Journal of Electroceramics 4:1, 201–206, 2000

A Stackable Bonding-Free Flextensional Piezoelectric Actuator

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Submitted March 25, 1999; Revised July 13, 1999; Accepted July 28, 1999

Abstract. A flextensional actuator was designed using commercial multilayer stacked actuator so as to produce large displacements at intermediate force levels. The simple design chosen eliminated the need for bonding the actuators into the frame and permitted easy series connection of multiple units. To satisfy the need for a fiber grating tuning device to interrogate an array of Bragg grating fiber optic stress sensors, a tuning device using four series connected units was constructed. The unit performs well, but the actual measured amplification is less than theoretical expectation. The problem was traced to unwanted flexing of the simple original frame and a hinged more robust flexing beam construction was shown to eliminate the problem.

Keywords: piezoelectric actuator, flextensional amplifier, optical fiber grating system

1. Introduction

The use of precisely tuned fiber optic grating system to permit the monitoring of local strain at a number of locations along a long glass fiber stress sensor has important applications in specialized space structure. To interrogate such gratings sequentially, it is desirable to have an agile sensor which can be tuned over a range of optical frequencies. Such an agile filter can be envisaged using a fiber optic grating system whose period is varied by mechanically stretching the fiber. For this type of application, typical requirements are a gauge length of 45 mm with a tuning range of $\pm 100\,\mu$m which for a conventional fiber would require a generative force at order 10 N. Clearly, the strain required $\pm 0.22\%$ is beyond the range of a simple piezoelectric material driven through d_{31} or d_{33} [1] and some amplification is necessary if a piezoelectric device is to be used [2]. In this realization, a simple flextensional device is demonstrated in a design that can use commercial multilayer co-fired stacked actuators and eliminates the need for glue bonds. The design also permits easy series connection of the flextensionals and four such series connected device (named Dual Opposing Actuator, U.S. patent applied for) are shown to satisfy the current tuning need.

2. Experimental Procedure

The single-cell flextensional actuator is shown in Fig. 1. The metal frame is made by EDM (Electric Discharge Machining) from a whole piece of brass for both single cell and array. The piezoelectric multilayer actuator used is a commercial Tokin actuator, the dimension of the single cell is $5 \times 5 \times 18$ mm, with the displacement capability of $15\,\mu$m/100 V and blocking force of 87 kg/100 V. Two single actuators were bonded to a steel substrate by J.B. Weld epoxy. Both metal frame and the steel substrate base have a hole at the center position in order to let the fiber pass

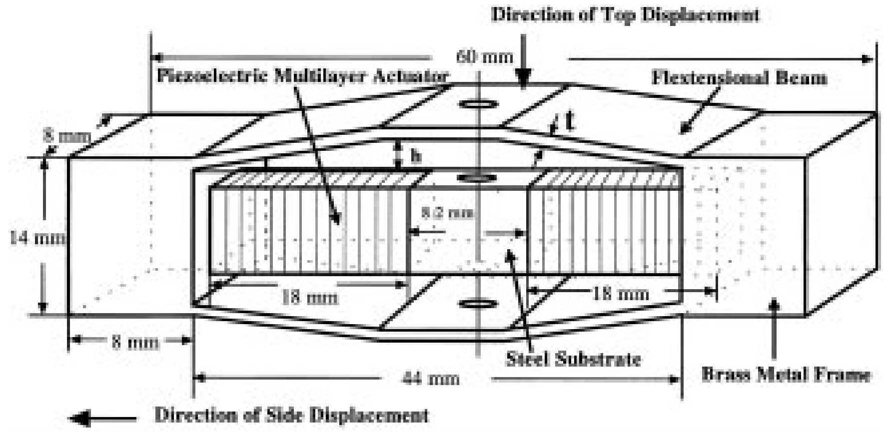

Fig. 1. Configuration of bonding-free flextensional piezoelectric actuator with rectangular shape.

through. The total length of the actuator plus substrate is 0.2 mm longer than the inside wall distance of the metal frame, so the actuator can be loaded into the metal frame by deforming the frame and is fixed in position by the resulting prestress. The stretching function can be realized by arrangement of single-cell actuators in an array. The configuration view of such an array is shown in Fig. 2. The displacement and the generative force for single-cell actuator are measured by a Fontonic sensor MTI 2000 (MTI Instrument) and a load cell ELF-TC (Entran, Inc.). The schematic view of experimental set-up for displacement and generative-force measurement is shown in Fig. 3. Brass is used as the metal frame material. The amplification factor of the frame will be determined by the height *h* (Fig. 1) if the length of the actuator is fixed. The height is set as 3.6 mm for current metal frame. Therefore, the theoretical amplification factor should be 5 for each side. The rigidity and the capability to generate force for the frame are strongly dependent on the stiffness of the flextensional beam in the frame.

