Proceedings of IDETC/CIE 2005
ASME 2005 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conference
September 24-28, 2005, Long Beach, California USA

DETC2005-85596

NONLINEAR CONTROL OF HYBRID ELECTROSTRICTIVE/PIEZOELECTRIC POLYMERIC STRUCTURES: THEORY AND EXPERIMENT

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ABSTRACT

Electromechanical response of electrostrictive materials behaves quadratically, while that of piezoelectric material behaves linearly. This study is to evaluate quadratic control response of electrostrictive actuators with reference to linear signal generation of piezoelectric sensors. A hybrid beam structure coupled with an electrostrictive RTV 270 actuator layer and a polyvinylidene-fluoride sensor layer is fabricated and its control response evaluated. Mathematical model is established first, followed by finite-difference discretization resulting in a set of finite difference equations used in numerical simulation of controlled and uncontrolled responses. The physical model connected to a bang-bang controller, a high-voltage amplifier, a data acquisition system is setup in laboratory. Due to the quadratic behavior of the electrostrictive actuator, the bang-bang controller activates the electrostrictive actuator only in the upward motion of the beam, according to the signals generated from the piezoelectric sensor. Vibration control characteristic (i.e., damping ratio estimation) of the beam subjected to various control conditions are evaluated. Experimental data are compared favorably with simulation results.

INTRODUCTION

Electrostrictive materials, in which the strain is proportional to the square of the applied field, have been used in many areas, such as precision mirrors, artificial muscles, electromechanical robotic actuators, vibration and noise controllers, etc. Distributed actuation of a cantilever aluminum beam with surface bonded electrostrictive wafer made of lead magnesium niobate with lead titanate, i.e., Pb(Mg1/3Nb2/3)O3-PbTiO3 or PMN-PT, was developed and studied [1]. Adaptive strain and vibration sensors composed of PMN-PT were investigated [2]. A constitutive model for electrostrictive ceramic materials concerning key state variables of stress, strain, polarization and temperature was developed [3]. Characteristics of PMN strain response, hysterisis and dielectric permittivity was studies [4]. Model of electrostrictive relaxor ferroelectric was tested under various conditions [5,6]. Mechanical properties and the response of the electrostrictive ceramic were studied based on a cantilever beam model [7,8]. Possibilities of using electrostrictive ceramic for active vibration control were proposed [9].

Other than hard electrostrictive ceramic, development of soft electrostrictive polymers has also been advancing in recent years. Electroacoustic transducer that uses the electrostrictive polymer film was studied [10]. The electrostrictive effect of polyurethane elastomer (PUE) was utilized as an monomorph actuator [11,12], micro-actuators [13] and artificial muscle actuators [14]. Many other polymeric materials, such as silicone, polyurethane, fluorosilicone, isoprene and polybutadiene, have also been tested to evaluate their electrostrictive characteristics, e.g., especially polyurethane Deerfield PT6100S, silicone Dow Corning Sylgard 186, silicone Dow Corning RTV730 and polyurethane 2103-80AE [15]. However, a recent study reported that the electrostrictive effects in certain polymers are actually due to the Maxwell stress effect [16].

The room temperature vulcanized (RTV) fluorosilicone products used in this study are economic and ready-to-make or molded into any shapes, as compared with any other smart materials. Thus, development cost of RTV electrostrictive actuators is low. This study is to evaluate bang-bang vibration control effectiveness of a hybrid cantilever beam coupled with a polymeric fluorosilicone RTV 270 layer and a polyvinylidene fluoride (PVDF) layer, in which the former serves as a distributed actuator and the latter a distributed sensor. A mathematical model based on the experimental model is established. Fabrication of the physical model and its laboratory testing procedures, including experimental apparatus and control electronics, are presented. Damping ratios of the physical hybrid beam model under various conditions are estimated and compared with finite-difference simulation results based on the analytical model.

MATHEMATICAL MODELING

As discussed briefly, the hybrid beam model is made of Plexiglas bonded with an electrostrictive polymer (fluorosilicone black RTV270) on the top surface as an actuator and a piezoelectric polyvinyldene fluoride (PVDF) polymer on the bottom surface as a sensor, **Figure 1**. Note that the sensing characteristic of PVDF is based on the direct piezoelectric effect and the actuation capability of electrostrictor is based on the (direct) electrostrictive effect [17,18]. An analytical model of the cantilever sensor/actuator beam model is developed based on the electrostrictive thin shell theory and a generic piezoelectric neuron sensing theory [19]. The mathematic models of the actuator and the sensor are respectively developed, however, only the distributed electrostrictive actuation effectiveness of the beam is emphasized later in this study.

