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A Piezoelectric Actuator for Miniature Trailing-Edge Effectors for Rotorcraft

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ABSTRACT

This work focuses on the design and testing of a piezoelectric actuator for a Miniature Trailing-edge Effector (MiTE). MiTEs have the ability to increase performance of rotorcraft. A MiTE actuator is designed for a VR-12 rotorcraft airfoil with a chord of 0.356 m (14 in.). The requirements for this design include having a natural frequency of greater than 50 Hz to allow for quasi-static operation and a maximum deflection of 3.56 mm. Design of this actuator, a piezoelectric bimorph augmented by centrifugal loads, was done in conjunction with the design of a flap assembly. A tapered bimorph connected to a flexure hinge was the result of the design process. A full scale bench-top model was fabricated and tested and the design requirements were met.

Keywords: Piezoelectric Actuator, Gurney Flap, Rotorcraft

1. INTRODUCTION

The goal of this research is to design and test configurations for a Miniature Trailing-edge Effector (MiTE) with applications to rotorcraft. A MiTE is an active Gurney flap (a small tab on the lower surface of the airfoil near the trailing edge) which, when deployed perpendicular to the flow, increases the maximum lift coefficient of an airfoil section [1]. There has been significant research on the performance enhancement of rotorcraft outfitted with MiTEs, which have shown, for example, a potential to increase forward flight speed by 7% [2]. Figure 1 shows the MiTE concept as well the effect on the lift coefficient, c_l, due to size and location of the MiTE as a function of airfoil chord length.

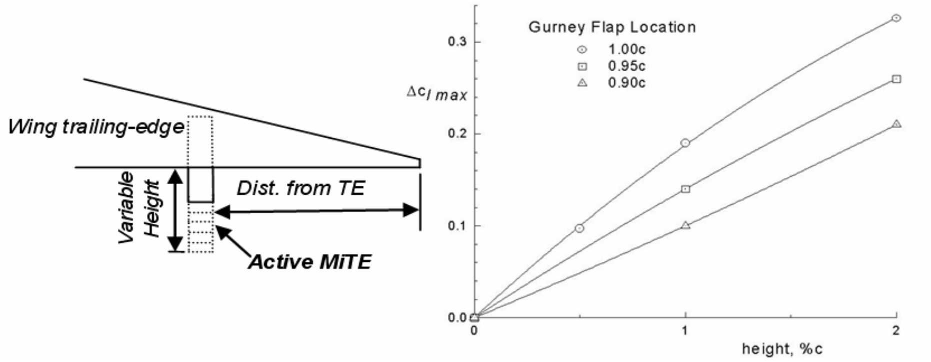

Figure #1. MiTE concept and the effect on maximum lift coefficient due to size and location.

The rotorcraft performance gains (increased maximum speed, take-off weight, etc.) are produced by deploying the MiTE on the retreating side of the rotor disk in forward flight. Rotor blades experience stall on the retreating side due the subtraction of the rotor speed from the vehicle forward speed [3]. The onset of stall is one of the limiting factors in forward flight. (Conversely, the advancing side can experience transonic effects as the rotor speed is added to the vehicle forward speed and also limits vehicle forward speed.) Since stall only occurs on the retreating side, the actuation of the MiTE would be a once per revolution (1/rev) deployment, although not necessarily harmonically. (Typical rotors have rotational frequencies of 4 – 6 Hz.)

With the ability to control sectional aerodynamic properties of the blade, an active MiTE can be used wherever active flow control is needed. On rotorcraft, high vibration loads are due to the aerodynamic forces on the blades which adversely affect pilot and passenger comfort. Control of vibration loads through the use of traditional trailing edge flaps has been extensively researched and tested [4, 5]. Actuation for vibration control generally occurs at frequencies on the order of N_b/rev, where N_b is the number of rotor blades (typically between 2 and 6). There has also been research on the use of MiTEs as primary control surfaces on fixed wing UAVs [6].

