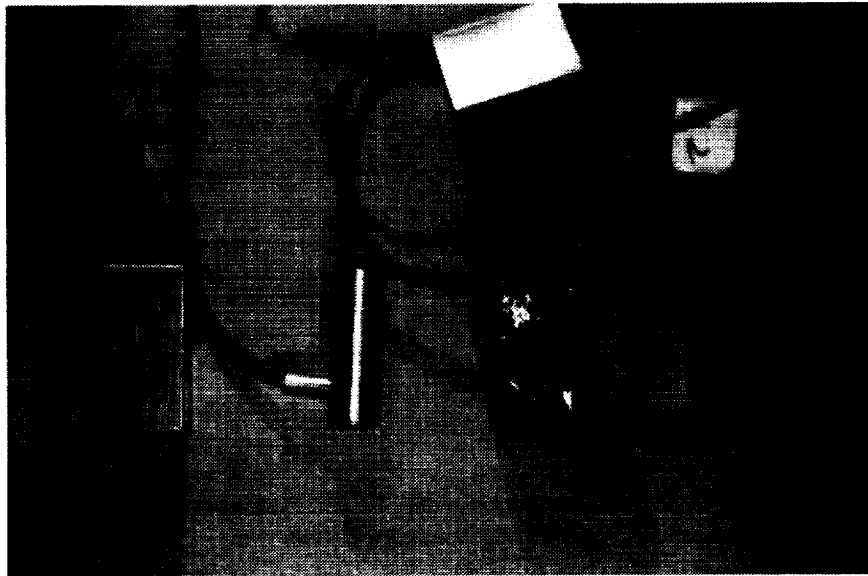


Figure 1. Actuators evaluated (from left to right: Morgan Matroc, PI, PSI, and Tokin).

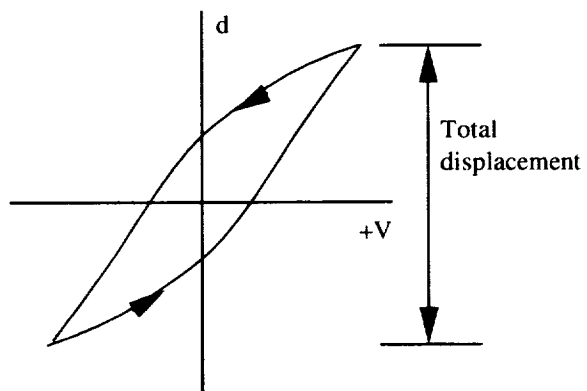


Figure 2. Typical example of the displacement d versus voltage V behavior of piezoelectric actuators.