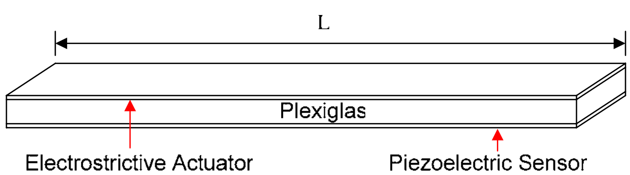


Fig.1 A hybrid electrostrictive/piezoelectric polymeric beam.

To develop the hybrid beam mathematical model based on the generic electrostrictive thin shell theory and the generic piezoelectric neuron sensing theory, three geometric definitions are required: the Lamé parameters ($A_1 = 1$ and $A_2 = 1$), the radii of curvature ($R_1 = \infty$ and $R_2 = \infty$), and the principal coordinate axes ($\alpha_1 = x$ and $\alpha_2 = y$). The signal generation ϕ^s of the distributed PVDF sensor laminated on the cantilever beam, due to the direct piezoelectric effect, can be simplified from the generic shell sensor equation [19]

$$\phi^s = (h^s / S^e) \int_{\alpha_1} \int_{\alpha_2} (h_{31} S_{11} + h_{32} S_{22}) \cdot A_1 A_2 d\alpha_1 d\alpha_2 \, , \quad \text{(1a)}$$

where S_{ij} are the induced linear or nonlinear strains; h_{ij} is the piezoelectric constant; h^s is the sensor thickness; S^e is the effective electrode area; and A_1 and A_2 are Lamé parameters. The surface integration denotes the total charge generated over the effective electrode area defined in the α_1 and α_2 directions. Since a beam has constant width and the strain in the width direction is usually neglected, thus, the signal generation on the cantilever beam becomes

$$\phi^s = (b\, h^s / S^e) \int_{\alpha_1} (h_{31} S_{11}) \cdot dx \, . \quad \text{(1b)}$$

On the other hand, the coupled motion/control equation for a transversely vibrating Euler-Bernoulli beam laminated with an electrostrictor is

$$-\frac{\partial Q_{13}^m}{\partial x} + \rho h \frac{\partial^2 u_3}{\partial t^2} = 0 \, , \quad \text{and}$$

$$Q_{13}^m = \frac{\partial [(M_{xx}^m - M_{xx}^c)]}{\partial x} \, , \quad \text{(2a)}$$

where h is the elastic beam thickness; ρ is the mass density of the elastic beam per unit length; Q_{13}^m is the transverse shear effect; M_{xx}^m is the mechanical bending moment and M_{xx}^c is the "electric" (or control) bending moment induced by the electrostrictive actuator. Note that both the polymeric electrostrictor and piezoelectric sensor are thin and soft, as compared with the elastic Plexiglas beam. Thus, their physical properties are not considered, although the electrostrictor induced control action is considered. With substitution and simplification, the dynamic motion/control equation becomes

$$-\frac{\partial^2 (M_{xx}^m - M_{xx}^c)}{\partial x^2} + \rho h \frac{\partial^2 u_3}{\partial t^2} = 0 \, . \quad \text{(2b)}$$

Moreover, the mechanical bending moment of the beam is defined as $M_{xx}^m = Y I k_{xx}$ where Y is Young's modulus of the elastic beam; I is the area moment of inertia per unit width of the elastic beam and $I = \frac{h^3}{12}$; k_{xx} is the bending strain and $k_{xx} = -\frac{\partial^2 u_3}{\partial x^2}$. The actuator is assumed isotropic and only the induced transverse action (m_{12} = 2.3 x 10^{-22} m^2/V^2) of the actuator is considered. The electrical control moment induced by the electrostrictive material is defined as

$$M_{xx}^c = \frac{Y_{e_v} m_{12} (\phi_3^a)^2 r^a}{h^a} \, , \quad \text{(3)}$$

where Y_{e_v} is Young's modulus of the actuator; m_{12} is the electrostrictive strain constant; r^a is the moment arm measured from the neutral axis of the beam; ϕ_3^a is the applied voltage in the transverse direction and h^a is the thickness of the actuator. Note that m_{31} in triclinic material becomes m_{12} in isotropic material, i.e., m_{31}=m_{12} [20]. Since $M_{xx}^m = -Y I \frac{\partial^2 u_3}{\partial x^2}$ and