This paper addresses the development of a MiTE driven by a tapered piezoelectric bender designed to operate quasi-statically at a frequency well below that of the first resonant frequency. The actuator was designed to actuate a MiTE with a height of 0.01c within a VR-12 airfoil with a 0.3556 m (14 in.) chord. The required deflection would therefore be 3.56 mm. The design of the piezoelectric bender (bimorph), when placed in a rotorcraft, will be augmented by the centrifugal (CF) loads present in the blade. The CF loads will put the bimorph in compression and thus increase the coupling coefficient and displacements [7]. Both the bimorph and the flap assembly were designed using a genetic algorithm developed in previous work [8]. The bimorph alone and the completed flap assembly were tested dynamically.

2. CONCEPT DEVELOPMENT

2-1. Concept introduction

Figure 2 shows the full scale MiTE concept from a perspective and top veiw. The flexure hinge is used to turn the chord wise motion of the bimorph into a motion of the flap. The hinge and flap assembly were designed to have minimum weight and maximum span of the flap. The bimorph and flap assembly were designed concurrently to have an overall natural frequency greater than 50 Hz. Having a natural frequency sufficiently high enough allows for the quasi-static operation of the flap over a broad range of frequencies including 1/rev for performance enhancement and N_b/rev for vibration control. The design method used a finite element code developed in MATLAB along with an evolutionary algorithm to develop the bimorph [8, 9].

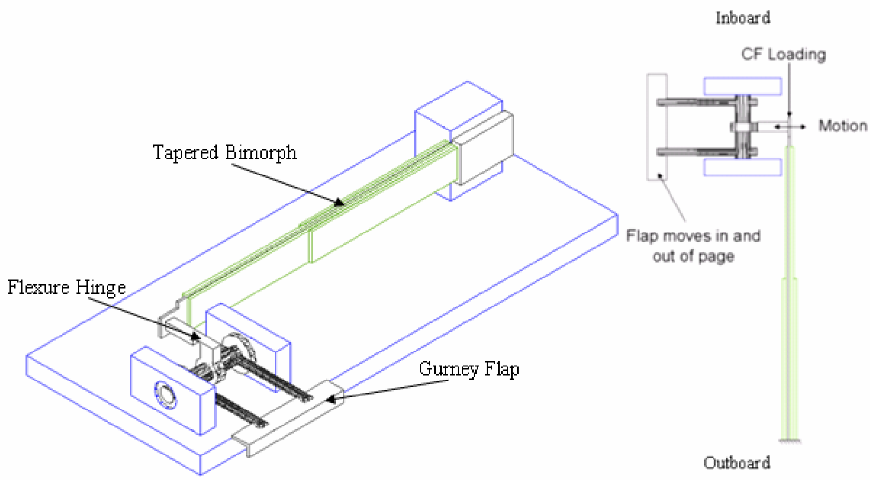

Figure #2. Gurney flap concept with CF-augmented bimorph.

2-2. Design of flexure hinge and flap assembly

The flap assembly was designed and optimized to be driven by the CF-augmented bimorph (Fig. 3 shows a sketch of the concept). In order to reduce friction and prevent binding under CF loads, a compliant hinge is used to turn the chord-wise motion of the bimorph into a rotation of the Gurney flap. The hinge was designed using a static analysis that takes into account the axially, bending, and rotational compliances of the hinge [10]. The flap assembly was optimized to maximize the span of the flap while meeting a constraint on the total mass/inertia of the system. This was successfully carried out using a static analysis of the flap meeting the design requirement.

