Optimizing Energy Harvesting of a Composite Unimorph Pre-Stressed Bender

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ABSTRACT

Energy harvesting of piezoelectric actuators has been studied in the past. One of the biggest challenges is designing the circuitry necessary to harvest the energy of high impedance piezoelectric actuators and determining what factors affect their performance. Experiments have been conducted using a pre-stressed unimorph ferroelectric actuator (Thunder®) with matching circuitry to measure the electrical energy produced by a single stroke mechanical action. This particular piezoelectric actuator is a composite of a ceramic, a polyimide adhesive, and a metal pre-stressed at elevated temperatures. The parameters varied for this particular set of experiments were the adhesive composition, and the thickness and type of the metal. Displacement under no-load, capacitance, physical dimensional parameters, and electrical energy output were measured for each configuration. The circuit utilized to measure energy used a voltage regulator, and a combination of resistors, and capacitors, so that the electric output of the actuators is controlled eliminating voltage peaks. The energy is then measured by the length of time the voltage can be sustained when loaded with a resistor and appropriate capacitor. Input capacitors were varied in order to measure the best possible combination circuitry for each actuator. The results showed that increasing the conductivity of the polyimide adhesive, determining the appropriate metal thickness, and varying the type of metal used, are all characteristics that not only improve the electrical energy produced but also allow for more flexibility in circuit design. There also seems to be a definite trend between the geometry of the actuators and the energy produced. This trend indicates that pre-stress plays a significant role in the output produced.

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INTRODUCTION

Due to the energy problems faced in the last few years, research into harvesting energy using natural resources has become an area of great interest [1]. Government agencies have a renewed interest in applications where "energy from the environment" can be used to provide either supplementary power to existing devices, or enough power to energize remote devices. [2, 3]. For instance, military applications could significantly benefit from a system that would integrate harvesting energy from some human activity (such as walking, breathing, etc.) to convert or store energy for later use to lengthen a mission [4]. Research has been conducted on the possibility of harvesting energy through human mechanical means, i.e., movement or functioning of the human body and using piezoelectric materials in one form or another to convert or store that energy [5, 6]. The feasibility of using piezoelectric actuators on a shoe for this purpose was explored, and it was concluded that the energy transformation depends highly on the application (low or high power, space available, shape adaptability, etc.)[6, 7]. Nevertheless, there is very little information available on the efficiency of piezoelectric materials in generating electric power. Goldfarb and Jones studied this phenomenon analytically and experimentally using piezoelectric stacks and obtained efficiencies of only 40% [8]. Others such as Umeda et al have looked at the efficiencies of a piezoelectric vibrator under various mechanical and electrical boundary conditions, obtaining a maximum efficiency of 55 % [9]. The major conclusion is that optimization of the system is needed to improve efficiency under any conditions. Hence, equivalent circuits and designs have to be considered on an application basis. For example, studies have shown that in BioMEMS applications, the approach of using piezoelectric materials to supply the electrical energy needed is a viable option. [10].

The present study describes the optimization of a part of the energy conversion system—namely the piezoelectric actuator. The actuator used for this study, Thunder®, consists of a pre-stressed laminate that utilizes a PZT ceramic, a metal substrate, and a polyimide adhesive [11]. It has been demonstrated that many parameters in its construction affect its performance as an actuator [12, 13, 14]. However, the parameters that affect or influence its power conversion capabilities have not been studied. The main objective of this study is to identify and investigate these factors. The circuit utilized is a generic remote control switch, and the devices deliver power based on mechanical to electrical transduction utilizing a "standard" switch.

EXPERIMENTAL PROCEDURE

The THUNDER devices were fabricated from PZT 3195HD piezoelectric ceramic plates, supplied by CTS wireless. The adhesive utilized was the polyimide LaRC-SI, and the metal substrates were brass or stainless steel, available from McMaster-Carr. There were 16 different cases studied, and each case is an average of 5 to 10 pieces. A description of each is provided in Table I for the elements made with stainless steel, and Table II for the brass pieces. For each case, total thickness, dome-height, capacitance, free displacement, and energy output were measured. A description of each one of the measurements made is provided below.