$M_{xx}^{c} = \frac{Y_{e_v} m_{12} (\phi_3^a)^2 r^a}{h^a}$, the dynamic motion/control equation can be rewritten as

$$\frac{\partial^2}{\partial x^2}[YI\frac{\partial^2 u_3}{\partial x^2} + \frac{Y_{e_v} m_{12}(\phi_3^a)^2 r^a}{h^a}] + \rho h \frac{\partial^2 u_3}{\partial t^2} = 0 \quad , \quad (4)$$

Furthermore, since the electrostrictive actuator is fully distributed, the electrostrictor induced control moment vanishes when carrying out the surface integration from one end to the other end of the beam. The original distributed control becomes “boundary control” with an actuator induced counteracting control moment lumped at the free end [21]. Thus, boundary conditions of the cantilever beam with a fully distributed electrostrictive actuator are

1) $u_3 = 0$ and $\frac{\partial u_3}{\partial x} = 0$ at x = 0,

2) $\frac{\partial^3 u_3}{\partial x^3} = 0$ and $-YI\frac{\partial^2 u_3}{\partial x^2} = \frac{Y_{e_v} m_{12}(\phi^a)^2 r^a}{h^a}$ at x = L.

Using the finite difference discretization and numerical simulation, dynamic control effect of the hybrid beam with the boundary control is evaluated next.

FINITE DIFFERENCE DISCRETIZATION AND SIMULATION

Due to the difficulty of analytical procedures involving partial differential equations and controllable boundary conditions, control characteristics of the hybrid beam system is simulated via the finite difference discretization technique. Thus, finite difference discretization of the beam is presented first, followed by finite difference representations of physical boundary conditions and boundary control action. Recall that the equivalent control effect of a fully distributed electrostrictive actuator is lumped at the free-end. Thus, the dynamic equation of the plexiglas beam without the electrostrictive actuator becomes

$$\frac{\partial^2}{\partial x^2}(YI\frac{\partial^2 u_3}{\partial x^2}) + \rho h \frac{\partial^2 u_3}{\partial t^2} = 0 \quad , \quad (5)$$

which can be rearranged to

$$\frac{\partial^2 u_3}{\partial t^2} = \frac{1}{\rho h}(-YI\frac{\partial^4 u_3}{\partial x^4}) \quad . \quad (6)$$

The finite difference method is utilized to discretize the beam equation. The finite difference beam equation of the i-th node is represented as

$$\frac{\partial^2 u_3}{\partial t^2} = \frac{1}{\rho h}(-YI\frac{u_{i+2} - 4u_{i+1} + 6u_i - 4u_{i-1} + u_{i-2}}{\Delta x^4}) \quad , \quad (7)$$

where u_i is the displacement at the i-th node; Δx is the finite difference and $\Delta x = L/n$, where L is the beam length and n is the number of elements or segments, **Figure 2**.

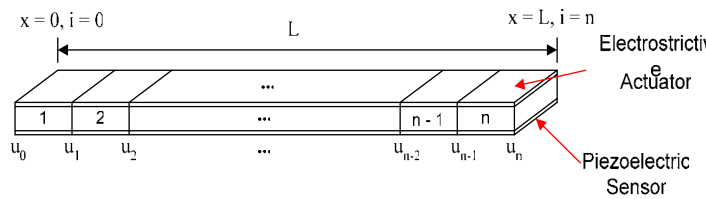


Fig.2 A hybrid polymeric electrostrictive/piezoelectric beam divided into n elements.

Figure 3 illustrates the solution procedures to determine the i-th node displacement u_i and it is implemented in all nodal blocks (subsystems) constituting the complete hybrid beam system. Note that although the original equation does not have the damping in the system equation, the damping constant c is added to emulate the experimental model in the simulation diagram. The saturation blocks in the simulation diagram are to prevent the simulated results from instability.