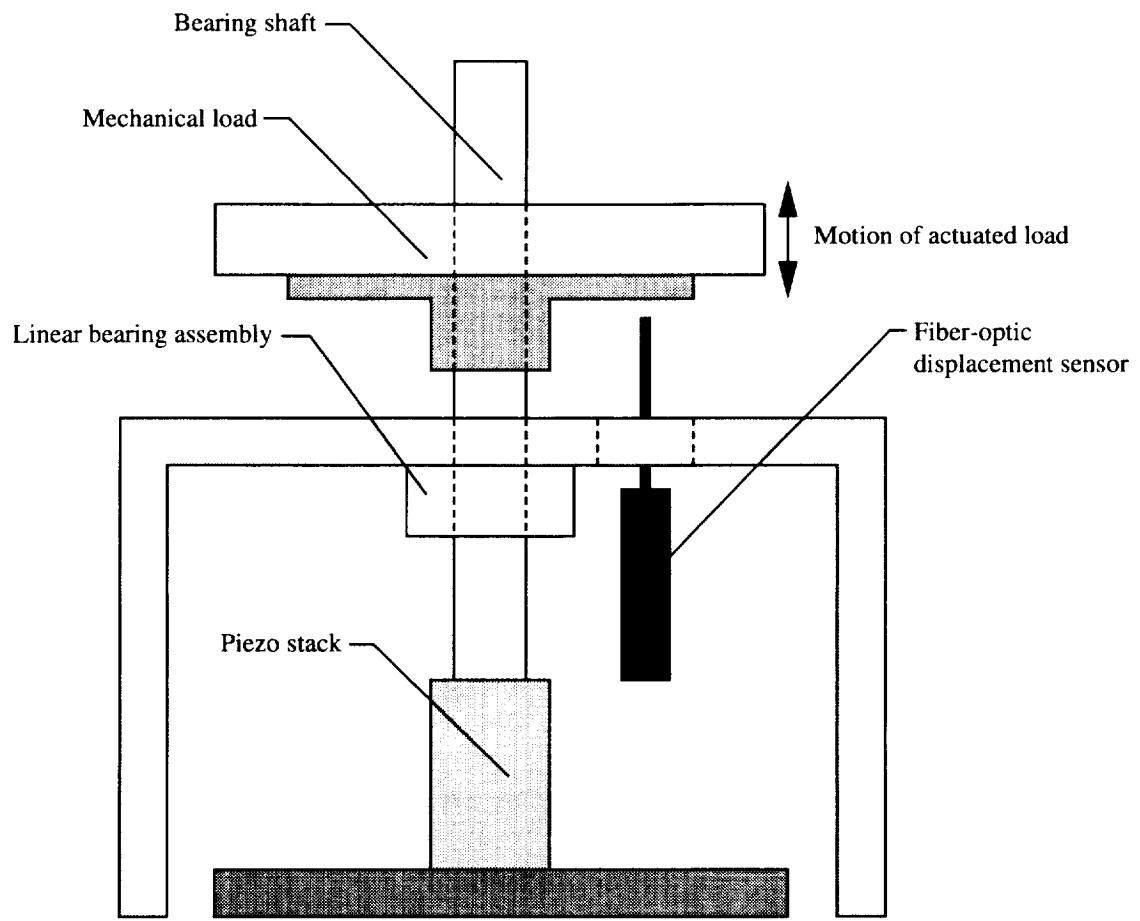


Figure 3. Test configuration for measuring the displacement properties of piezoelectric actuators under load.

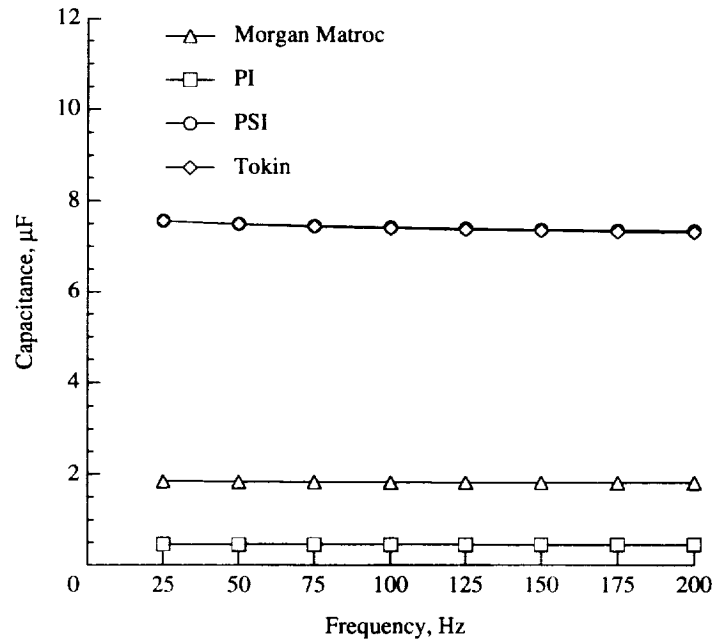


Figure 4. Capacitance versus frequency behavior of the piezoelectric stacks from 25 to 200 Hz.