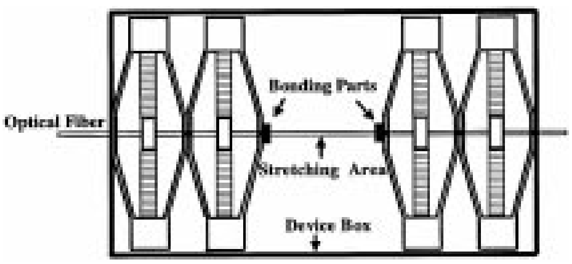

Fig. 2. Schematic view of array system for optical fiber stretching.

3. Experimental Results and Discussions

3.1. Simple Metal Frame

The metal frame with a flat-flextensional-beam with a thickness of 1 mm was first studied. The single cell actuator was characterized first under unloaded dc conditions. The side displacement of the metal frame and the axial displacement of the flextensional beam were measured at different driving voltage levels. The results are listed in Table 1, from which we can calculate the amplification factor of the metal frame. The displacement and the amplification factor listed in Table 1 are the sum for the two actuators and the two sides of the metal frame. There is a difference between the designed and measured amplification factor for this simple-metal-frame. The reason for this difference will be discussed later.

The loaded capability of the single cell actuator is usually represented by the term blocking force. The blocking force is defined as the external force needed to completely restrain to zero displacement the actuator at some driving voltage. The blocking force of the actuator was derived in the following procedure. The load cell was mounted on a movable station, which provides the possibility to apply an external force to pull back the actuator in a direction opposite to the one driven by the applied electric field. Theoretically speaking, we could read the blocking force directly by pulling the actuator to its original position. This concept leads to the present approach to measure the blocking force. We can drive the actuator to the unloaded displacement state at some set

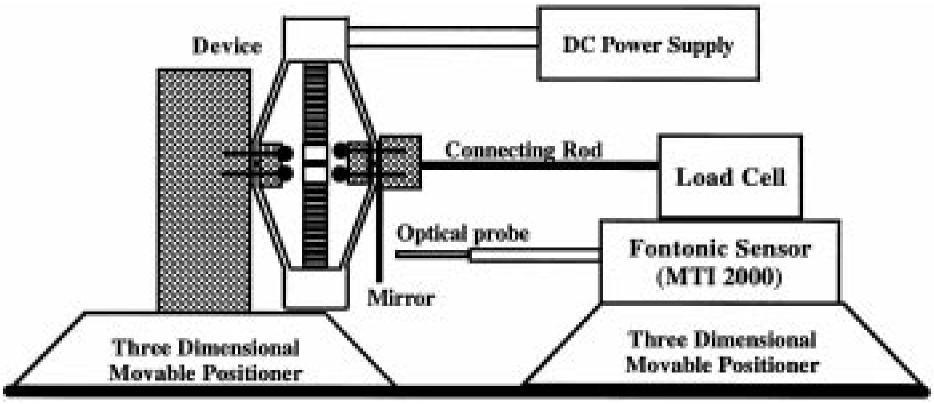

Fig. 3. Experimental set-up for measurement of displacement and generative force.

voltage, pull the actuator back to its original position. For every displaced position, the required pulling force is measured establishing the load line for the actuator. In order to avoid the nonlinear response and possible breakage of the actuator, the external pulling force is restricted to below 12 N. By curve fitting from linear line based on the measured points, as shown in Fig. 4. We can simply extrapolate the curve to the pulling force axis where the displacement is zero. The corresponding pulling force is also equivalent to the blocking force. The blocking force measured by this method for the single-cell actuator driven at 50 V voltage is 15.1 N.

The experimental results show that the generative force from the simple metal frame can satisfy the requirement. Unfortunately, the single cell actuator can not provide enough displacement for the optical fiber stretching. Thus, a four-cell array was fabricated in order to achieve the required displacement. The picture of the prototype device is shown in Fig. 5. A special designed energy recovery circuit for piezoelectric device was developed to operate it at very low-power consumption (2 W) [3]. It was shown that the design has excellent performance in stretching a erbium doped Bragg grating fiber and the detail will be discussed in a later paper.