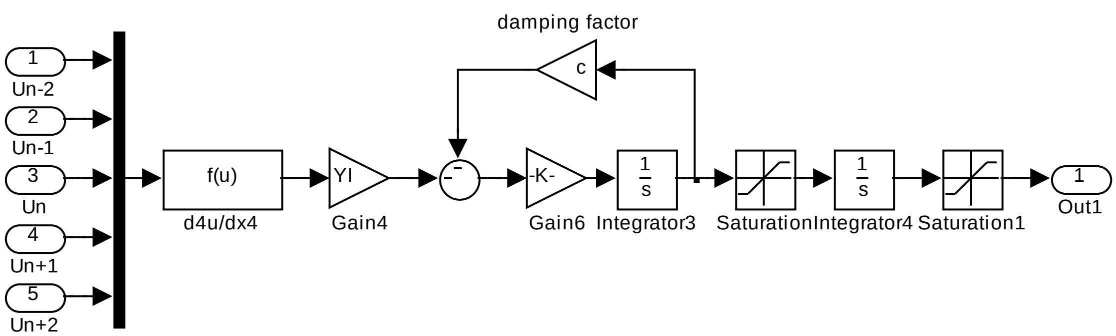
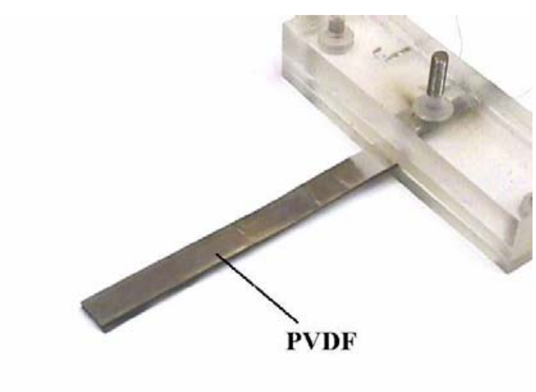


Fig.3 Simulation diagram of the i-th beam element.

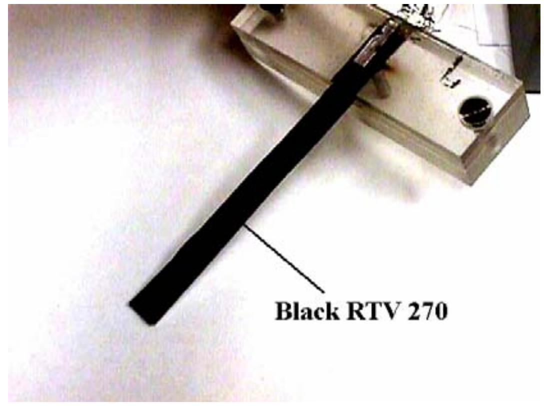
The beam is divided into eight elements, i.e., n = 8, in this case. Accordingly, there are a total of nine nodes (from node 0 to node 8). With all finite difference equations established for all nodes, the cantilever beam system can be either programmed in FORTRAN or simulated by MATLAB-Simulink, while the latter is used in this study. Accordingly, the i-th beam diagram can be extended to include all eight elements, physical boundary conditions and boundary control induced by the electrostrictive actuator. Note that the physical boundary conditions at the fixed end are described as zero displacement $u_0 = 0$; the boundary conditions at the free end are zero moment and zero shear force implemented at Node 8; and the equivalent counteracting control moment $\frac{Y_{e_v} m_{12} (\phi^a)^2 r^a}{h^a}$ induced by the electrostrictive effect is implemented at the free end of the beam, as illustrated in **APPENDIX**: **Figure A1**. The initial applied voltage for the experimental model is 2V and the damping ratio is estimated to be ~0.0176 (averaged of 25 data). Thus, an initial damping ratio of 0.0175 is implemented into the numerical simulation, and all geometric/material properties of the hybrid beam are incorporated into the numerical simulation, too. Design, fabrication and experimental setup of a physical model are discussed next. Simulation results are compared with experimental data acquired from laboratory experiments, which are presented later.