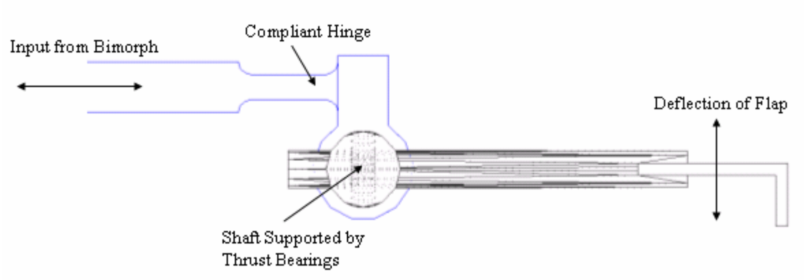

Figure #3: Flap assembly with compliant hinge concept.

A dynamic analysis was also conducted to ensure that there were not resonances within the operating frequency range and that the deflection requirement was met. Within the dynamic analysis, the drag force on the flap, the damping in the bearings, and the stiffness of the piezoelectric bimorph was accounted for in addition to the axial and rotational stiffness of the compliant hinge. The drag force is modeled as a function of the flap deflection and thus acts like a weak spring. The bearings are modeled as viscous dampers. Finally, the effective stiffness of the bimorph is modeled as a linear spring with a spring constant determined by the ratio of the blocked force of the bimorph to the free displacement. The system dynamics are simulated using a linear state space model. The simulation showed that the required deflection is met and that the system has a natural frequency of 51 Hz.

3 FULL SCALE TESTING

3-1. Fabrication

The tapered bimorph-driven MiTE was fabricated and tested. Figure 4 shows the bench-top model. All parts are made from aluminum except for the piezoelectric patches which are made from PZT-850, supplied by APC International. The flexure hinge is press fit onto a keyed shaft to ensure alignment. The shaft is supported by ceramic bearings (note: thrust bearings are turned around to allow rotation due to the distance between the bearing brackets being slightly too small) and allow for smooth rotation. Table 1 provides a summary of key dimensions.

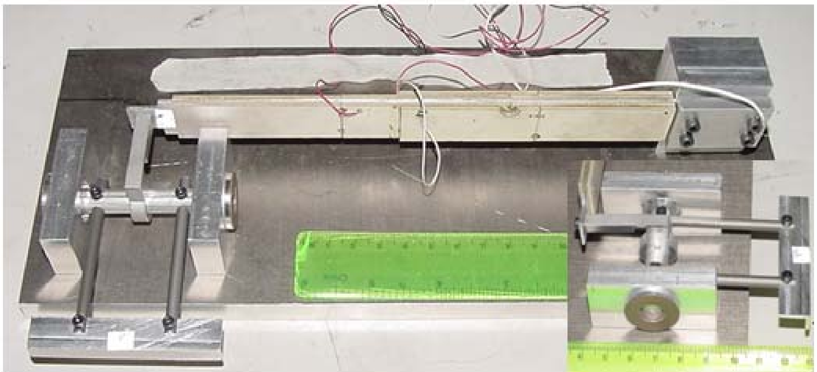

Figure #4. Fabricated bench-top model.

Table #1: Summary of Dimensions

Shim Thickness	1.63 [mm]
PZT Thickness (both layers)	1.90 [mm]
Bimorph Width	20.50 [mm]
Bimorph Length	211.74 [mm]
1st PZT Layer Length	194.00 [mm]
2nd PZT Layer Length	108.00 [mm]
Flap Span	69.60 [mm]
Flexure Thickness	0.635 [mm]

The bimorph was assembled with each layer comprising multiple patches of PZT material. The inner layer is made up of three patches and the outer layer is made up of two patches. An outer sheet on each side of the bimorph had to be notched to gain access to the inboard sheet of the inner layer. To ensure each layer gets the same voltage, the outermost surfaces were connected to the shim and then ground and the exposed surfaces on the inner layers were connected to the positive terminal of the amplifier. Each sheet in a layer is aligned the same with respect to poling direction. Small leads connect each sheet in a layer to ensure the same voltage is applied across each sheet. Figure 5 shows a schematic of the bimorph with the poling directions, **P**, the direction of the resulting electric field, **E**, when a positive voltage is applied and the resulting expansion, or contraction of the piezoelectric material to produce the desired moments.

