Extended Life PZT Stack Test Fixture.

M. Badescu[a*], S. Sherrit[a], X. Bao[a], J. Aldrich[a], Y. Bar-Cohen[a], C. Jones[a]
[a]Jet Propulsion Laboratory, California Institute of Technology, (MS 67-119), 4800 Oak Grove Drive, Pasadena, CA 91109-8099

ABSTRACT

Piezoelectric stacks are being sought to be used as actuators for precision positioning and deployment of mechanisms in future planetary missions. Beside the requirement for very high operation reliability, these actuators are required for operation at space environments that are considered harsh compared to normal terrestrial conditions. These environmental conditions include low and high temperatures and vacuum or high pressure. Additionally, the stacks are subjected to high stress and in some applications need to operate with a very long lifetime durability. Many of these requirements are beyond the current industry design margins for nominal terrestrial applications. In order to investigate some of the properties that will indicate the durability of such actuators and their limitations we have developed a new type of test fixture that can be easily integrated in various test chambers for simulating environmental conditions, can provide access for multiple measurements while being exposed to adjustable stress levels. We designed and built two test fixtures and these fixtures were made to be adjustable for testing stacks with different dimensions and can be easily used in small or large numbers. The properties that were measured using these fixtures include impedance, capacitance, dielectric loss factor, leakage current, displacement, breakdown voltage, and lifetime performance. The fixtures characteristics and the test capabilities are presented in this paper.

KEYWORDS: Extended life test, test fixtures, piezoelectric stacks.

1. INTRODUCTION

A variety of NASA missions, including, the Space Interferometer Mission (SIM), use precision mechanisms for the control of mirrors surface position. The precision requirements of these mechanisms are in the microns to nanometers range. In some of these applications the working environment is considered harsh compared to normal terrestrial conditions. These environmental conditions include low and high temperatures and vacuum or high pressure. Additionally, the drive actuators are subjected to high stress and in some applications they need to operate over a very long lifetime. Many of these requirements are beyond the current industry design margins for nominal terrestrial applications. The use of piezoelectric multilayer actuators has been increasingly proposed as a solution to achieve the required high precision position control. The stability of the actuation mechanism and the ability to sense and control the actuation at this level can be compromised by hysteresis, thermal instability, piezoelectric creep, aging, and material property degradation. A number of manufacturers produce co-fired multilayer actuators but the working conditions for which these products were developed do not cover the extended lifetime operation that we are seeking to investigate. Since the development of new products to meet specific requirements beyond the limits of the existing industry standards is expensive and time consuming we decided to assess the appropriateness of existing products made by four separate suppliers.

In order to investigate some of the properties and limitations of existing piezoelectric stacks we have developed a new type of test fixture that can be easily integrated in various test chambers for simulating environmental conditions, can provide access for multiple measurements while being exposed to adjustable stress levels, and can accommodate various stacks in a defined size range. The fixture can be adjusted for testing different dimensions stacks and can be easily used in small or large numbers. One test fixture model that we fabricated can be used for testing piezoelectric stacks with cross sections up to 10mmx10mm and length from 15mm to 20mm. The properties

[*] Mircea.Badescu@jpl.nasa.gov; phone 818-393-5700; ndeaa.jpl.nasa.gov

that were measured using this fixture include impedance, capacitance, dielectric loss factor, leakage current, displacement, breakdown voltage, and lifetime performance. Another test fixture model that was developed can accommodate one or two piezoelectric stacks with diameter up to 20mm and length from 10mm to 20mm. The fixtures characteristics and test capabilities are presented in this paper.

1.1 Piezoelectric Multilayers

Piezoelectric co-fired stacks or multilayers are used in a variety of applications that require relatively high stress and larger strain than bulk piezoelectric materials can produce. These applications include micro-positioning systems[1] solid state pumps and switches[2], noise isolation mounts[3] and ultrasonic drills and stacked ultrasonic transducers[4]. A variety of papers[5,6,7], have been published on fabrication and characterization of the piezoelectric stack using quasistatic techniques. Figure 1 shows the nominal configuration of a piezoelectric multilayer. The piezoelectric layers are connected mechanically in series and electrically in parallel. The piezoelectric and the electrode materials are placed in a consolidated form and co-fired to produce a monolithic block of material with electrodes that are alternately connected. After co-firing, the stack is poled by raising the temperature closer to the Curie temperature and applying an electric field greater than the coercive field. In some cases, small chips of these co-fired stacks are bonded together to form longer stacks.

