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Smart Patch Piezoceramic Actuator Issues

S. F. Griffin, K. K. Denoyer, B. J. Yost
Phillips Laboratory
Edwards AFB, CA

Abstract

The Phillips Laboratory is undertaking the challenge of finding new and innovative ways to integrate sensing, actuation, and the supporting control and power electronics into a compact self-contained unit to provide vibration suppression for a host structure. This self-contained unit is commonly referred to as a smart patch. The interfaces to the smart patch will be limited to standard spacecraft power and possibly a communications line. The effort to develop a smart patch involves both contractual and inhouse programs which are currently focused on miniaturization of the electronics associated with vibrational control using piezoceramic sensors and actuators. This paper is comprised of two distinct parts. The first part examines issues associated with bonding piezoceramic actuators to a host structure. Experimental data from several specimens with varying flexural stiffness are compared to predictions from two piezoelectric/substructure coupling models, the Blocked Force Model and the Uniform Strain Model with Perfect Bonding. The second part of the paper highlights a demonstration article smart patch created using the insights gained from inhouse efforts at the Phillips Laboratory. This demonstration article has self contained electronics on the same order of size as the actuator powered by a voltage differential of approximately 32 volts. This voltage is provided by four rechargeable 8 volt batteries.

Introduction

The Phillips Laboratory has had a great deal of success in actively controlling vibration of structures with piezoceramic sensors and actuators, primarily through contractual efforts with TRW in Redondo Beach, CA. The manufacturing of composite structures with embedded or attached piezoceramic sensors and actuators, or smart structures, has advanced to the degree of at least a 99% success rate in the Advanced Composites with Embedded Sensors and Actuators program with TRW. TRW has built smart specimens ranging in size from less than one foot long by two inches to seventeen foot long by five inch diameter tubes for the ASTREX test bed located at the Phillips Laboratory. Critical damping and beyond has been introduced into lightly damped structures using this technology.

The part of this technology that still needs further advancement is in the area of the support electronics. Since our goal is to eventually make this technology a viable solution to vibration problems in spacecraft, it is important to optimize the size and weight of the support electronics and to consider space environmental effects. For this reason, approaches which use low voltage per force output are being considered to minimize step up requirements on spacecraft voltage and thereby reduce the size and number of components in the necessary power electronics. The end result of satisfying these miniaturization goals will be the development of a small, lightweight smart patch which will have the ability to sense and control unwanted vibrations in a host structure. The smart patch will be very useful in providing solutions to unanticipated vibration problems in spacecraft programs without the need for major redesign. Also, surface mounted vibration suppression technology may be necessary for structures whose manufacturing process is too harsh to allow embedment of sensors, actuators, or electronics. With a surface mounted smart patch, issues such as bonding and actuator-structure interaction become even more important than the case where embedded sensors and actuators are designed into the structure.

At the Phillips Laboratory, our inhouse smart structures program is addressing some of the questions concerning smart patch technology. This paper describes two parts of this effort. The first part is a description of recent experimental efforts to better understand piezoceramic actuator and structure interaction. The second part of the paper concentrates on integration of sensor, actuator, and electronics into a smart patch. It describes a demonstration article constructed using insights gained from earlier inhouse efforts. This article consists of a graphite/epoxy substructure with an attached smart patch. The patch meets the basic goals of inherent sensing, actuation, and control. It runs on a voltage differential of approximately 32 volts.

Surface-Bonded Piezoceramic Actuator Models

There are several models in the literature that predict how a structure behaves with a surface bonded piezoceramic actuator when a voltage is applied to the piezoceramic. In this research, we were primarily interested in the bending behavior of a structure with surface bonded piezoceramics. For this reason, we will only review models as they relate to bending (in the models reviewed, there is a simple path to go from bending behavior to extension and compression). The actuator/structure interaction has been modeled both analytically and through the use of finite element codes. The analytical models we examined range in complexity from a simple blocked force model which neglects the effects of the substructure and bending of the actuator and treats the piezoceramic as being "blocked" in extension and compression all the way to Uniform Strain Models which include the effects of the actuator, bonding layer, and substructure [3]* and two-dimensional models based on laminated plate theory. The finite element approach models the piezoceramic as a thermoelastic element and treats the applied actuator voltage as a temperature differential.† The models considered in this work are the blocked force piezoelectric model and the Uniform Strain models consisting of one model which assumes there is a finite bonding layer between the piezoelectric and the substructure and a second which assumes that the piezoelectric actuator is perfectly bonded. Both of the Uniform Strain Models assume that there is uniform strain in the piezoelectric and a linear Euler-Bernoulli strain distribution in the substructure. It will be shown that all three of these models are related and, in fact, converge on each other depending on material properties and geometry of the structure, piezoelectric actuator, and the bonding layer.

Uniform Strain Model with Finite Thickness Bonding Layer

The Uniform Strain Model with Finite Thickness Bonding Layer assumes a finite thickness bonding layer between the piezoceramic actuator and the substructure. Force is transferred in shear from the piezoceramic to the substructure through the bonding layer, leading to the classic shear lag problem. The amount of shear lag depends on the shear lag parameter Γ where

$$\Gamma^2 = \frac{G}{t_s}\left(\frac{1}{E_c t_c} + \frac{\alpha}{E_b t_b}\right) \tag{1}$$

G is the shear modulus of the bonding layer, t_s is the thickness of the bonding layer, E_c is the modulus of the piezoceramic, t_c is the thickness of the piezoceramic, E_b is the modulus of the substructure, t_b is the thickness of the substructure, and α is 6 for bending. When the shear lag parameter Γ is greater than 30, the assumption that the piezoelectric is perfectly bonded to the substructure "will provide results sufficiently accurate for engineering models" [1]. In light of this, we decided to establish the necessity of using this model for our experimental specimens. Using equation (1), we calculated the values of Γ for each of our experimental specimens. Since the lowest value of Γ was over 200, we elected to make our experimental comparisons using the Uniform Strain Model with Perfect Bonding and the Blocked Force Model which are described below. It has been shown that in the limit as Γ approaches infinity, the finite bonding layer

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*References 1–3 are cited in the text.