TABLE I. THUNDER ELEMENTS WITH A STAINLESS STEEL SUBSTRATE

Model	PZT Thickness (mm)	Metal Thickness (mm)	Thickness Ratio
A[1]	0.25	0.20	1.25
B[1]	0.25	0.20	1.25
C	0.25	0.20	1.25
D	0.51	0.20	2.50
E	0.20	0.15	1.33
F	0.20	0.20	1.00
G	0.20	0.25	0.80
H	0.20	0.30	0.67

[1]Element with a top layer of 1 mil Aluminum

TABLE II. THUNDER ELEMENTS WITH A BRASS SUBSTRATE

Model	PZT Thickness (mm)	Metal Thickness (mm)	Thickness Ratio
K[1]	0.20	0.15	1.33
L[1]	0.20	0.20	1.00
M[2]	0.20	0.15	1.33
N[2]	0.20	0.20	1.00
O	0.20	0.15	1.33
P	0.20	0.20	1.00
Q	0.20	0.25	0.80
R	0.20	0.30	0.67

[1] 50.8 mm wide
[2] 38.1 mm wide

Thickness Measurements. Thickness was measured across the surface of the elements at three different locations along the actuator's length using a micrometer (Mitutoyo ball tip digital micrometer). The average value was then used.
Dome-Height Measurements. Dome height was measured using a non-contact laser (NAIS micro Laser Sensor LM10). The sample was attached with Scotch tape to a linear ball motion bearing slide from one end only Three different locations along the length of the device were measured for the highest point on each element and the results were averaged (See Figure 1)
Capacitance Measurements. Capacitance is measured at 120 Hz using an LCR Digibridge Meter (GenRad 1693).

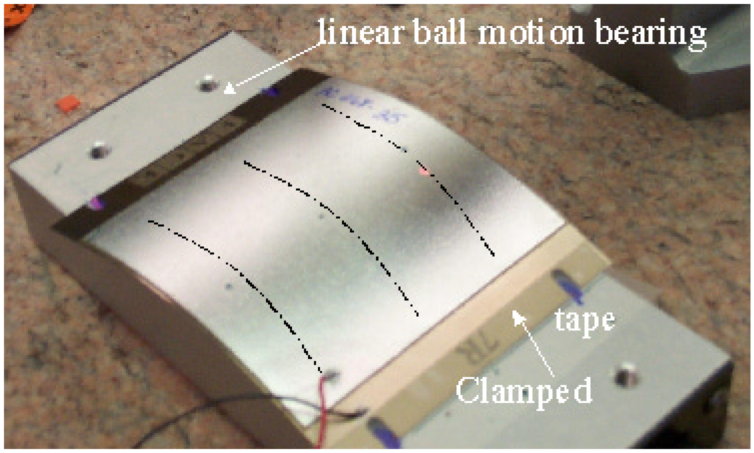

FIGURE 1 Dome Height Measurement

Displacement Measurements. Displacement was measured at voltages between 100 to 600 Volts peak to peak at 1 Hz and no-load using a non-contact laser, a Trek power supply, and a signal generator. Simply supported boundary conditions were used with one end free to translate and the other one clamped.

Output Energy. The element is measured using the circuit shown in Figure 2, placed on the fixture shown in Figure 3. This device uses the red button to push the actuator. The bright purple part is the clamp block for the Thunder element, the green and blue represent the Thunder element as seen from a top view, the gold represents the base-support, the light purple sections are the sides, and the black is the tripping pin mechanism. At the end of the motion of the push bottom a trip pin releases the Thunder element. The output energy of each element is then measured using the circuit described with different input capacitors. Output power is measured by squaring the voltage produced (~3.3 V_{rms}), divided by the load resistance (1 kΩ). Energy output is calculated by multiplying the power and the time of the duration of the signal. See Figure 4 for a typical output curve.