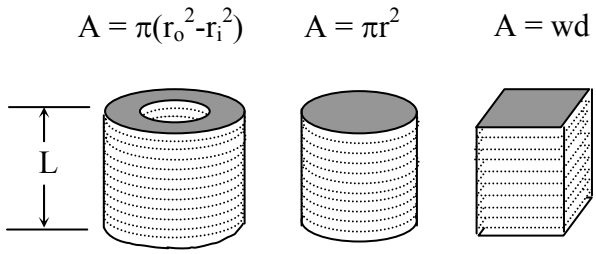

FIGURE 1: A schematic diagram of possible stack configurations.

1.2 Lifetime tests

In an effort to determine the lifetime and fatigue behavior under AC operation we designed, fabricated and tested a test system that addresses the need to test the ability of piezoelectric stacks to operate over a long time simulating an equivalent minimum of 5 years. Since there are many possible actuation mechanisms that need to be tested and these mechanisms have considerably different performance, it is impossible to perform a single lifetime test that encompasses all mechanisms. Therefore, a choice was made to reduce the scope of the accelerated testing to mimic or at least bound one mechanism which required large stroke. The tests that were sought to be made are intended to provide a guide on the performance of PZT stacks. In order to accelerate the lifetime test we had to increase the frequency of excitation which also increases the dissipated power and temperature of the actuators however the rise was kept to levels below 55°C. To decrease potential errors in the measurements we made changes to the test system during the lifetime tests. For example the initial 2 billion cycles displayed significant crosstalk in the electrical measurements and methods were devised to reduce this. Cooling fans were used to create air convection but they were found to cause fatigue of the stack wires at the electrical terminators (not at the stack). In one instance a stack was driven without the forced air convection and the generated heat was enough to cause burning of the electrical buss-bar and melt the solder. It is interesting to note that when the buss-bar was re-soldered the stack returned to nominal values. Much of the initial effort was dedicated to designing a suitable test fixture that was reasonably inexpensive to manufacture and met the requirement of the test.

2. TEST FIXTURES DESIGN AND ANALYSIS

The fixtures to be designed needed to be highly versatile to allow easy handling, accommodate a range of stacks, accommodate a range of test instruments, and be able to be installed in small test chambers. The design requirements of the test fixtures were:

a) allow for the removal of the piezoelectric stack,
b) allow for prestressing the stack,
c) allow for the measurement of the stack displacement,

d) allow for the measurement of the prestress level,
e) allow for air flow about the stack,
f) allow for temperature measurement of the stack,
g) had no appreciable resonance in the measurement frequency,
h) accommodate different test stacks in a given size range.

2.1 Test fixture 1

A schematic CAD model and a photograph of the actual test fixture are shown in Figure 2.

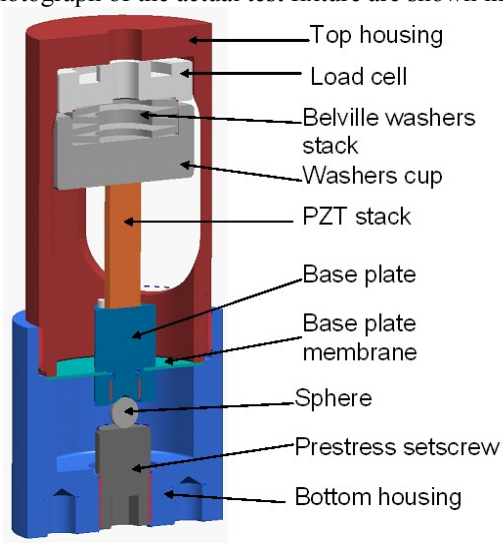

FIGURE 2: CAD model and photograph of the test fixture for lifetime and fatigue testing of the piezoelectric stacks.