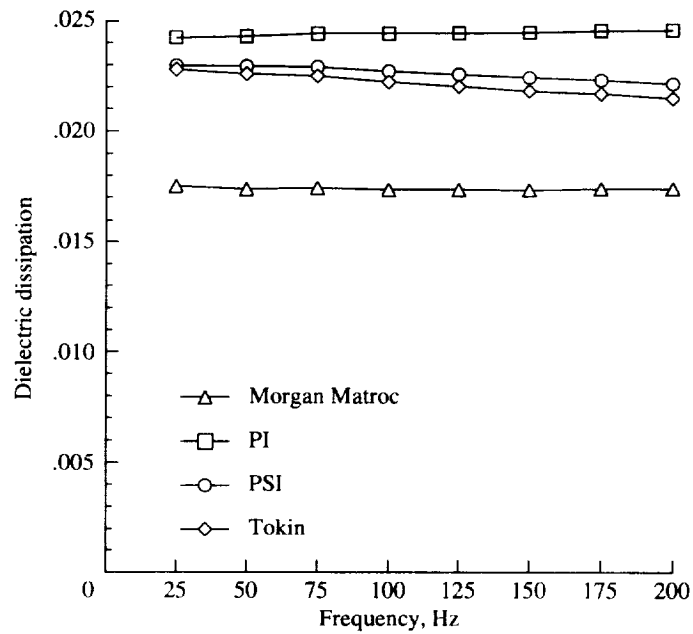


Figure 5. Dielectric dissipation ($\tan \delta$) versus frequency behavior of piezoelectric stacks from 25 to 200 Hz.

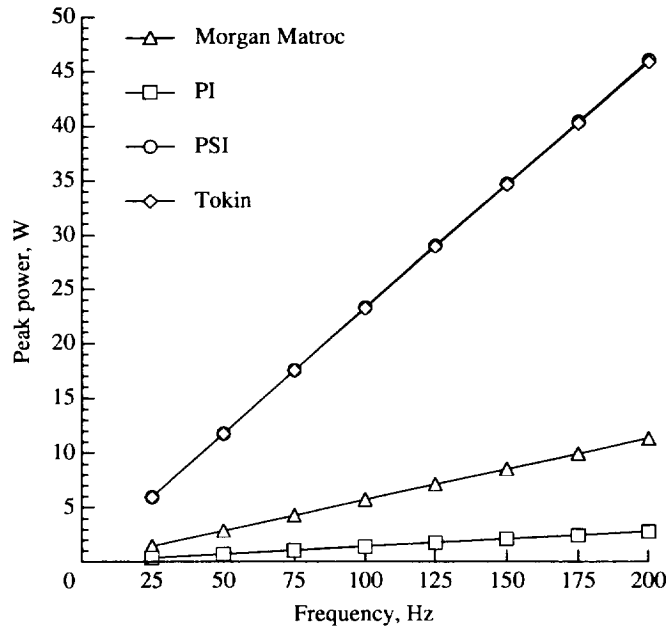


Figure 6. Peak power consumption versus frequency behavior of piezoelectric stacks from 25 to 200 Hz.

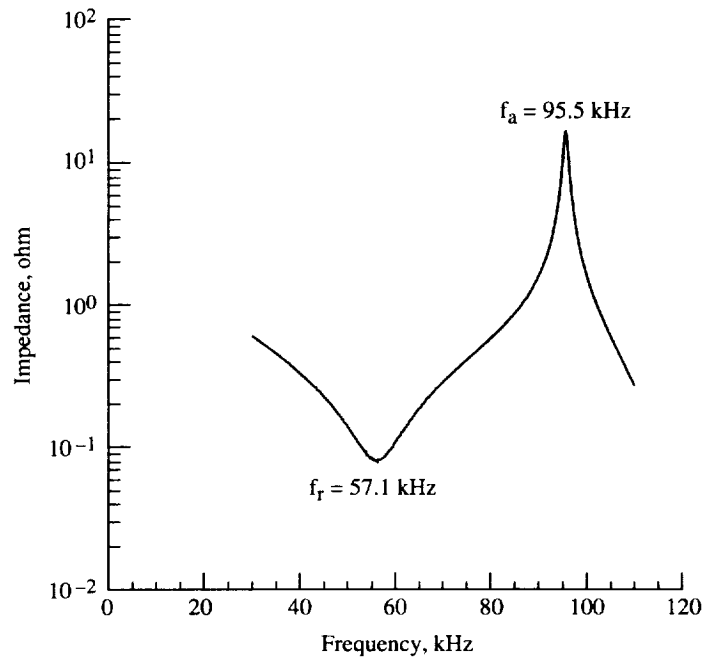


Figure 7. Typical example of an impedance-versus-frequency plot for PSI actuator that indicates the resonance frequency (f_r) and the antiresonance frequency (f_a).