PHYSICAL MODEL AND EXPERIMENT SETUP

The physical model used in laboratory experiment is a Plexiglas beam laminated with an electrostrictive fluorosilicone layer on the top surface and a piezoelectric polyvinylidene fluoride (PVDF) sensor layer on the bottom surface, as original illustrated in **Figure 1**. Fluorosilicone RTV products studied in this experiment are low cost, ready-to-make and commercially available, which are commonly used as sealants for household usages, water pumps and thermostat gaskets. There are four RTV materials been tested: Black RTV270, Red RTV650, Blue II RTV777 and Gray RTV. However, Black RTV270 is selected in the investigation due to its better actuation performance, as compared with the others. Fluorosilicone RTV270 is a black sticky paste that can be spread on a piece of wax paper and molded into any desirable shapes. The thickness of Black RTV270 can be adjusted as well. Graphite powder is used as the electrodes on the actuator surfaces in this experiment. A large number of RTV 270 specimens were tested to calibrate the control actions and material characteristics. The hybrid beam model is shown in **Figure 4**, in which the top and bottom surfaces are respectively photographed. Dimension and material properties are summarized in **Table 1**.



(a) PVDF layer (bottom)



(b) RTV-270 layer (top)

Fig.4 A PVDF layer (bottom) (a) and a RTV-270 layer (top) on the beam surface.

Table 1 Material properties of the hybrid beam.

	Plexiglas Beam	RTV 270	PVDF	Units
Y	3.1×10^{9}	5.0×10^{5}	2.0×10^{9}	N/m^2
ρ	1190	1000	1800	Kg/m^3
h	1.0×10^{-3}	3.0×10^{-4}	5.0×10^{-5}	m
b	5×10^{-2}	5×10^{-2}	5×10^{-2}	m
L	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	m

Recall that the electrostrictive actuator always generates a positive strain regardless the sign of control voltages, since it is a quadratic relationship between the induced strain and the input voltage. Accordingly, the actuator needs to expand to generate a counteracting control moment when the beam is moving upward. However, the PVDF sensor layer generates both positive and negative signals when the beam is oscillating. Thus, a reference signal corresponding to the upward beam motion needs to identify in order to induce a positive control action in the electrostrictive actuator. Thus, the activation of the electrostrictive actuator is based on the direction of the beam oscillation. Now, let $u_3 = u_3(x, \phi^a)$, $\left|\phi^a\right| \le \phi^a_{max}$ and $\phi^a_{max} \le 600V$. Thus, the control voltages are set as ϕ^a = -2V, -200V, -400V and -600V, if $u_3 \ge 0$ or upward motion and $\phi^a = 0$, if $u_3 < 0$ or downward motion. Note that the high-voltage source generates a negative voltage which is squared to induce control strain in the electrostrictive actuator.

The hybrid beam laminated with an electrostrictive actuator and a piezoelectric sensor is clamped to a plexiglas fixture and then mounted on a stable base. The electrical lead connected between the actuator and the voltage source, and the electric lead connected between the sensor and the data acquisition system/controller of the hybrid model are located at the fix end of the beam where the beam area is clamped by the Plexiglas fixture, **Figure 4**. In this way, the influence of loosed connecting wires to structural dynamics can be eliminated. A DSP Siglab unit is used for data acquisition in this experiment, and a bang-bang controller circuit is designed for activating the electrostrictive actuator. Sensor signals are simultaneously sent to the controller and the data acquisition. Signals sent to the controller serve as a reference in activating the actuators; signals sent to the data acquisition are for monitoring the dynamic responses of the beam. An oscilloscope is also added to the setup to monitor the controller as well, and a high-voltage supply source is connected to the actuator via a bang-bang controller. **Figure 5** illustrates the experimental setup and all key electronics; **Figure 6** shows the hybrid beam mounted on a shaker.

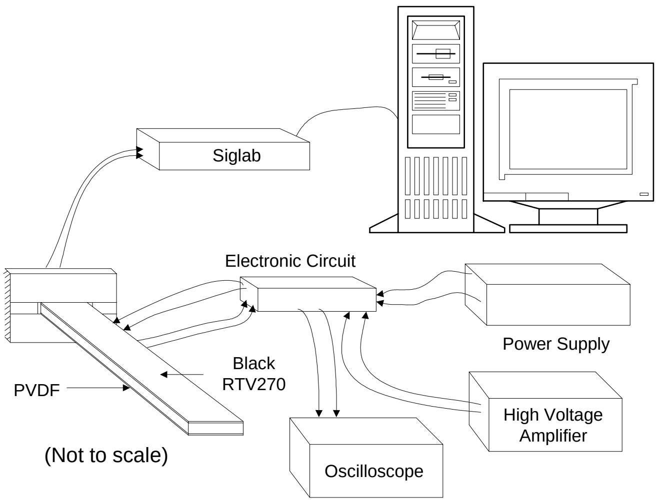


Fig.5 Schematic diagram of the experimental setup.