†Bronowicki, A. J., Betros, R. S., course notes from "Active Damping Workshop."

solution converges to that of perfect bonding [1].

Uniform Strain Model with Perfect Bonding

In the Uniform Strain Model with Perfect Bonding, it is assumed that the piezoceramic actuator is perfectly bonded to the substructure. Since the shear stress applied to the substructure by the piezoelectric is concentrated at the ends of the piezoelectric in this case, the piezoceramic can be thought of as delivering a line force at its ends to the substructure. Briefly, the derivation of the forcing term involves a strain at the outer surface of the substructure due to bending given by

$$\varepsilon = -\frac{My}{E_b I} \tag{2}$$

where I is the moment of inertia, y is the distance from the neutral axis and M is the applied moment. This strain is assumed to be the same as the uniform strain in the piezoelectric actuator which is given by

$$\varepsilon = \frac{\sigma}{E_c} + \frac{d_{31}V}{t_c} \tag{3}$$

where σ is the in-plane longitudinal stress in the piezoceramic, d_{31} is a piezoelectric charge constant of the piezoceramic, and V is the applied voltage. Combining these equations and using the fact that the applied moment M in (2) is due to the line force generated by the piezoelectric, the expression for force applied to the substructure is given by

$$F = -\frac{E_b t_b b\left(\frac{d_{31}V}{t_c}\right)}{\frac{E_b t_b}{E_c t_c} + 6} \tag{4}$$

where b is the width of the piezoceramic.

Blocked Force Model

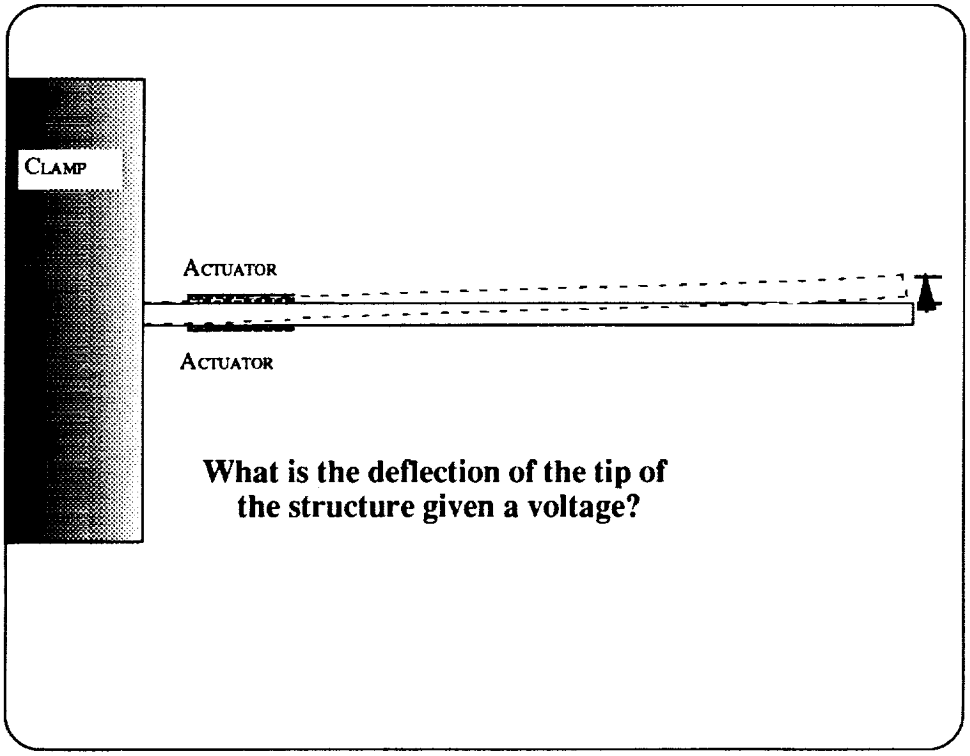
The Blocked Force Model makes the assumption that the force applied to the piezoelectric is exactly the same as the force that would be produced if the voltage were applied to the piezoelectric with its ends fixed in place. This results in the following force expression

$$F = -E_c b d_{31} V \tag{5}$$

It is easy to see that this expression is the limit of (4) as the ratio of $\frac{E_b t_b}{E_c t_c}$, the effective stiffness ratio, approaches infinity. It is interesting to note that since this expression exhibits no dependence on piezoceramic thickness in a voltage limited, but not necessarily power limited application, it would make sense to operate many thin piezoceramics in parallel rather than one thick one to increase force output. For example, if there were .010" of space allocated for piezoceramics and one .010" thick piezoceramic provided one unit of force per volt, two .005" thick piezoceramics would provide two units of force per volt. If this same exercise is undertaken by substituting typical piezoceramic values into the Uniform Strain Model with Perfect Bonding, a value of even higher than twice the original value is obtained. This neglects losses in actuation due to the additional bonding surfaces and no allowance is made for the thickness of the bonding layer. Also, there is a saturation limit that defines a maximum amount of voltage per thickness of the piezoceramic that has to be considered. However, even with these factors which will tend to decrease the force values from a multi-piezoelectric approach, it still may be more efficient from a size and power efficiency standpoint when compared to stepping up the voltage on a single thicker piezoelectric. Obviously this will be an optimization problem that will have to be solved for a given application.

Model Verification Experiment

To compare different actuator models and vary parameters of interest on several different test specimens, it was important to come up with a simple, reproducible test configuration. The configuration decided on was a cantilevered beam with surface bonded actuators near the base as shown in Figure 1. The poling directions of each of the piezoelectric wafers face the top of the page. The predicted and measured parameter was the deflection of the tip of the beam given a voltage applied to the piezoelectric actuators. A voltage could then be applied in the poling direction of one piezoceramic and in the opposite direction of another with the substructure providing a common ground. This configuration makes the entire structure a bender element with voltage applied in parallel and a large moment arm.