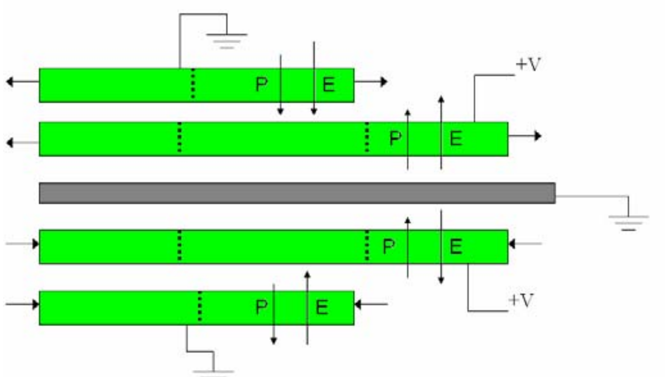

Figure #5: Wiring and poling directions of the PZT material (green) and shim (gray). Dashed lines represent the different patches composing a layer. (Note: not to scale.)

3-2. Testing of the bimorph and flap

Several tests were conducted to determine the performance of: the bimorph free from the flap; the bimorph with the flap attached; and the entire assembly. The goals of the initial tests were to determine the natural frequencies of the system, the deflection of the flap, and the frequency response function. All tests were conducted using a laser vibrometer which provided velocity data (then converted to position in the processing of the data) with the bimorph receiving a chirp signal as an input that went from 1 to 1600 Hz. The frequency response data was measured over 25 averages (after applying a Hanning window) and saved along with the coherence and power spectrum (to make damping ratio calculations). The first test was to determine the frequency response of the bimorph free from the flap. The data was taken at the contact point where the hinge attaches to the end of the bimorph. The hinge and flap assembly was then attached to the bimorph and velocity data was taken at the same point. Lastly, the velocity of the flap was measured at the midpoint of the flap (the reflective tape used can be seen in the close up of the flap). The magnitude of all three frequency response functions are shown in Figure 6.

3-2-1. Initial testing

Initial test results were not entirely satisfactory. First, the natural frequency of the free bimorph was significantly lower (39 Hz) than the predicted value of 72 Hz. Second, the frequency response function obtained when attaching the flap to the bimorph does not show a peak near the first natural frequency of the bimorph. Attaching the flap has the effect of drastically damping the response of this mode. The source of the damping can be attributed to the bearings. The magnitude of the frequency response function obtained at the flap and at the attachment point have the same shape and relative magnitudes. A uniform increase in magnitude across the entire frequency range is present which is expected.

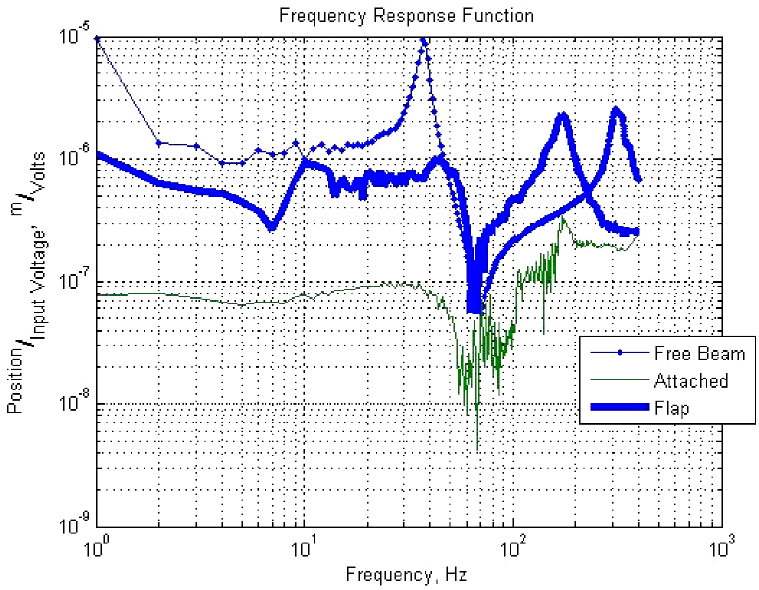

Figure #6: The frequency response functions for the bimorph alone, "Free Beam," with the flap assembly attached to the bimorph, "Attached," and at the Gurney flap, "Flap."