Fig.6 A hybrid beam mounted on a shaker.

DESIGN OF A BANG-BANG CONTROLLER

P n electronic circuit is designed and set up to achieve the bang-bang control of the hybrid beam system, **Figure 7**. The circuit consists of two parts. The first part, **Figure 8**, is to eliminate the sensor signal generated by the downward motion of the beam, since only the signal related to the upward motion triggering the bang-bang control of the electrostrictive actuator. The second part, **Figure 9**, consists of a mechanical relay that allows the high-voltage control signal flowing into the electrostrictive actuator when triggered by the Part 1 circuit.

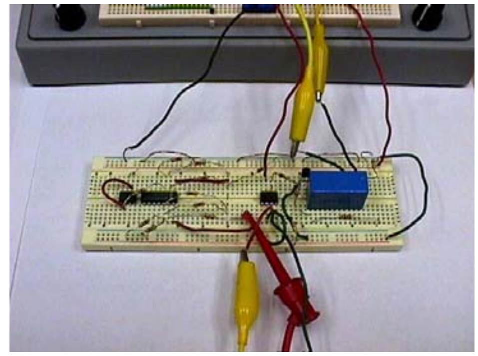


Fig.7 A bang-bang Controller.

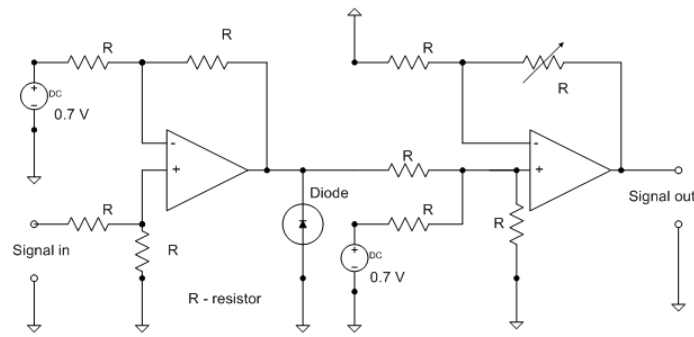


Fig.8 Schematic diagram of the controller – Part 1.

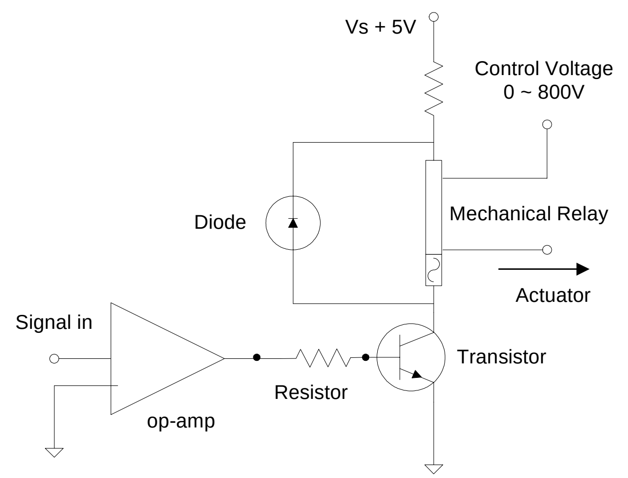


Fig.9 Schematic diagram of the controller – Part 2.

Combination of the two circuits provides the bang–bang control function required by the electrostrictive actuator. A series of experiments is then carried out with various control voltages.

Snap-back responses with the bang-bang control technique are evaluated in laboratory experiments. The tip of the beam is displaced downward slightly and released when reaching a reference initial displacement. The beam vibrates freely and the control action takes place according to the sensor signal input and the applied control voltages. A set of time-history responses generated from the piezoelectric sensor, with and with control, is shown in **Figure 10**, in which the enhanced damping effect shows, so the high-frequency noise. Due to large deflection of the beam, the controlled response doesn't show well. Accordingly, damping estimations of control responses at various control voltages are conducted. The damping ratio ς of the beam is estimated by the logarithmic decrement:

$$\varsigma = \frac{\ln\left(\frac{y_i}{y_{n+i}}\right)}{2\pi(n)}, \quad (8)$$

where y_i is the amplitude of the i-th peak; y_{n+i} is the amplitude of the n-th peak after the reference peak; and n is the n-th cycle after the reference peak i. The applied control voltages are 2V, 100V, 200V, 400V and 600V, where the negative sign is neglected due to its quadratic relationship. The time-history responses of the beam system subjected to various control voltages are recorded and their inferred damping ratio corresponding to each applied voltage is calculated from an averaged of twenty-five data sets. Comparisons between the experimental data and the simulation results are presented next.