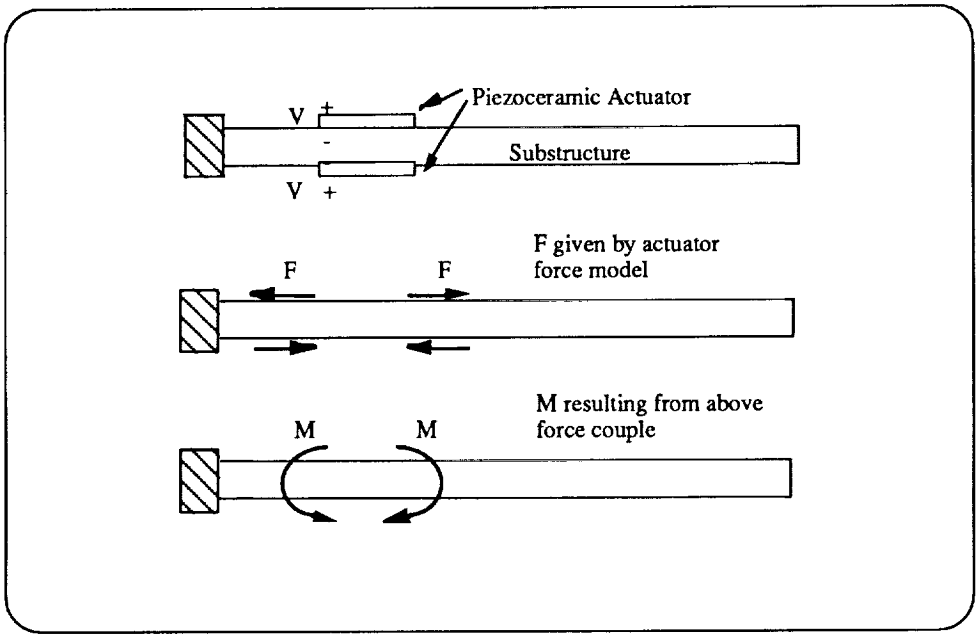


What is the deflection of the tip of the structure given a voltage?

Figure 1

Voltage-Tip Deflection Relationships

To get the predicted voltage-tip deflection relationships, equations from elementary mechanics were used to calculate a tip deflection due to the force couples resulting from the actuator forces predicted by the piezoelectric/substructure coupling models. The evolution of these forces to applied moments is shown in Figure 2.



Development of Voltage - Tip Deflection Relationship
Figure 2

From elementary mechanics, the cantilever tip deflection is found to be

$$\Delta = \frac{M}{2E_b I}(2LX - 2La - L^2) \qquad (6)$$

where I is the moment of inertia of the substructure, E_b is the flexural modulus of the substructure, M is the applied moment, L is the length of the piezoceramic and X is the length of the substructure. For each model, the appropriate M must be substituted into (6) to get the voltage-tip deflection relationship for that model.

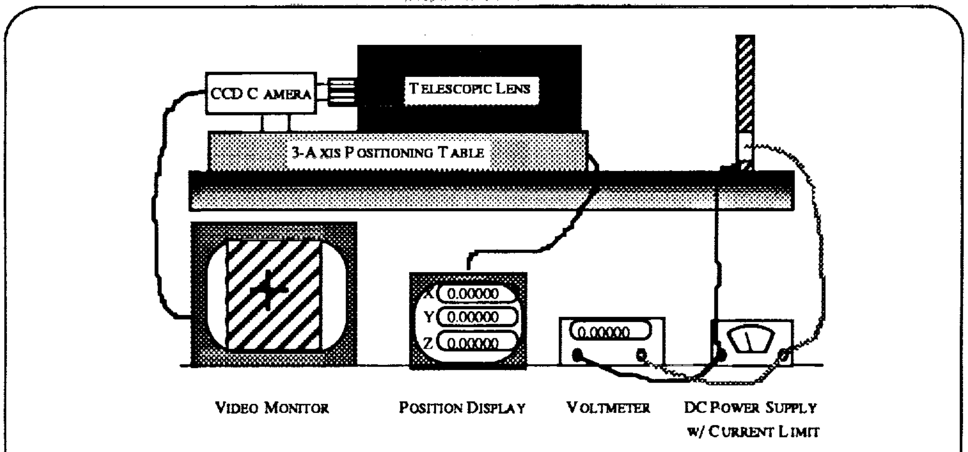
Experimental Specimens

Experimental specimens were fabricated as described with piezoceramic actuators located symmetrically near the base. The piezoelectric actuators used were PZT-5A, each wafer measuring 1.5" x 2.5" x .010". Specimens included aluminum and steel specimens and five composite specimens of varying flexural stiffness. The specimens had a clamped length of approximately 14 in., were 1.5 in. wide, and had thicknesses of about 0.05 in. The composite specimens were all fabricated from unidirectional graphite/epoxy prepreg. The fibers were relatively stiff (IM7) and the resin was a toughened resin suitable for spacecraft applications, 977-2. The composite specimens were 10 plies each with the most flexible lay-up to least flexible lay-up as follows:

[0,90,90,90,90]s, [0,0,90,90,90]s, [0,0,0,90,90]s, [0,0,0,0,90]s, [0,0,0,0,0]s, where s denotes a symmetric lay-up. Composite specimens were given the letter names A,B,C,D and E with A corresponding to the least flexible specimen and E corresponding to the most flexible specimen. Flexural modulus of the specimens was found by measuring the first resonant frequency of a cantilevered specimen and backing out the equivalent Euler beam flexural modulus from the Euler-Bernoulli frequency equation for a cantilever beam after measuring all other relevant beam parameters [2]. This method gave us a slightly lower, and we felt more realistic, flexural modulus than that predicted from manufacturer's properties and laminated plate theory which tend to give optimistic values for the modulus.

Experimental Setup

The experimental setup for measuring tip deflection given a voltage is shown in Figure 3.