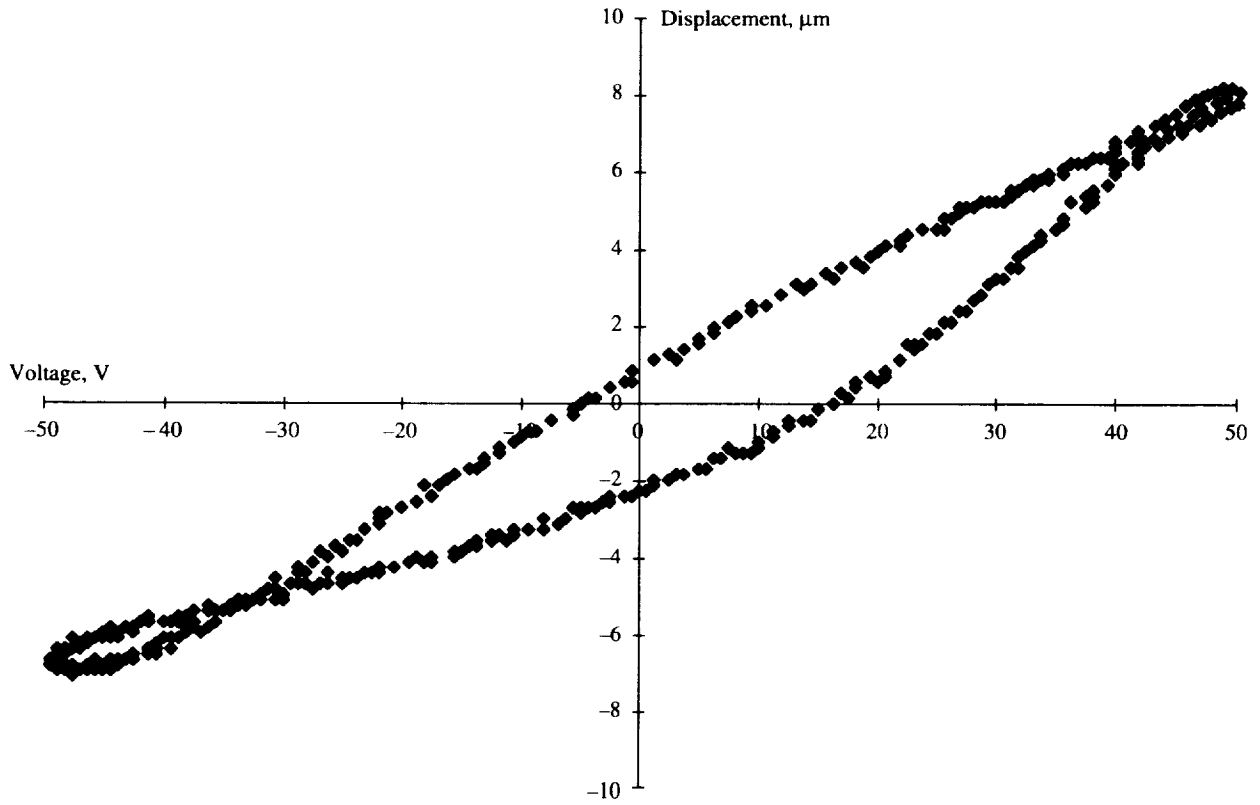


Figure 8. Typical example of the *butterfly* strain behavior of a PSI piezoelectric stack operated under no load at a frequency of 1 Hz by using a voltage of $100 V_{p-p}$ ($\pm 50 V$) with no dc offset. The total dynamic motion shown is approximately $16 \mu m$ ($\pm 8 \mu m$).