3.2. Hinged Metal Frame

From actual measurement, it was found that the amplification factor of simple-metal-frame is approximately only half of the value designed (as seen in Table 1). The most probably reason is that the rigidity of the simple flat-flextensional-beam is not high enough to transfer the displacement without bending. That is the flextensional beam deforms before it can transfer the motion. A simple analysis shows the rigidity of the flextensional beam is proportional to the thickness of the beam if the width of the beam is fixed. However, it is required that the metal frame should not be too rigidity to limit the flextensional function of the structure. Flexure hinges are usually used to design the flextensional beam with a combination of high stiffness and appropriate elastic compliance [4]. In the present study, the flat-flextensional-beam of simple-metal-frame was modified to the hinged-metal-frame. For the hinged frame, the thickness of the flextensional beam was increased from 1 mm to 3 mm in order to increase the rigidity of the metal frame. Two flexture hinges were introduced to each beam in order to increase the flextensional function of the metal frame. The thinnest part of the hinge was 1 mm. The schematic diagram of hinged-metal-frame is shown in

Table 1. The unloaded and dc properties of the simple-metal-frame

Driving voltage (V)	Side displacement μm	Top displacement μm	Amplification factor	Unleaded actuator displacement μm
40	9.21	51.42	5.58	12
50	11.56	64.19	5.61	15

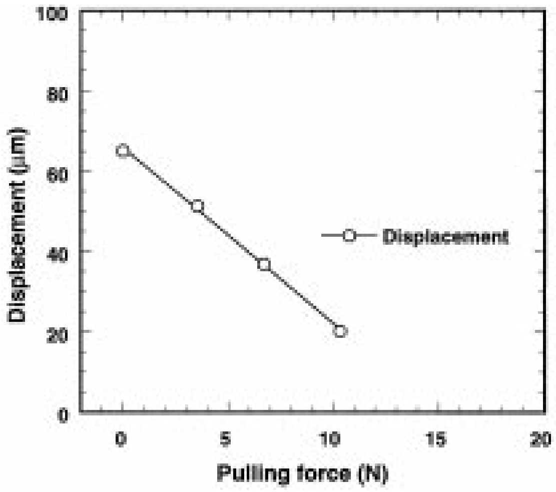

Fig. 4. Capability of displacement as a function of opposite pulling force.

Fig. 6. Schematic diagram of hinged-metal-frame.

Fig. 6. The other dimensions are identical to the simple-metal-frame. The same actuator was used to drive the hinged-metal-frame. Firstly, the unloaded and dc properties of hinged-metal-frame were characterized at different driving voltages. The results are listed in Table 2.

As previously, the actuator was fixed inside the metal frame by a prestress from the metal frame. The side displacements of the Table 1 and 2 are actually the sum of the clamped displacement of the actuator. The clamped displacements are controlled by the rigidity of the metal frame. In the simple-metal-frame, the clamped displacement of the actuator is 76% of the unloaded condition. However, the clamped displacement of the hinged-metal-frame is only 30% of the unloaded condition. Therefore, there is a dramatically enhancement in the rigidity of the metal frame by increasing the thickness of the beam from 1 mm to 3 mm.

The amplification factor of the hinged-metal-frame, however, reaches to 9.5, which is very close to the designed value. That means the rigidity of the structure is a critical point to acquire the designed amplification ability. However, the increasing of the rigidity of the metal frame will increase the clamping

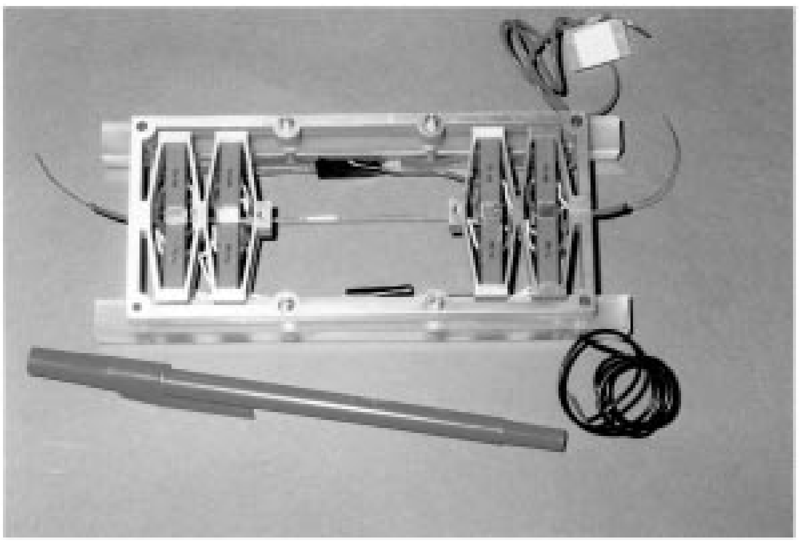

Fig. 5. Picture of the four-cell array prototype device.