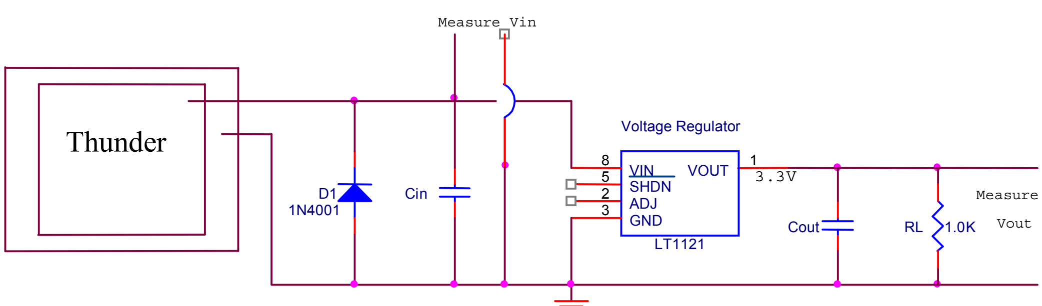

FIGURE 2 Power Measurement Thunder Circuit

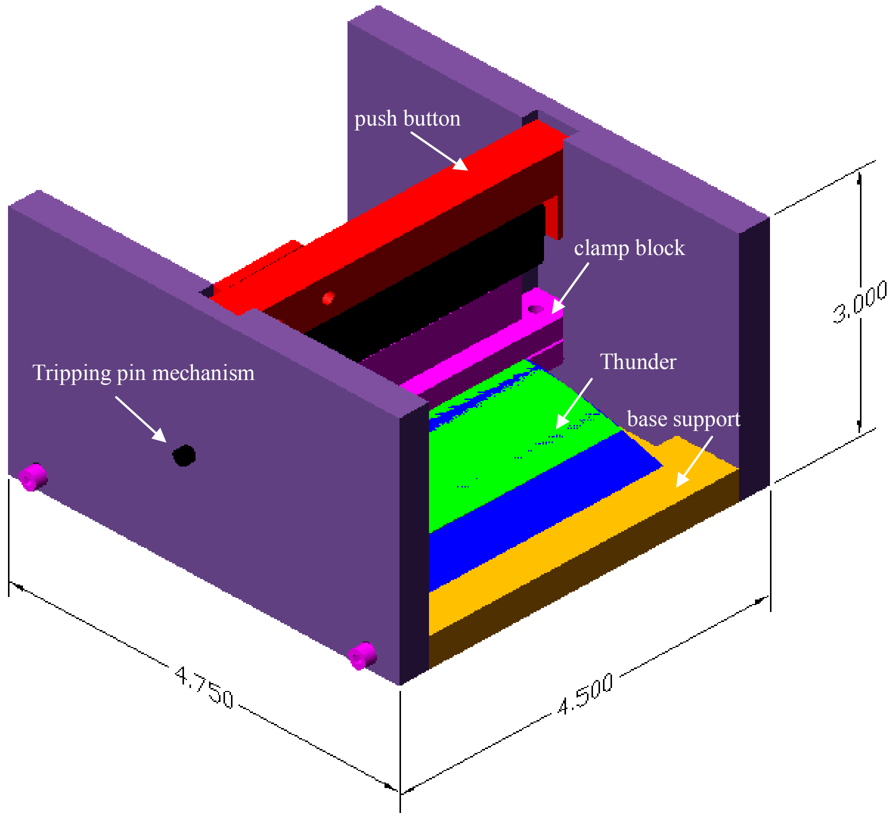

FIGURE 3 Thunder Tripping Mechanism

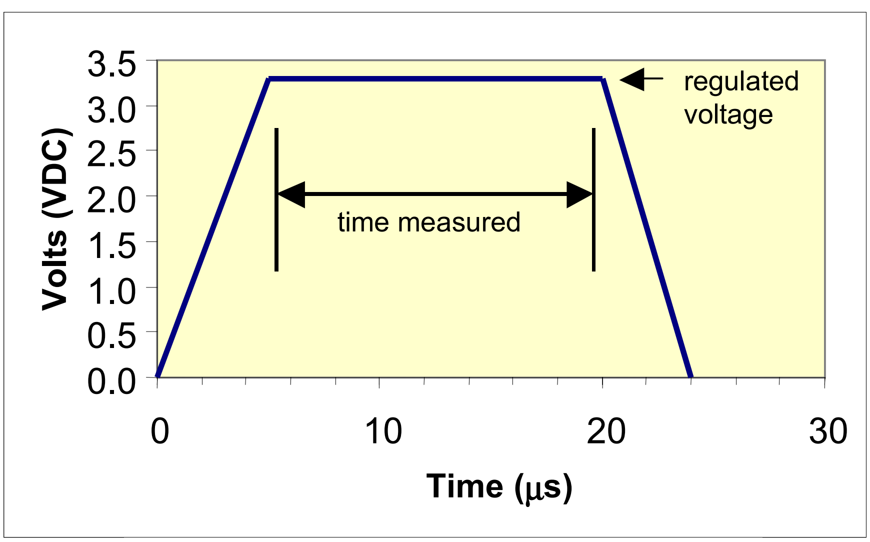

FIGURE 4 Typical Output Waveform

RESULTS

First Optimization Stage: Displacement performance of each element was measured. Generally, it was observed that an actuator that produces the highest displacement does not necessarily produce the highest energy.