The test fixture is composed of a housing machined in two components: an upper housing and a lower housing. The two housings couple together using a thread and sandwich between them a membrane used to center and stabilize in the radial direction a base plate that will support the PZT stack. An axial prestress bolt is screwed into the bottom housing and can control the axial position of the base plate thru a ball. The base plate can transmit axial load to the PZT stack from the prestress bolt. On the other side of the PZT stack a washers cup includes a stack of Belleville washers that helps maintain a more constant PZT preload in the PZT range of motion during both static and dynamic testing and provides a soft coupling to the PZT test fixture. In this way, the bottom end of the stack is in contact with the test fixture thru a stiff component while the top end is in contact with the test fixture thru a soft component. Doing that we can monitor only the displacement of the top end of the PZT stack and this test should account for the total displacement of the stack. Between the washers stack and the upper housing of the test fixture we placed a load cell to monitor the load on the PZT stack during the static and dynamic testing.

The washers cup provides the alignment of the PZT stack while the base plate rolls on the ball to avoid inducing bending moment on the PZT stack. The inside of the washes cup has a reflective surface with mirror finish for the interferometer measurements. The prestress screw in the bottom housing sets the PZT prestress level. The ball joint and the baseplate membrane block the toque transmission from the prestress setscrew to the PZT stack.
The inner surface of the washer cup, polished to mirror finish, as used to determine the stack displacement as a function of voltage without removing the stack from the assembly.

2.2 Test fixture 2

In another configuration of the test fixture we allowed for test of two PZT stacks at the same time, accommodating a larger size range for the stacks. As the PZT stacks to be tested in this fixture required more power the washers cups were designed as heat sinks. A CAD model of this fixture is shown in Figure 3 and an exploded view is shown in Figure 4. For this test fixture an additional setscrew was added to the top housing for adjusting the height of the tested PZT stack or stacks. For this fixture the optical surface was eliminated and an additional Belleville washers stack was added at the bottom of the PZT stack. This additional spring was introduced to reduce the influence of the test fixture natural resonance frequency in selecting the frequency at which the stack was to be tested. The larger number of cycles for the lifetime test of these stacks required a much higher driving frequency and so additional design provisions were made to increase the structure resonance frequency.