- **One pair of PZT-5A piezoelectric actuators mounted at the base of each cantilever to provide bending.**
- **Voltage applied through a standard DC voltage supply.**
- **Static tip deflections measured to within 1/1000 inch using Questar optical measurement system.**

Experimental Setup
Figure 3

Voltage was applied with a standard DC voltage current limited power supply. A precision voltmeter was placed in parallel with the voltmeter. Beam tip deflection was measured through a telescope with a magnification of approximately 100 to 1. The telescope was attached to a CCD camera which had an accompanying reference monitor with cross hairs. The camera and telescope were mounted on a high precision three axis positioning table. The position of a focused object could be tracked to at least .001". Actual repeatable accuracy was closer to .0001", but only the one mil, or .001", digit was treated as accurate for the experimental data.

Figures 4 through 10 show measured tip deflection and predicted tip deflection versus applied voltage for each of the aluminum, steel, and composite specimens.

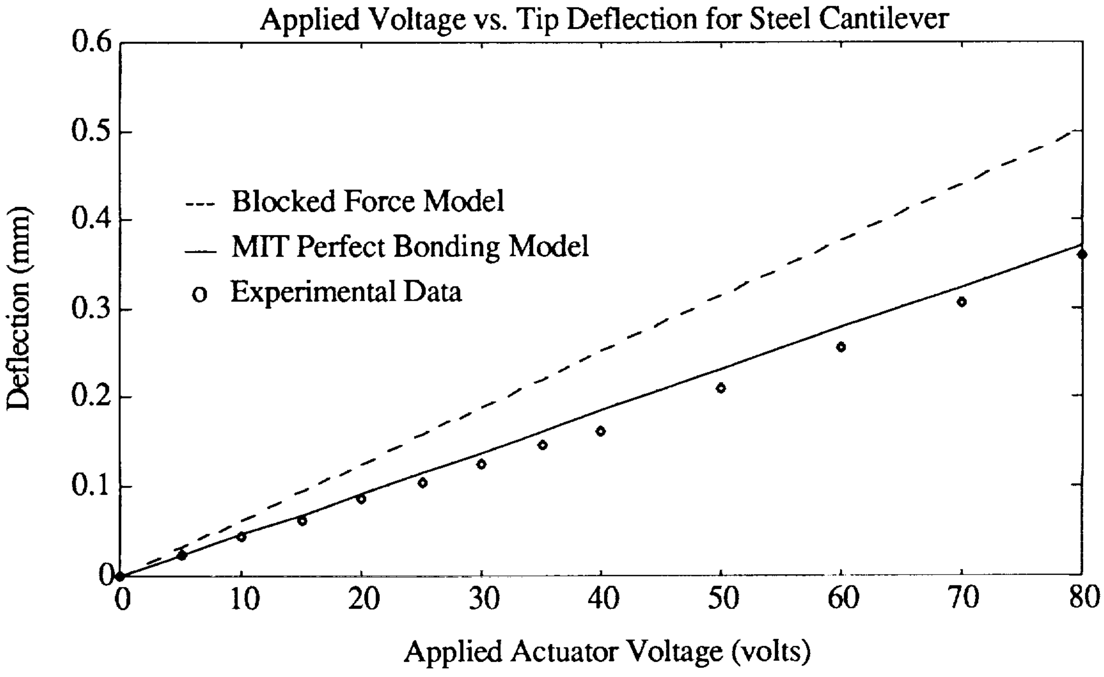


Figure 4

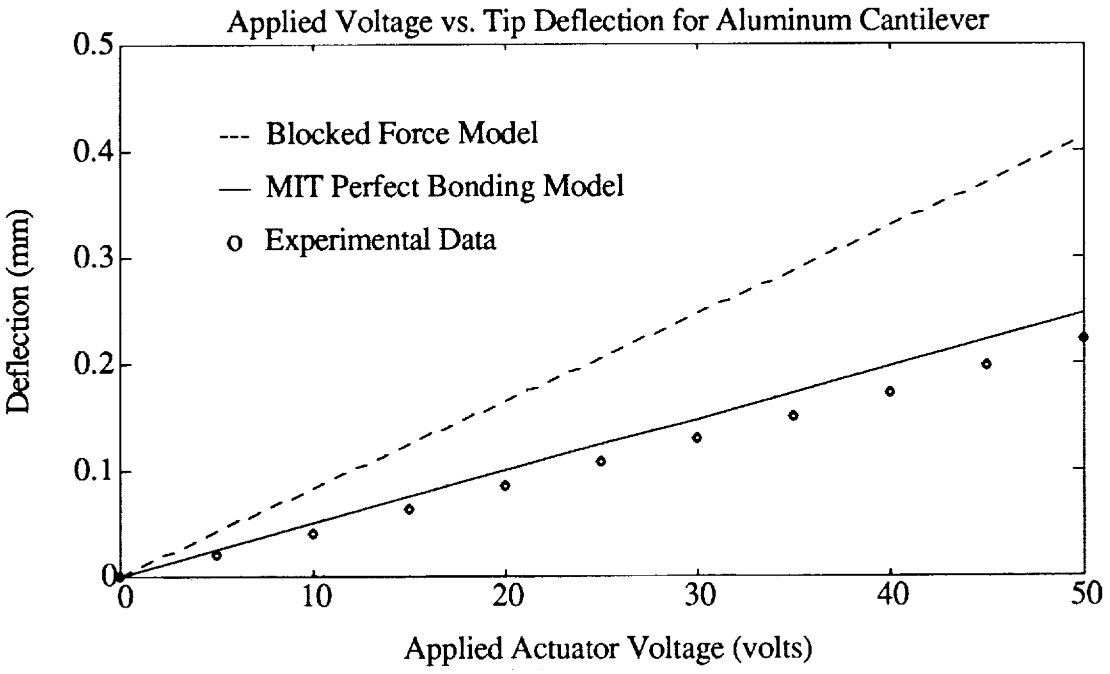


Figure 5