The optimization process starts by studying the properties of a standard Thunder element**.** This standard element has from the top down: a layer of aluminum, a polyimide adhesive film, a PZT ceramic, and a stainless steel substrate. The capacitance of this device is 176.60nF, much lower than that of the ceramic alone, 330nF.

If the element is strictly seen as a capacitor, then increasing the thickness diminishes the value of the overall capacitance, since capacitance is inversely proportional to thickness. However, the decrease could also be due to poor contact between the electroded PZT ceramic and the bottom stainless steel layer. This question does not arise with the top layer, since the aluminum is perforated to ensure adhesion and to ensure point contacts. In order to test this theory, particles of nickel were used to increase the conductivity of the polyimide adhesive layer. The particles are mixed thoroughly in the adhesive film before casting. The effects of the conductive adhesive layer on displacement, thickness, and dome-height, were negligible, however, capacitance and energy output were different as a result (See Table III). The capacitance change was small (a 3% decrease form the standard), however energy production improved by 15%. Other advantages obtained included more reliability in manufacturing and consistency when measuring energy.

TABLE III. THUNDER MANUFACTURED WITH NON - CONDUCTIVE ADHESIVE VS. CONDUCTIVE ADHESIVE

	STANDARD	CONDUCTIVE
Thickness (mm)	5.21 ± 0.056	5.41 ± 0.254
Dome Height (mm)	105.82 ± 4.343	109.35 ± 3.124
Capacitance (nF)	176.60 ± 7.110	171.90 ± 4.35
Max Displacement[1] (mm)	27.84 ± 2.743	27.18 ± 1.702
Max Energy (μJ)[2]	206.91 ± 18.820	239.03 ± 8.660

[1]Simply Supported, one end fixed, other end free, no-load at 1Hz and 600 Volts peak to peak.
[2]Using 3.9 μF Capacitors.

Second Optimization Stage: Once it was determined that the conductivity of the polyimide adhesive influenced the energy produced, subsequent Thunder elements were fabricated using a conductive adhesive. Next, the top aluminum layer effect was investigated. A summary of the results is shown in Table IV. Note that thickness, dome-height, and capacitance changes again are not significant. However, a 25% increase in displacement is observed when the aluminum layer is removed. Furthermore, there is evidence that the energy production would be higher, although the values could not be measured. The circuit for the standard remote switch utilizes a regulator that can dissipate up to 25 Volts only. If the regulator receives more voltage, it burns up. In the case of the elements with no aluminum top, higher voltages were observed, indicating that higher energy levels would have been obtained.

TABLE IV. THUNDER MANUFACTURED WITH TOP VS. NO TOP LAYER

	TOP	NO-TOP
Thickness (mm)	5.49 ± 0.25	5.33 ± 0.12
Dome Height (mm)	109.35 ± 3.12	111.73 ± 2.68
Capacitance (nF)	171.9 ± 4.35	178.5 ± 4.19
Max Displacement (mm)	27.18 ± 1.70	33.93 ± 1.14
Max Energy (uJ)	239.03 ± 8.66	NA*

*Voltage produced higher than the circuit could dissipate, hence energy could not be measured

Third Optimization Stage: Different ratios of metal to total thickness were utilized for this stage. Two types of metal were used — stainless steel and brass. These cases are described in Table I and II. The results obtained for maximum displacement and metal thickness ratio, defined as the metal thickness divided by the measured total thickness of the actuator, are shown in Figure 6. In this case, it seems that the metal thickness ratio describes maximum peak displacement independently of the metal used.