Table 2. The unloaded and dc properties of the hinged-metal-frame

Driving voltage (V)	Side displacement μm	Top displacement μm	Amplification factor	Unloaded actuator displacement μm
40	3.58	34.18	9.55	12
50	4.96	46.81	9.43	15

effect on the actuator. In the current case, the final top displacement of the hinged-metal-frame is lower as compared to the simple-metal-frame driven at the same voltage. Therefore, the current hinged-metal-frame is just an example to demonstrate the effect of introducing the flexure hinges to the flextensional beam and is far from the idea design. For certain displacement and ideal generative force combinations, there will be an optimum dimension of the hinged-metal-frame. Finite element analysis will be employed to generate accurate models of the hinged-metal-frame designs in the future work.

The loaded properties as a function of driving voltage of both simple-metal-frame and hinged-metal-frame were measured, as shown in Fig. 7. The derived blocking forces as a function of driving voltages are shown in Fig. 8. The blocking forces show very good linear relationship with the driving voltage.

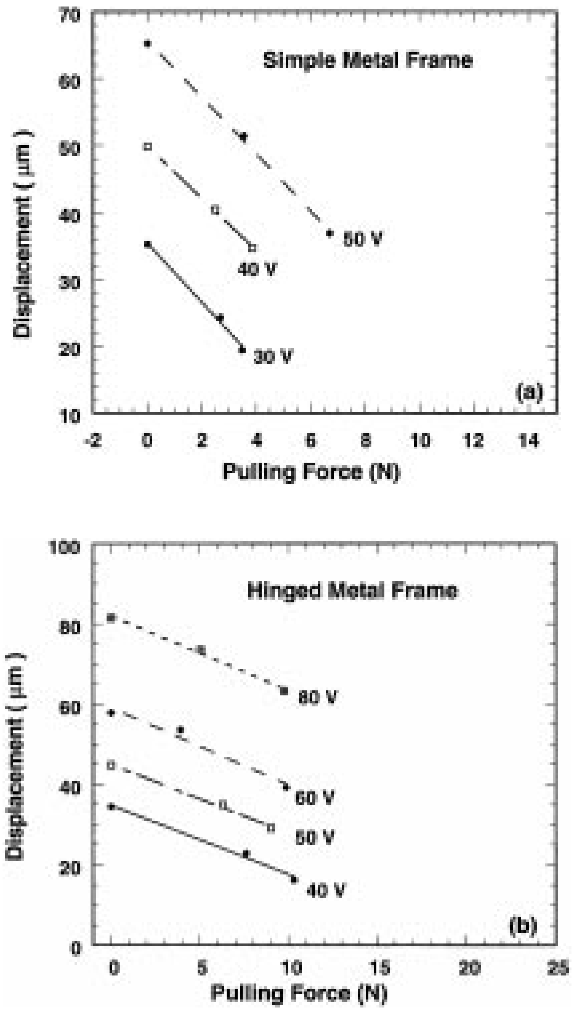

Fig. 7. Measured curves for derivation of the blocking forces at different driving voltage; (a) simple-metal-frame, (b) hinged-metal-frame.

Acknowledgment

This work was supported in part by NASA under contract NAS1-97147 and NAS8-98109. The authors would like to thank Dr. Richard Barday of NASA GSFC, Electromechanical Branch and Dr. Weicheng Chen of Center for the Acoustics and Vibration of Penn State University for helpful discussions.

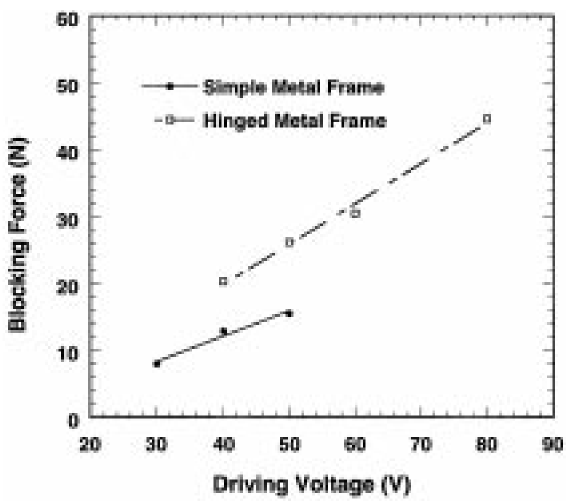

Fig. 8. Comparison of blocking forces between simple and hinged metal frames as a function of driving voltage.

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