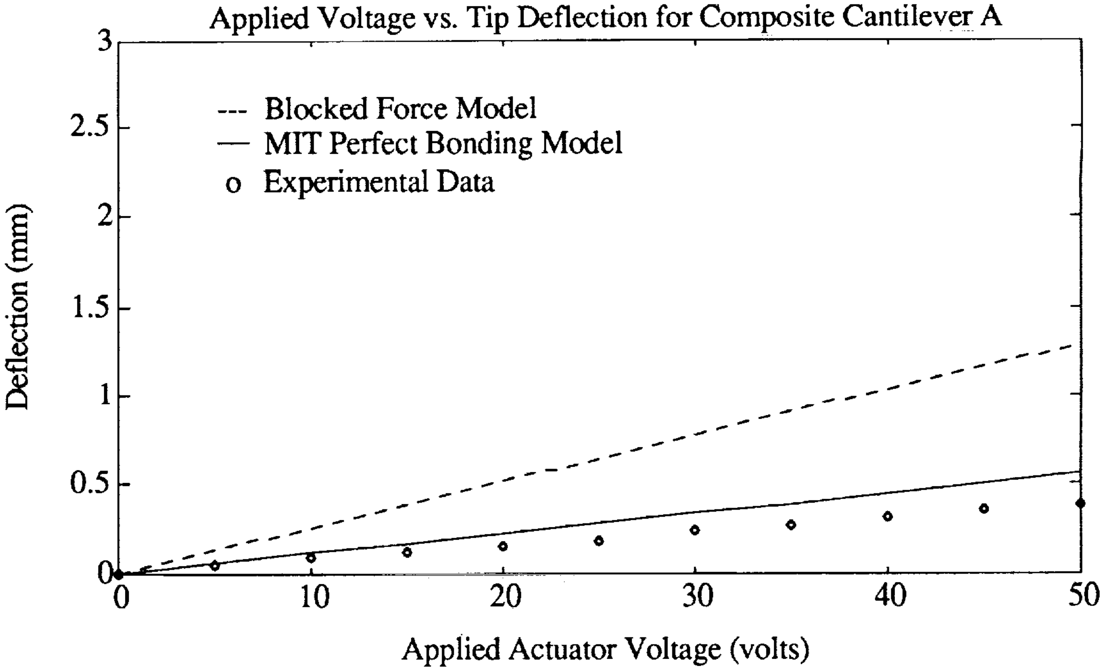


Figure 6

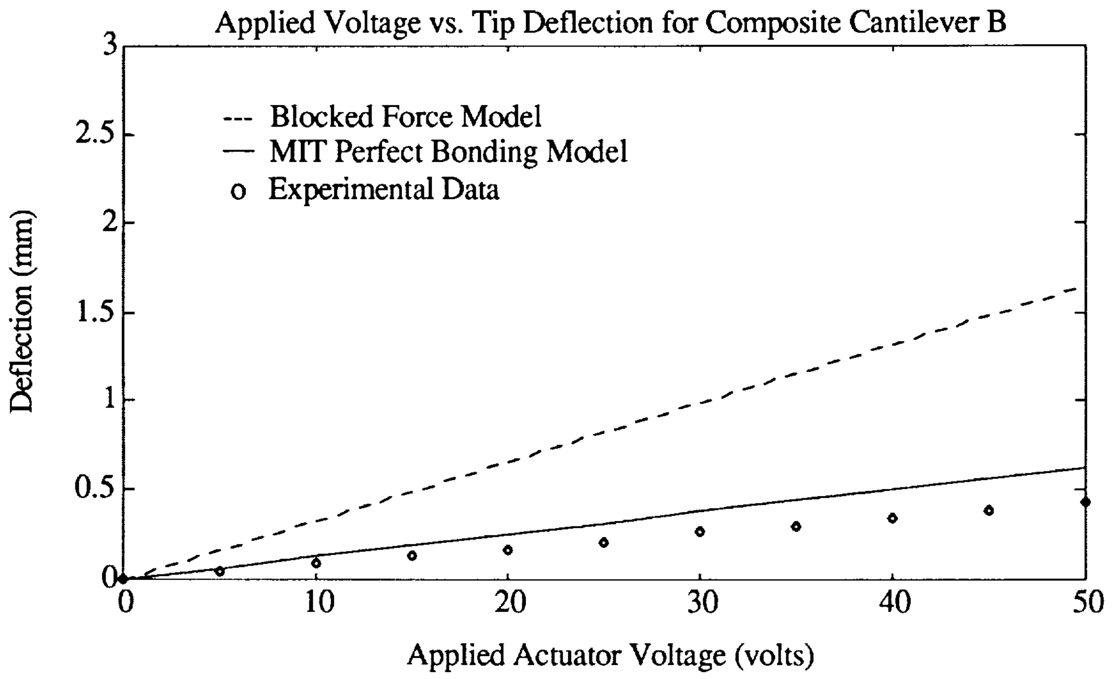


Figure 7

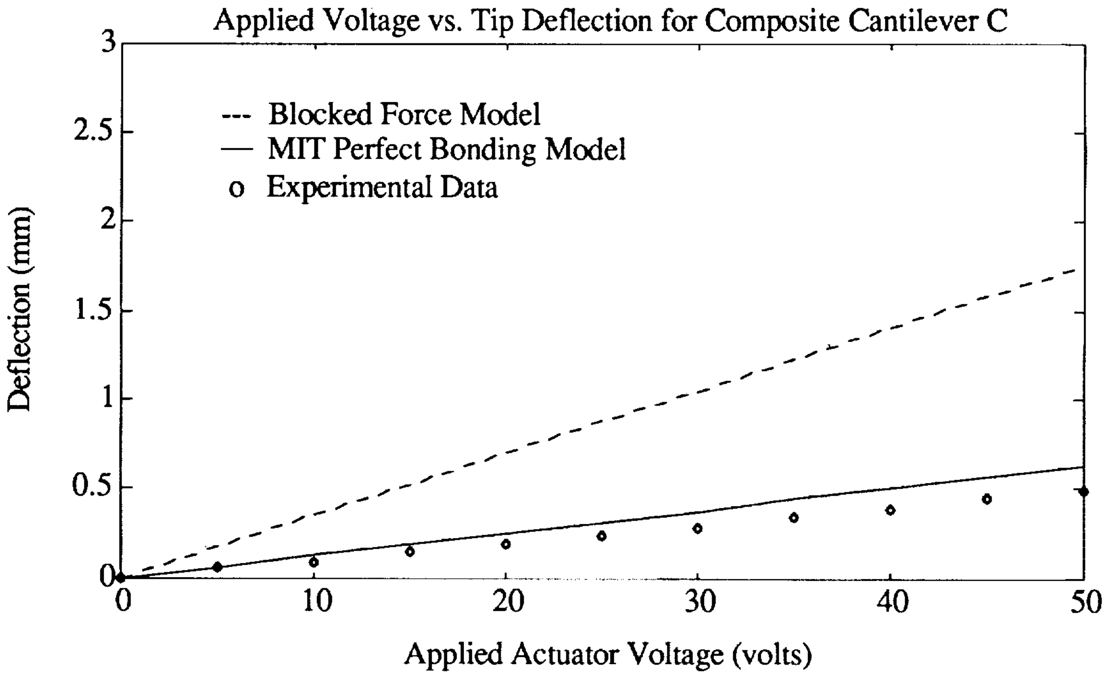


Figure 8

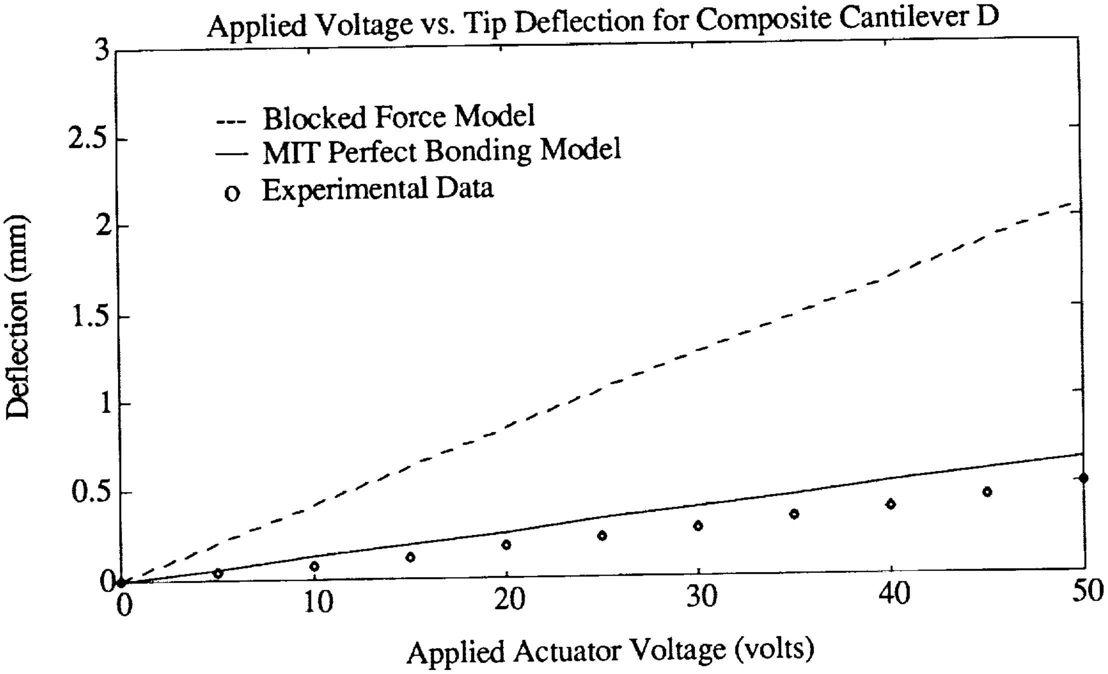


Figure 9

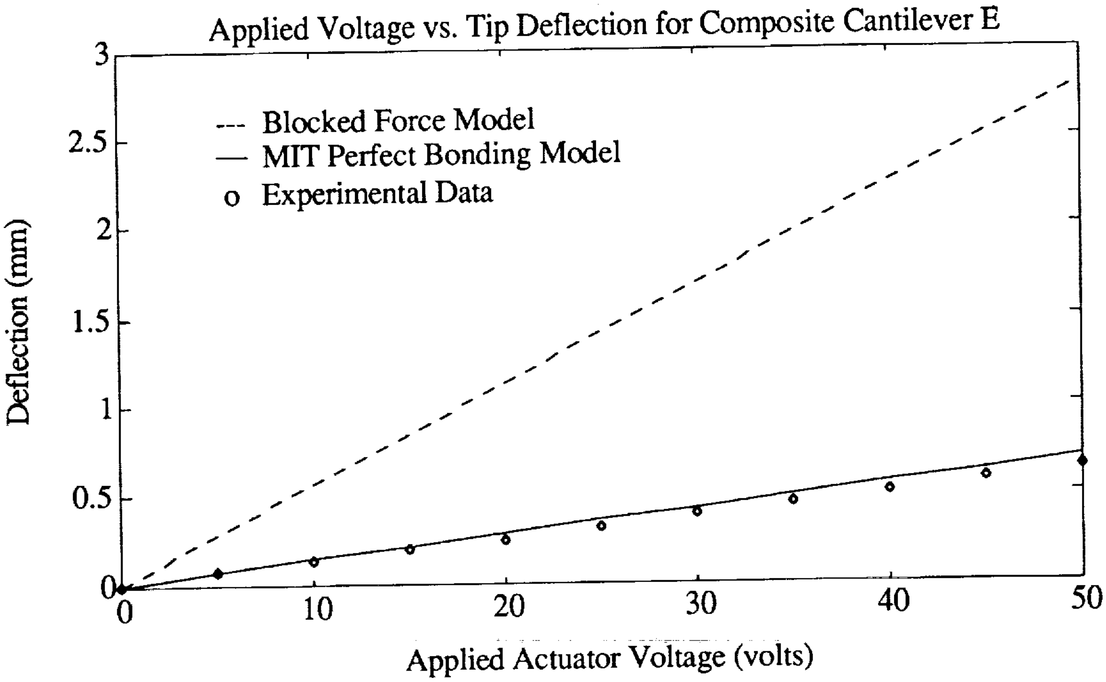


Figure 10

The first item to note from these plots is that the experimental data is consistent relative to the model predictions for all of the specimens showing the models give similar results for isotropic materials as well as the composite specimens. By examining the data for the composite specimens, several other trends become apparent.