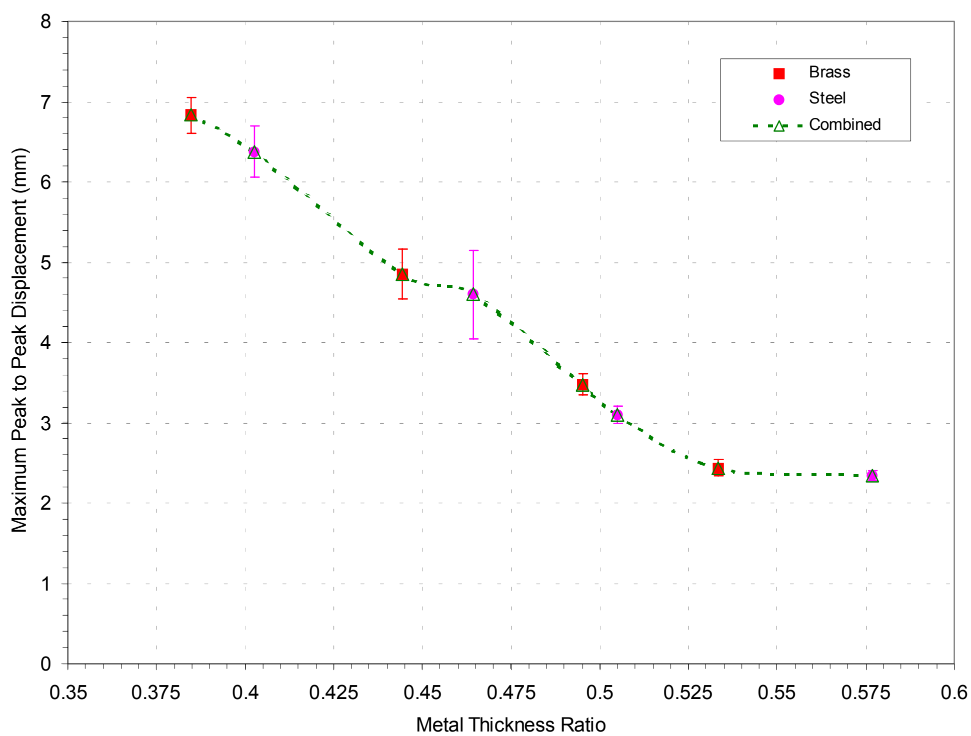

FIGURE 5 Displacement vs. Metal Thickness Ratios

Finally to look at the energy output, the metal thickness ratio and the dome height do not seem to be the relevant parameters, especially when considering pieces with a different width. Since dome height plays a dominant role on the output energy of the pieces, but does not include the width of the element, the volume under the device was considered. By using the measured dome height, a radius of curvature and a length of an arc can be calculated to obtain the area of a segment of a circle. Then, to obtain the volume under the actuator or volume displaced, the area is multiplied by the actuator's width. In this manner cases with a different width can be considered. See Figure 6.