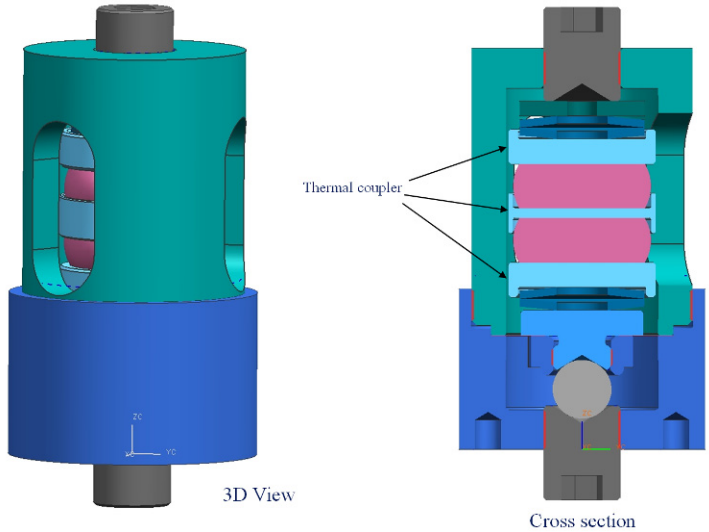

Figure 3 Double stack test fixture

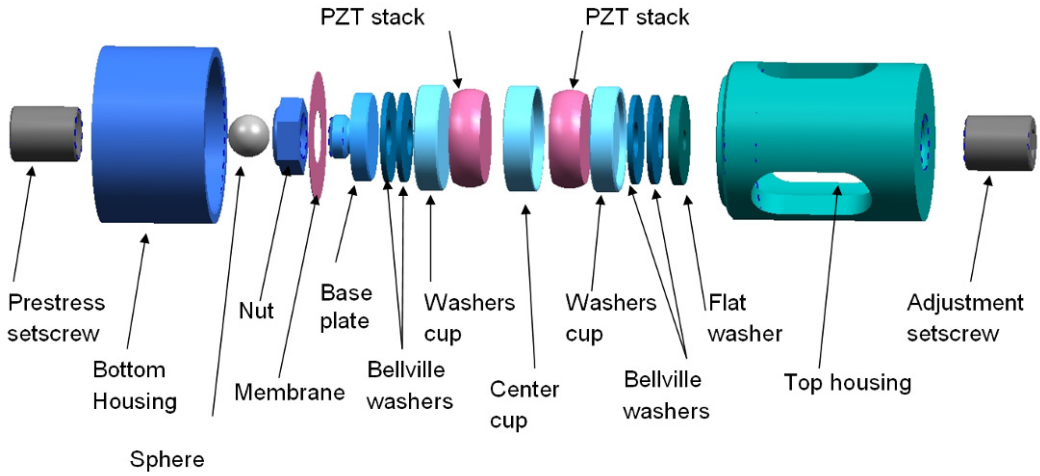

Figure 4 Exploded view of the double stack test fixture.

The test fixture was analyzed using ANSYS to determine its natural frequencies, stress level, and temperature distribution. Using the results of this analysis we designed the fixtures for lifetime testing the PZTs for a large number of cycles and a high frequency was required to be performed these tests is a reasonable amount of time. So, the FE analysis was performed to determine the test fixture resonant frequencies, the stack first axial resonant frequency, and stack stress and temperature levels for give boundary conditions. The results of this analysis are shown in Figures 5 and 6.

In the thermal analysis the following boundary conditions were considered: heating power = 20W, the fixture housing has uniform temperature, environment air at 20ºC flowing at 5m/s; washer and center cups were made of aluminum and had at extremities the same temperature as the housing (narrow gap and use of thermal coupling grease). The maximum temperature reached inside the PZT was 59ºC, below the allowable temperature of 80ºC.

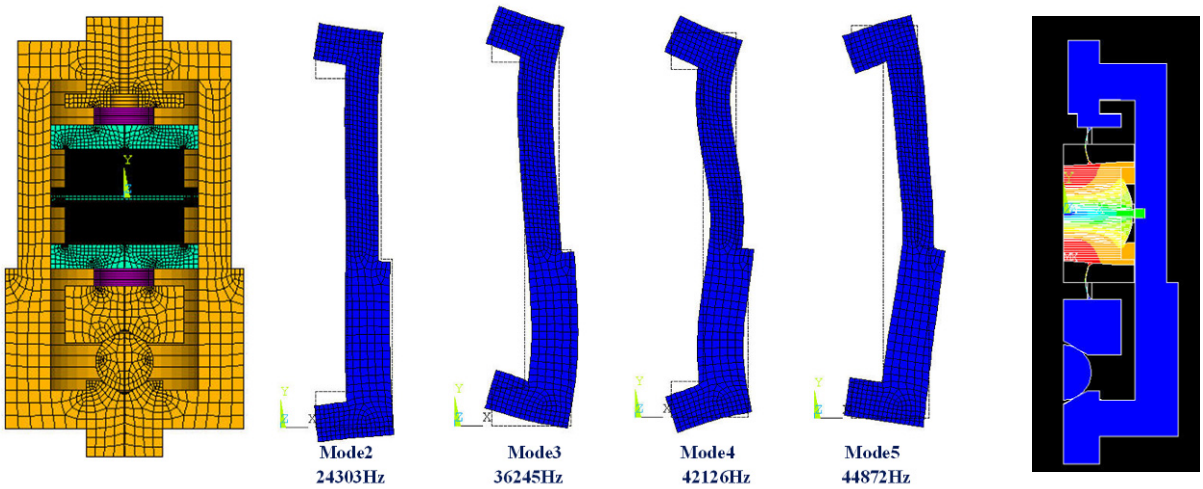

Figure 5 The FE model (left) and the first four resonance modes of the fixture (middle) and the first resonant frequency(50.3kHz) that shows a strong fixture-stack coupling (right).