* The predictions of the Blocked Force Model become worse as the substructure becomes softer. This is to be expected since a soft, flexible substructure is less like the blocked end condition assumed by this model.

* The predictions of the Uniform Strain Model with Perfect Bonding become better as the substructure becomes softer. This is also to be expected since the shear lag parameter (1) becomes larger for the softer structure and the bonding condition becomes more like that of a perfect bond.

* The predictions of the Uniform Strain Model with Perfect Bonding correlate better with the experimental data than the predictions of the Blocked Force Model but the two predictions converge as the structure gets stiffer. This is makes sense since the effective stiffness ratio (4) becomes higher and the Uniform Strain Model with Perfect Bonding begins to converge to the Blocked Force Model. Figure 11 shows how the two models would converge for a very stiff structure and diverge for a very soft structure.

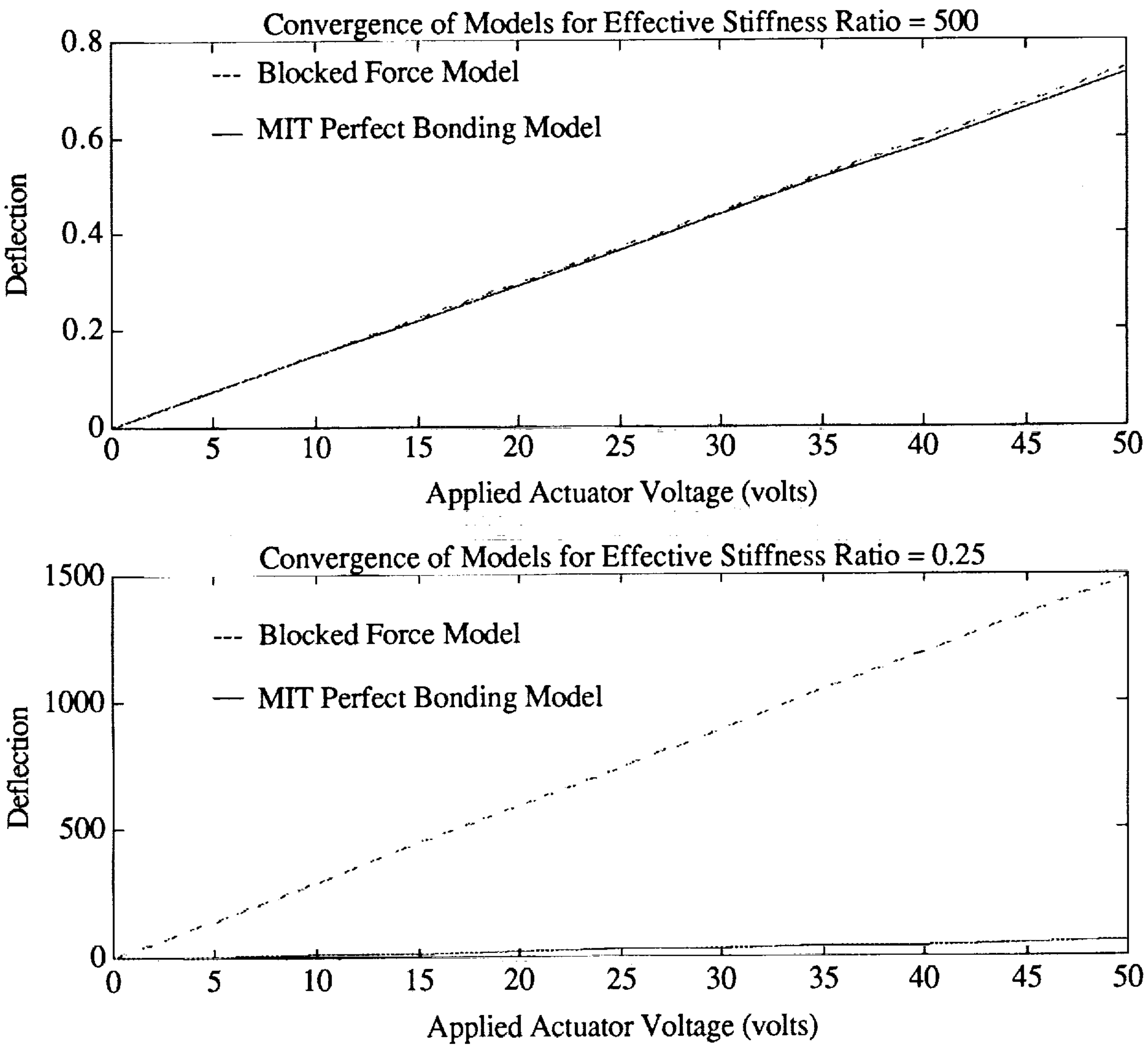

Convergence of Models for Effective Stiffness Ratio = 500
--- Blocked Force Model
— MIT Perfect Bonding Model
Deflection
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
45
50
Applied Actuator Voltage (volts)
Convergence of Models for Effective Stiffness Ratio = 0.25
--- Blocked Force Model
— MIT Perfect Bonding Model
Deflection
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
50
Applied Actuator Voltage (volts)

Figure 11

Construction of Smart Patch Demonstration Article

In this demonstration article, multilayer piezoelectric actuators are bonded to the base with a piezoelectric sensor and the necessary control and power electronics bonded to the substructure above the actuators. The size of the electronics is at least the same order of magnitude as the combined size of the sensor and actuators. The voltage differential provided to the electronics is approximately 32 volts. This is provided by four small rechargeable batteries housed in the base of the structure. The schematic of the demonstration article is shown in Figure 12.