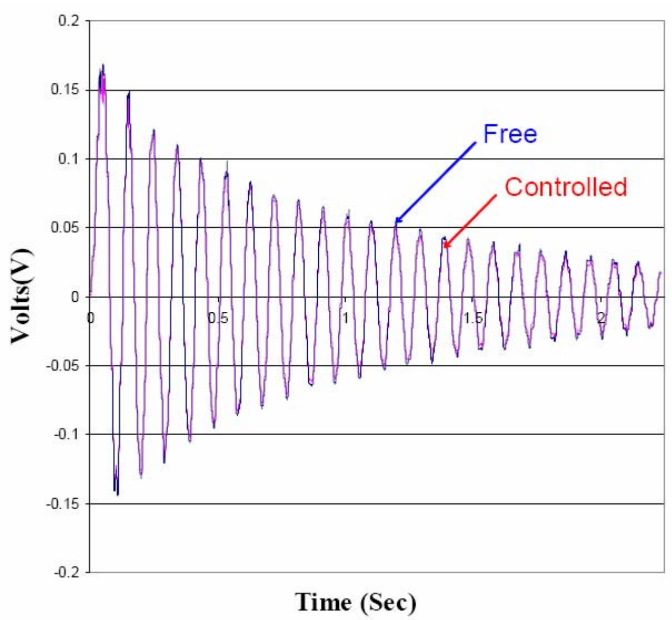


Fig. 10 Sample of controlled and uncontrolled time response of, applied voltage = 200V.

RESULTS AND DISCUSSION

As discussed previously, the hybrid electrostrictive/piezoelectric/Plexiglas beam is evaluated both experimentally and analytically. The bang-bang control voltages are respectively 2V, 100V, 200V, 400V and 600V. **Figure 11** shows the damping increases as the control voltage increases and it proves the quadratic relationship. Detailed estimation and comparison of the experimental data and simulation results are summarized in **Table 2**.

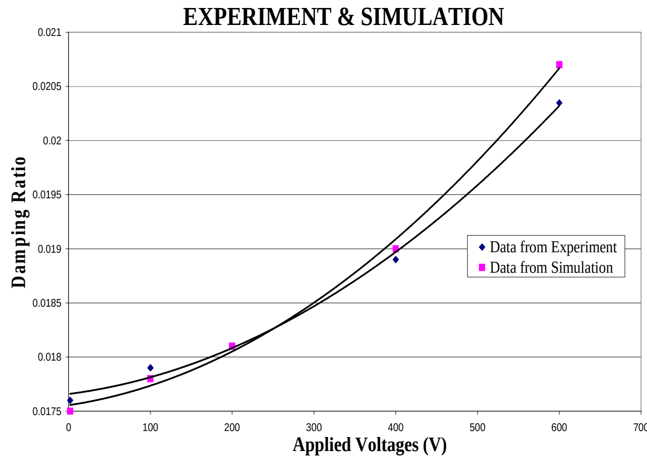


Fig.11 Applied voltage vs damping ratio. (♦: Experimental data; ■: Simulation results.)

Table 2 Comparison of damping variations due to bang-bang control voltages.

Applied Voltages	Experiment Damping Ratio	% Increase	Simulation Damping Ratio	% Increase
2	0.0176		0.0175	
100	0.0179	1.70	0.0178	1.71
200	0.0181	2.84	0.0181	3.42
400	0.0189	7.38	0.0190	8.57
600	0.0203	15.6	0.0207	18.2

In laboratory experiments, the data are acquired from an averaged of twenty-five data points. However, there are only eight data points acquired for the 600V control voltage. This is because 1) the mechanical relay doesn't work well under the high control voltage and 2) the electrostrictive actuator cannot withstand the high voltage for a long duration. The damping ratio increases approximately 1.7 % for the applied voltage from 2V to 100V. The damping ratio further increases to 2.84 % when the applied voltage tuned up to 200V, 7.38 % for 400V and 15.6 % when the applied voltage is 600V.