The boundary condition at the root of the beam was determined to be the source of the differences between simulations and measurements because of the difference quasi-static displacements. If the boundary was not as "stiff" as modeled, the first natural frequency, which depends heavily on the boundary condition, would be lower. The MATLAB simulation modeled the boundary condition as perfectly clamped, with a 1 mm gap between the end of the PZT material and the clamp corresponding to the physical gap present. A larger gap would have the effect of lowering the root stiffness and thus the natural frequency. The commercial code Abaqus was first used to examine this with varying lengths of the gap and Figure 7 shows the result with a gap of three shim thicknesses. Abaqus allowed for a higher number of elements to be used, as well as the modeling of the bond layer. The bond layer was included as an extra layer of elements with the density and stiffness of the epoxy. The natural frequency of the first mode, with this larger gap, was found to be 32.823 Hz, which is very close to the measured value of 35 Hz.

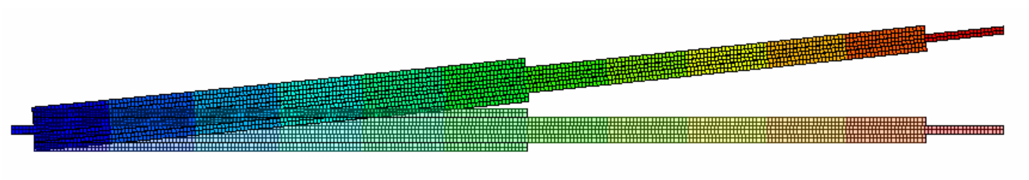

Figure #7: First mode (32.823 Hz) generated in Abaqus with a gap of 4.89 mm between the clamp and PZT material.

During testing it was also determined that the innermost PZT patches were not connected and were not supplying any force. The simulation was run with both the inner sheet of the bimorph contributing and not. Figure 8 shows the magnitude of the frequency response functions for the bimorph alone, obtained using an accelerometer.

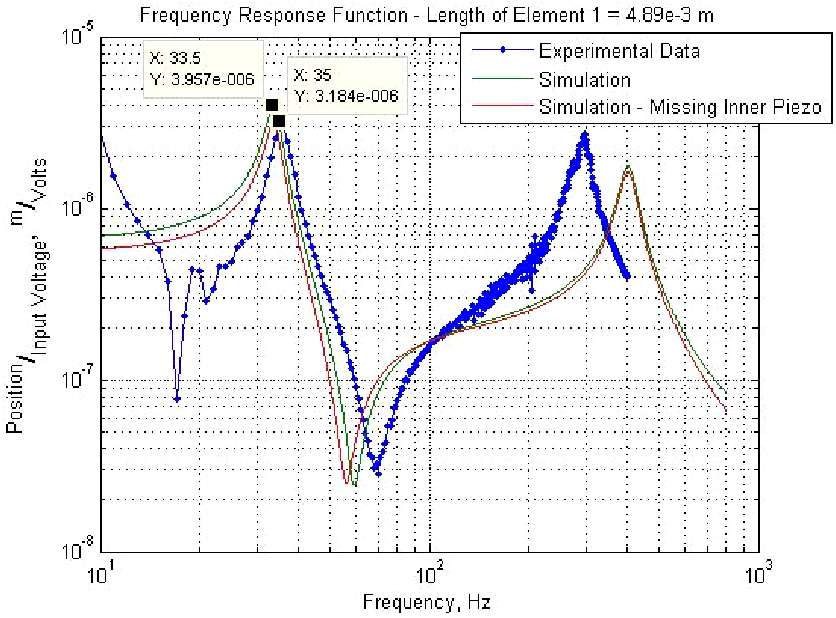

Figure #8: Magnitude of the simulated frequency response functions of the bimorph alone with a larger gap between the clamp and PZT material.