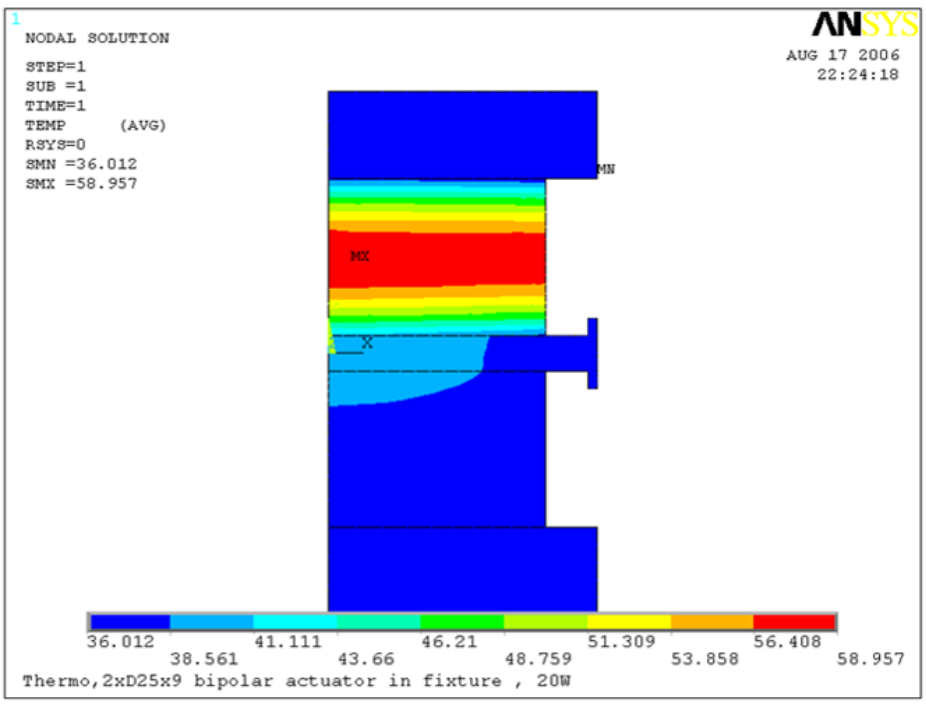

Figure 6 Temperature distribution for running one PZT stack

3. FIXTURES FABRICATION, INSTRUMENTATION, AND TEST RESULTS

Ten fixtures of the first type were manufactured and instrumented for lifetime tests. Figure 7 shows the test fixture with the PZT stack enclosed and instrumented with a load cell and an interferometer.

The stacks were tested and analyzed before being subjected to an alternate electric field for an extended period of time. The tests that were performed using this fixture include impedance, capacitance, dielectric loss factor, leakage current, displacement, breakdown voltage, and lifetime performance. The lifetime test was driven at 2000 Hz and 60 Volts between ground and Vpeak. The samples were actively cooled using fans to keep the temperature below a preset limit of 60ºC. The temperature, voltage, current into the stack including phase information were monitored as a function of the number of cycles. Spot checks including the impedance as a function of frequency, displacement as a function of voltage and the prestress were done at convenient intervals.

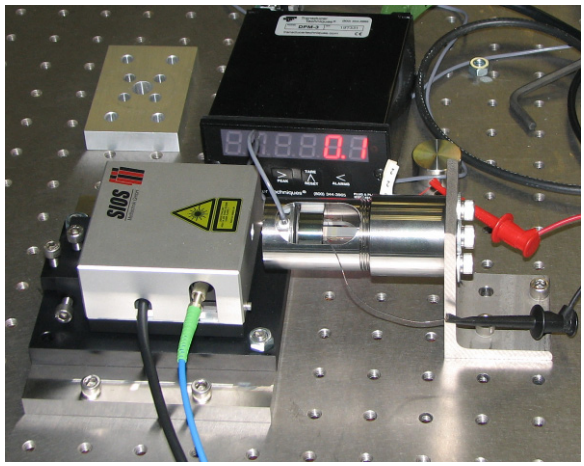

Figure 7 Test fixture integrated with the interferometer and load cell.

The measured impedance spectra of a stack is shown Figure 8 for a frequency range from 0 to 110kHz. The stack displacement versus voltage at the beginning of the lifetime test and after 7.661 billion cycles is shown in Figure 9.