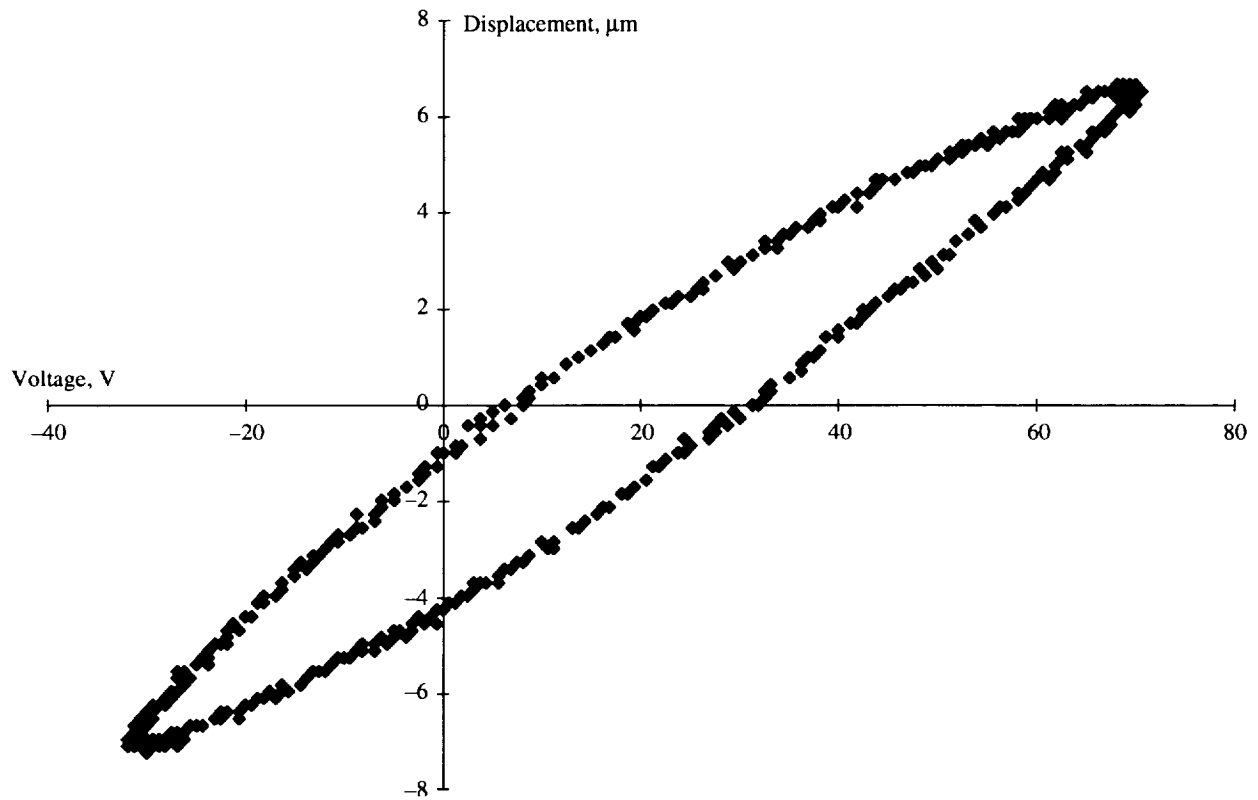


Figure 9. Typical example of uniform strain behavior of PSI piezoelectric stack operated under no load at a frequency of 10 Hz by using a voltage of $100 V_{p-p}$ with a 20-V dc offset (+70/-30 V). The total dynamic motion shown is approximately $14 \mu m (\pm 7 \mu m)$.