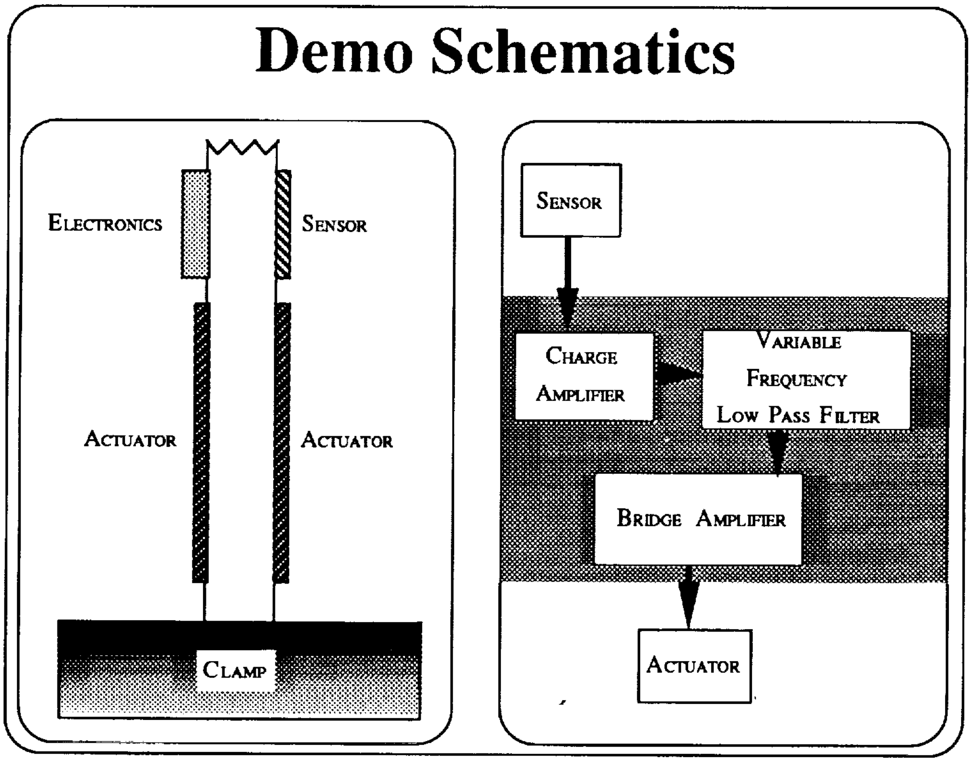


Figure 12

The control of the structure is provided by a two pole low pass filter which shifts the phase of the piezoelectric sensor output at the structures first resonance in relation to the output by 90 degrees of phase.* This provides active damping to the system which is illustrated by the open and closed

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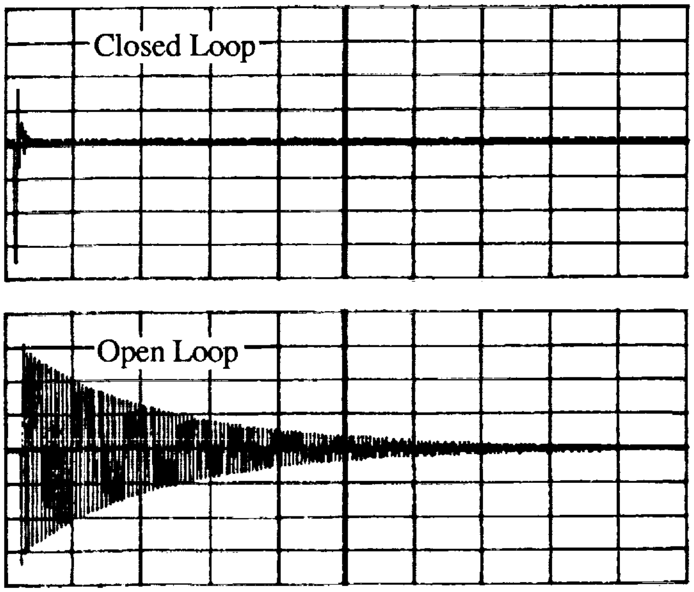
*Bronowicki, A. J., Betros, R. S., course notes from "Active Damping Workshop."

loop responses of the strain seen by the piezoelectric sensor which are shown in Figure 13.



Closed and Open Loop Response of Piezoelectric Sensor

Figure 13

Conclusions

We hope that the work presented in this paper will be useful to those interested in understanding some of the basic issues involved in the development of a piezoelectric based smart patch. The following are some of the important conclusions that can be made from this research.

* Given a surface bonded piezoceramic actuator of fixed size and shape, even the simplest Blocked Force Model may be adequate for a relatively flexurally stiff substructure and a very good bond. It is not necessary to always use a more complex model to achieve good practical results.

* The Uniform Strain Model with Perfect Bonding is necessary for relatively soft substructures. Given a fixed size and type of bonding layer, perfect bonding is a better approximation if the substructure is relatively flexurally soft. However, in

cases where bonding produces significant shear lag, it may be necessary to go to the more complex Uniform Strain Model with Finite Thickness Bond to adequately predict the actuator forces. Depending on the degree of accuracy needed, this may be necessary even for values of Γ greater than 30. Also, for substructure geometries other than an Euler-Bernoulli beam, it may be necessary to use other models such as those based on plate theory to get desirable results.

* Smart patch technology does not have to be costly and complex to be effective. This has been illustrated by the demonstration article which uses very simple strain rate feedback and a small compact smart patch design. The entire demonstration article material cost was less than $100.00.

References

[1] Crawley, E.F. and de Luis, J., "Use of Piezoelectric Actuators as Elements of Intelligent Structures", AIAA Journal, Vol.25, No.10, Oct. 1987, pp.1373-1385.

[2] Thomson, W.T., Theory of Vibration with Applications, 2nd Edition. New Jersey, Prentice-Hall, 1981, Section 7.4.

[3] Crawley, E.F. and Anderson, E.H., "Detailed Models of Piezoceramic Actuation of Beams", Journal of Intelligent Material Systems and Structures, Vol.1, No.1, Jan. 1990, pp.4-25.