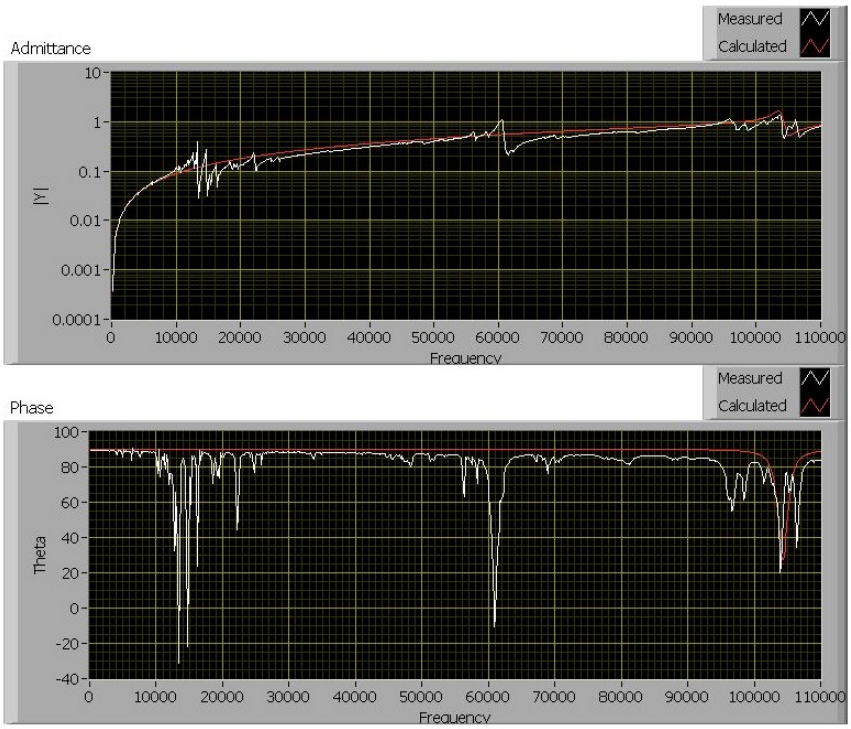

Figure 8 The resonance spectra of the PZT in the first test fixture for the 14MPa PZT prestress

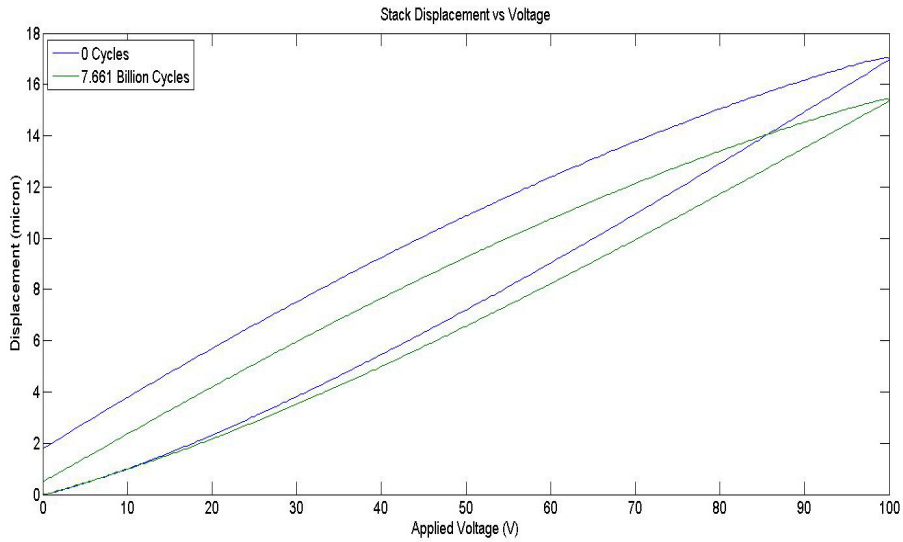

Figure 9 Stack displacement versus voltage at the beginning of the lifetest and after 7.661 billion cycles

SUMMARY

We reported here in our progress in developing a highly versatile test fixtures that we used for the characterization of a series of piezoelectric stacks. Te developed fixtures can be easily integrated in various test chambers for simulating environmental conditions, can provide access for multiple measurements while being exposed to adjustable stress levels, and can accommodate various stacks in a defined size range. One test fixture model that we fabricated can be used for testing piezoelectric stacks with cross sections up to 10x10mm and length from 15 to 20mm. The tests that were performed using this fixture include impedance, capacitance, dielectric loss factor, leakage current, displacement, breakdown voltage, and lifetime performance. A lifetime and fatigued tests were completed on set of stacks that were subjected to vibrations of up to 10.5 billion cycles. Another test fixture model that we developed can be used to test one or two PZT stacks with up to 20mm in diameter.

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