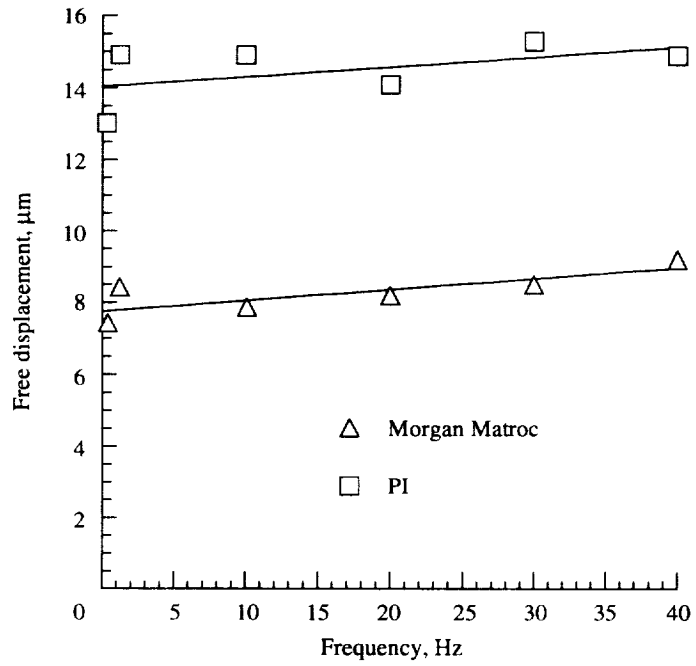


Figure 10. Average free displacement of Morgan Matroc and PI stacks as a function of operational frequency.

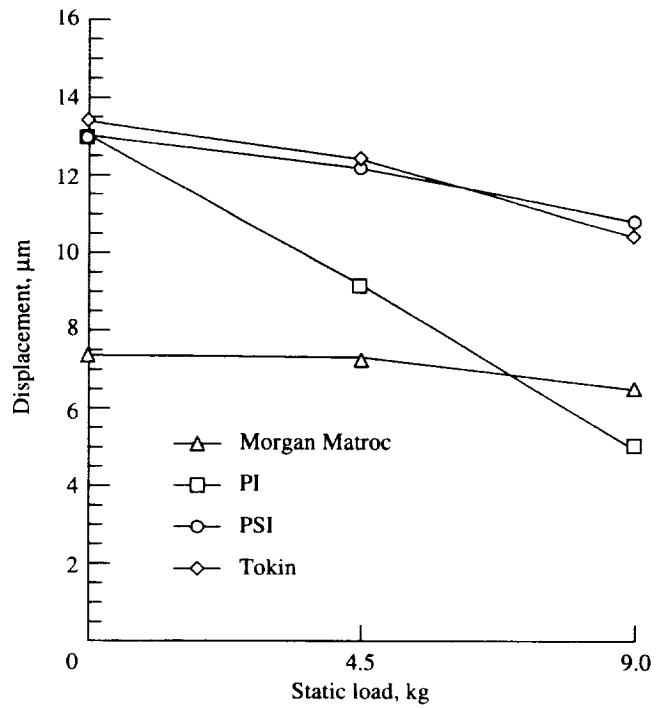


Figure 11. Average displacement of piezoelectric stacks measured under 0-kg, 4.5-kg, and 9-kg static loads at 0.2 Hz.

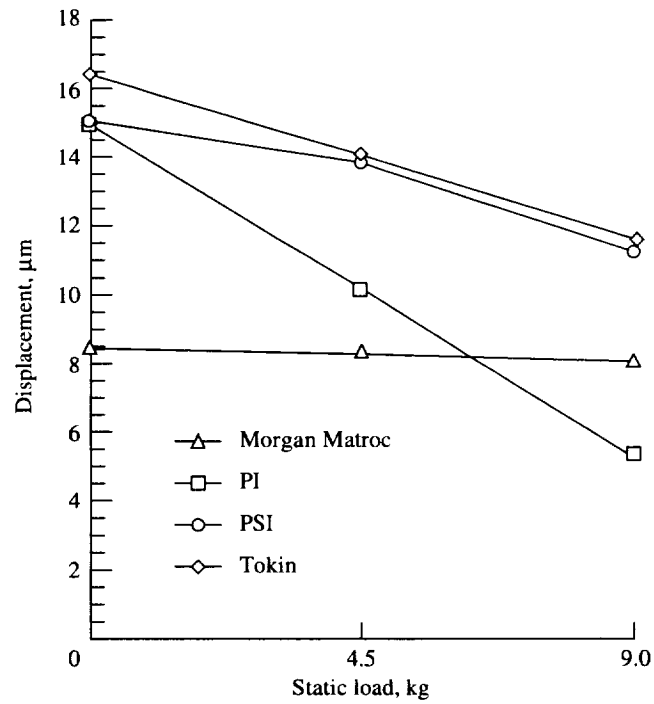


Figure 12. Average displacement of piezoelectric stacks measured under 0-kg, 4.5-kg, and 9-kg static loads at 11 Hz.

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