3.2.2. Testing with improved clamp design

An improved bench-top model was built with the goal of increasing the first natural frequency of the system. In order to operate quasi-statically, the natural frequency must be higher. To accomplish this, the method in which the bimorph was clamped was altered. Instead of clamping on the shim, the clamp was applied directly to the outer patches of piezoelectric material. A test was done in which the bimorph alone (the flap mechanism was not attached) was tested; the MATLAB simulation accurately predicted the response in terms of natural frequency and static deflection.

A clamp was then designed that could fit within an airfoil thickness. Since the width of the bimorph is selected to fit within the thickness of the airfoil, the clamp could not be much wider than the width of the bimorph. The clamp works much like a C-clamp and the shim is used to aid in the alignment. Clamping directly to the PZT material does not affect the wiring since the outer patches are connected to ground. Figure 9 shows a picture of the clamp.

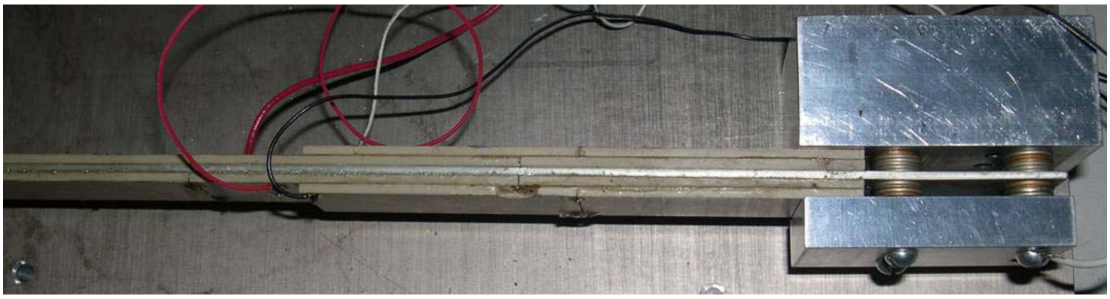

Figure #9. Improved clamp.

Dynamic testing was then performed with the flap attached and not attached to the bimorph. The data in Figure 10 shows that the predicted frequency response function matches the data fairly well. The natural frequency is also significantly higher than that measured in initial tests. To improve the agreement, the clamp effectiveness is that of a clamp located at the edge of the piezoelectric material which has the effect of increasing the effective length of the bimorph. Figure 11 shows the frequency response function for the flap. With a reasonable drive voltage of 200 volts, a displacement of over 3 mm is expected at low frequencies (<20 Hz), which meets the operational requirement.