The finite difference simulation results suggest that the initial damping ratio estimated under the influence of 2V is 0.0175. The damping ratio increases approximately 1.71 % with the applied voltage increased from 2 to 100V. Furthermore, the damping ratio increases 3.42 % when the applied voltage tuned up to 200V, 8.57 % for 400V and 18.2 % when the applied voltage is 600V. The detailed comparison summarized in **Table 2** suggests that the finite difference simulation results based on the analytical model are basically compared very well with the experimental data. However, circuit components and electrostrictive polymeric actuator did not perform well at high control voltages and this deficiency shows on the control effectiveness.

SUMMARY AND CONCLUSION

Electrostrictive actuators can potentially deliver superior control actions, due to the quadratic relationship between the induced strain and the electric field. This study is to evaluate the bang-bang control characteristics of a polymeric electrostrictive/piezoelectric/Plexiglas beam analytically and experimentally.

An experimental hybrid beam model made of a Plexiglas beam laminated with an electrostrictive RTV 270 actuator layer and a piezoelectric PVDF sensor layer was designed and fabricated. A bang-bang control circuit, consisting of the signal filtering and high-voltage input, was set up and connected to the hybrid beam model, along with other data acquisition equipment and high-voltage source. The bang-bang controller only activates when the beam moves upward, such that an expansion of the electrostrictive actuator can alleviate and control the beam vibration as specified. Furthermore, a mathematical model corresponding to the experimental model was also derived, based on the electrostrictive thin shell theory. Due to the difficulty related to analytical closed-form solution procedures, the finite difference discretization technique was adopted to discretize the beam, as well as physical and control boundary conditions. The resulting difference equations were set up and evaluated using Simulink.

Time history responses of the hybrid beam model with various control inputs were then evaluated experimentally and numerically. The inferred damping ratio corresponding to each control voltage was calculated and compared. All data indicate the quadratic relationship of the damping ratio and the control voltage, i.e., the typical electrostrictive characteristic, and the experimental data were compared very well with the analytical simulation results. The total damping ratio was enhanced by 15.6% in experimental results, and 18.2% in simulation data. Accordingly, the analytical model is fully validated by the experimental data and the favorable comparison suggests that the mathematical model can be further extended and applied to other advanced structures.

ACKNOWLEDGMENTS

This research is supported, in part, by a grant from the NASA-Glenn Research Center. This support is gratefully acknowledged. The authors are also grateful to Professor Lynn Penn who generously permitted her equipment be used in fabricating the samples.

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APPENDIX

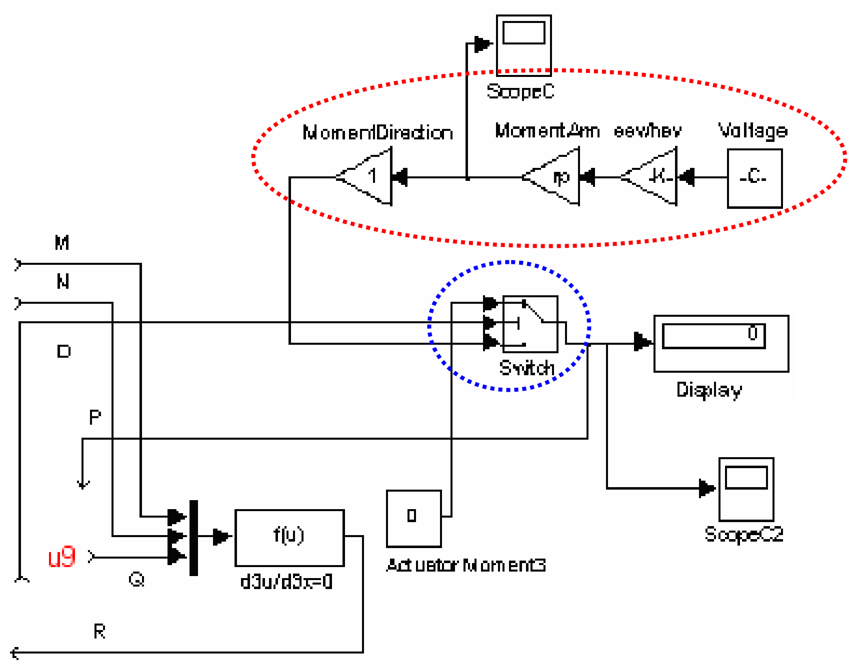

Fig.A1 Control moment implemented at the free-end boundary.