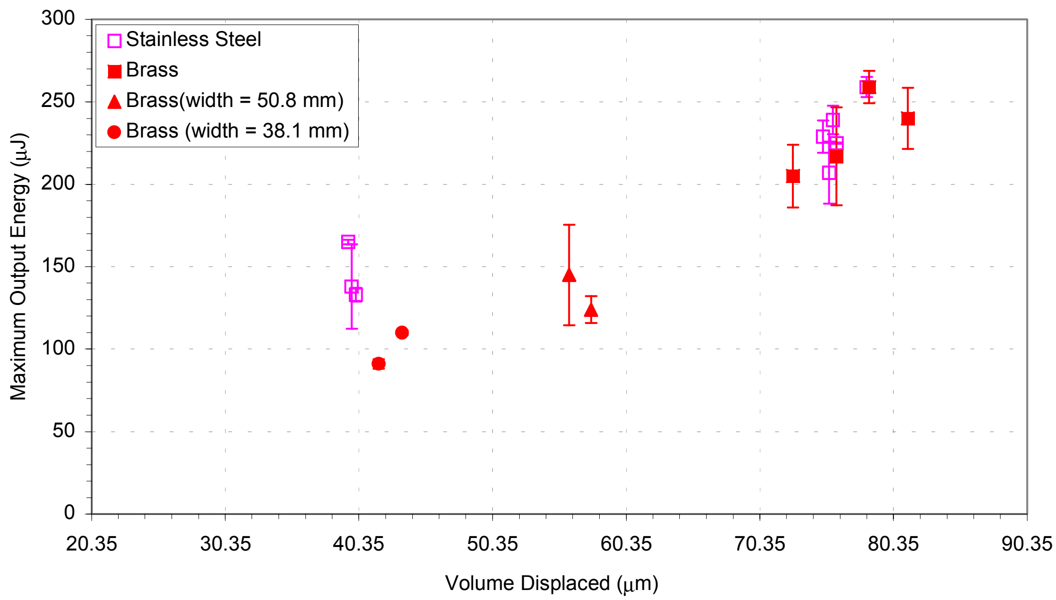

FIGURE 6 Maximum Output Energy vs. Volume Displaced

It can be seen from the data above that there is a pattern between the maximum energy output and the volume displaced and that the results can be applied to curved actuators easily. There is still the need to investigate the effects of different width to length ratios since all the pieces had the same length. Also, the amount of active material, PZT, is not accounted for directly, all the pieces used here had metal extensions.

The dome height of the device, and thus the volume under the device are undoubtedly dependent upon the type of metal used. Several researchers have shown that the mismatch between the moduli and CTE of the metal substrate and the PZT ceramic are primarily responsible for the actuator configuration, namely the curved geometry of the final device [15]. Table V lists the mechanical, physical and electrical properties of the metals used and compares them to those of the PZT ceramic. It is noted that the stainless steel used was initially annealed (full hard), increasing its Young's modulus. However, after undergoing the Thunder fabrication process at 300°C, the modulus decreases by 50-55%, to a value approximated at 95 GPa as shown in the Table V. The values of modulus for the aluminum and brass metals do not change appreciably.

TABLE V. MATERIAL PROPERTIES

Material	Modulus of elasticity (GPA)	Poisson's ratio	CTE (µm/m-°C)	Volume resistivity (Ohm-cm)
Aluminum	69	0.33	24	3E-6
Stainless steel	95		17	7E-6
Brass	100-110		20	
PZT	67		3	

An independent variable using the metal thickness ratio and the mismatch of Young's modulus is defined as

$$\gamma = \frac{t_{metal}}{t_{total}} \frac{E_{PZT}}{E_{metal}}$$

The above expression was chosen since the dome height should increase as the metal thickness decreases and the Young's modulus of the metal increases. Plotting the dome height and the energy as a function of this new ratio shows that they are no longer a function of metal type. See Figures 7a and 7b. The displacement behavior does not follow a similar trend because it is believed to be influenced by the geometry (hence the new ratio) as well as enhanced piezoelectric behavior of the PZT due to the pre-stress.