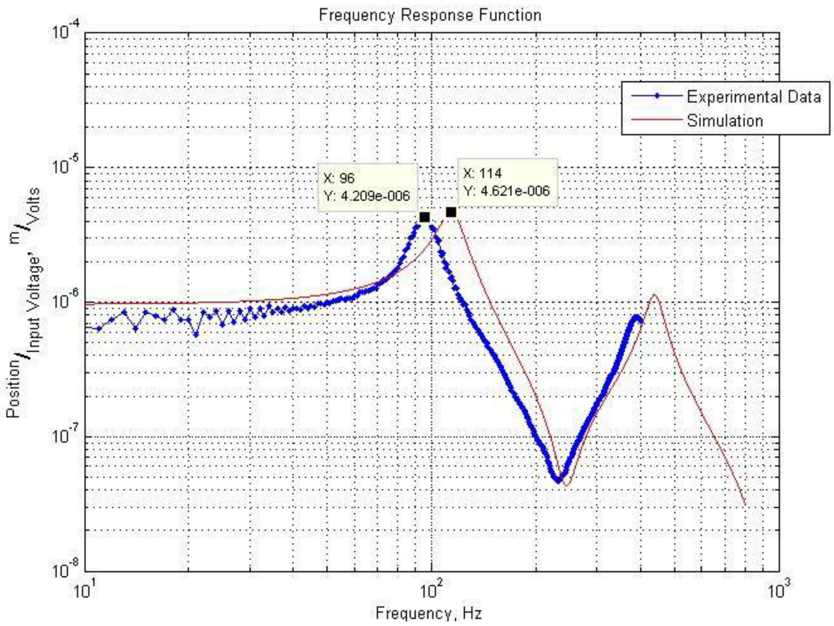

Figure #10. Frequency response function for the improved bimorph

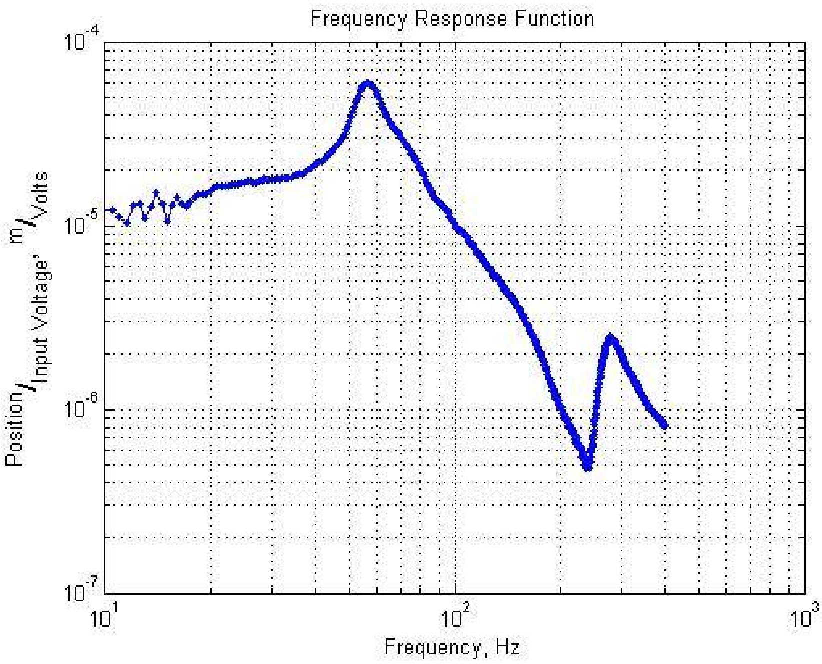

Figure #11. Frequency response function for the flap with the improved bimorph.

4. SUMMARY AND FUTURE WORK

Initial testing of the flap showed no resonances and a flat frequency response up to approximately 55 Hz. This is a desirable feature should the flap be implemented with different operating frequencies. However, the bimorph was not as stiff as predicted and an improved clamp was designed. The clamp for the bimorph was altered and the improved bench-top model was tested. By increasing the effective stiffness of the bimorph, there was enough force available to provide the necessary deflections. The dynamics of the bimorph with the improved clamp were predicted reasonably well. The flap assembly with the improved design exhibited favorable dynamics with a first natural frequency greater than 50 Hz. Calculations showed that the current design should be able to provide necessary deflections.

To further advance the concept, several options are available. First, the hinge and flap assembly could be redesigned taking advantage of the better clamp design. Doing this would allow new hinge concepts to be explored (with different shapes and materials). Ideally, using the same design process as before, except with confidence that the modeling of the bimorph is correct, a different concept can be explored using a tapered bimorph augmented by CF loads. More advance testing of the current and any future concepts is needed. These tests would include dynamic wind-tunnel tests where the actuator performance under aerodynamic loading can be verified. A whirl tower test, where the effect of CF loads on the performance can be understood would also be needed. Finally, the actual integration into a rotor blade presents challenges such as maintaining the structural integrity of the blade and providing the actuator with power.

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