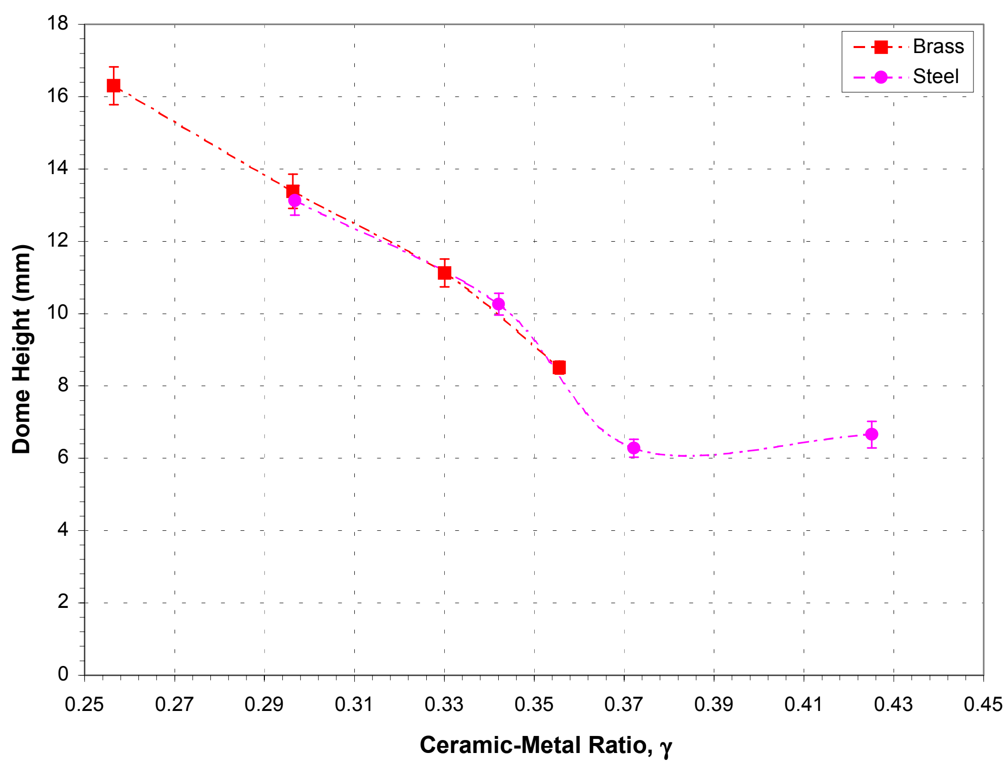

FIGURE 7a. Dome Height vs. Ceramic-Metal Ratio

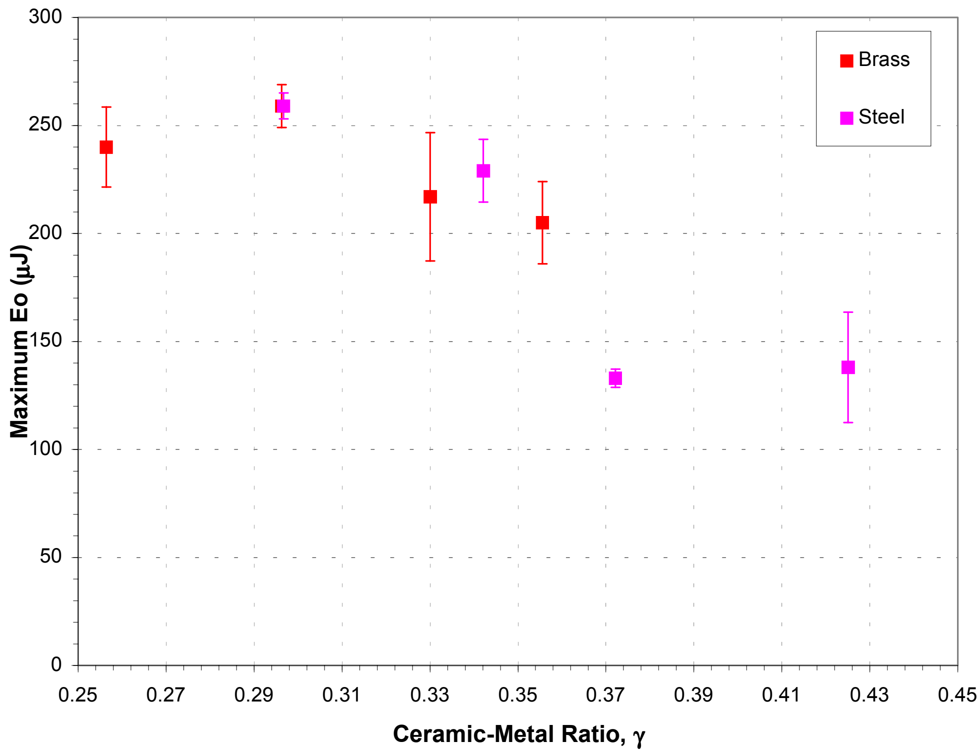

FIGURE 7b. Output Energy vs. Ceramic-Metal Ratio

It is noted that the final dome height is also a function of the repoling due to electrostatic strains resulting from alignment of dipoles with the electric field [14].

SUMMARY AND CONCLUSIONS

Energy output of a curved actuator, Thunder, was measured with the objective of optimizing and investigating the effects the materials may have on its construction. All the elements were monitored for displacement, dome-height, and energy output. It was demonstrated that by making the adhesive conductive and eliminating the top layer, significant improvements in energy output could be accomplished, however, not an improvement in displacement. The results also showed that the actuator could be adjusted in such a way that the same energy output could be obtained with different materials by adjusting the thickness ratios. This phenomenon showed that the metals mechanical and electrical properties have a significant effect and the values of these properties strongly influence numerical simulations. The same could be possible for adjusting width and length, however that effect was not investigated thoroughly in this study. There was enough evidence to suggest that the volume of the actuator can be tailored to suit a particular application where space is a concern. In other words, optimizing the actuator size and composition is crucial when considering the analysis of a system. Finally, it was demonstrated that many factors affect energy production and some of the parameters depend solely on the materials that the actuator is built with.

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