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CHARACTERIZATION OF AN ELECTRON GUN CONTROLLED MULTIPLE SPATIAL REGION PIEZOELECTRIC THIN FILM

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ABSTRACT OF THESIS

CHARACTERIZATION OF AN ELECTRON GUN CONTROLLED MULTIPLE SPATIAL REGION PIEZOELECTRIC THIN FILM

Piezoelectric bimorph thin films may hold solutions for many future applications, such as lightweight deployable mirrors and inflatable struts. Non-contact actuation by an electron gun has shown promise in preventing issues that arise from attaching many wire leads to a thin film surface. This study investigates piezoelectric bimorph thin film response to electron gun actuation when covered with multiple spatial regions of control. Desired parameter ranges are found that will lead to predictable control under certain circumstances. Under such circumstances, film response is influenced almost solely by the primary electrons incident on the film, and secondary electrons have negligible effect. Such information is vital before attempting closed loop control of a thin-film piezoelectric mirror with multiple electrodes.

KEYWORDS: piezoelectric, thin film, non-contact, electron gun, secondary electron

Benjamin Tyler Macke

Nov 25, 2003

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CHARACTERIZATION OF AN ELECTRON GUN CONTROLLED
MULTIPLE SPATIAL REGION PIEZOELECTRIC THIN FILM

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Nov 25, 2003
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CHARACTERIZATION OF AN ELECTRON GUN CONTROLLED
MULTIPLE SPATIAL REGION PIEZOELECTRIC THIN FILM

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering from the College of Engineering at the University of Kentucky

By

Benjamin Tyler Macke

Lexington, Kentucky

Director: Dr. John A. Main, Professor of Mechanical Engineering

Lexington, Kentucky

2003

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DEDICATION

I dedicate this work to my wife Caroline, the wind beneath my wings.
ACKNOWLEDGMENTS

My life has been greatly influenced by a select few people in my life. I would first like to thank my family, for molding me into the complete man I am today. My mother and father have given so much of themselves to give their sons limitless opportunities, and for that I am deeply grateful. My brothers and I have kept each other in check, and the strength of one has become an inspiration to the rest.

My educators at the University of Kentucky and Thomas More College deserve the next thanks. Their tireless efforts to drill knowledge into me have not been in vain. I would particularly like to thank Dr. Suzanne Weaver Smith and Dr. Sudhir Sen, whose personal interest in the well being of their students will not be forgotten.

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CHAPTER 1

Introduction

1.1 Introduction to Piezoelectric Deformable Mirrors

The cost of launching satellites and space-based telescopes into orbit is largely a function of the structure’s mass and volume. Since the dawn of the space program, scientists and engineers have been finding ways to make space-destined structures smaller and lighter while accomplishing the same goal with comparable safety. New metal alloys, especially those using titanium, and composite materials have shown significant promise in reducing the mass of a given supporting structure because of their high strength-to-weight ratio. Electronic components, such as op-amps and integrated circuits, have been optimized due to the commercial demand for smaller, lighter electronic devices. Nearly all components of satellites have been optimized for their purposes.

However, one component has remained nearly unchanged since its invention by Sir Isaac Newton—the primary mirror in a reflecting telescope. To compensate for atmospheric aberrations, the secondary mirrors are now being actively controlled using MEMS technology. Indeed, the secondary mirror has seen many improvements to its design and purpose. But the primary mirror is still manufactured by grinding and polishing glass to the correct shape, a process that can take more than a year and can cost in the millions of dollars. Besides the slow and expensive manufacturing process, these polished glass mirrors are heavy. Naturally they’re not nearly as heavy as primary lenses in refractive telescopes, but the material—glass—is the same, which by its nature has a relatively small strength-to-weight ratio. Moreover, glass is a brittle material, very susceptible to impacts and vibrations.

Such disadvantages with polished glass mirrors have lead to a surge in research on thin film mirrors. Early advances were made by forming the general spherical shape out of Kapton™, a lightweight thin material that is currently used in space applications for its inert response to thermal and electrical loads—it can tolerate large temperature ranges and is very dielectric. Once formed, the Kapton™ could be coated with a silver paint to create the mirror surface. Such
thin films can also be compacted for launch and deployed once in orbit. Though light and
deformable, however, a Kapton™ mirror could not be actively controlled because of its inert
properties. For the clearest visual results, active control becomes a necessary component when
dealing with deformable optical components, since the mirror could have creases and bumps
from the compacting process.

One method to have active control of the mirror surface uses a piezoelectric material to form the
mirror shape. Polyvinylidene fluoride (PVDF), a synthetic polymer thin film piezoelectric
material, has one of the strongest piezoelectric constants of all piezoelectric materials.
Furthermore, its flexibility makes it ideal for deformable mirror applications. However, its
operating temperature range makes PVDF inadequate for the aerospace environment.
Nevertheless, because it is inexpensive and readily available, it was chosen for this work.
Elsewhere, research is being done to find other piezoelectric polymers that may have adequate
operating temperature ranges, after which the research in this work will be useful.

1.2 Objectives

This research is being performed to learn how controllable a PVDF thin film is when it has
multiple spatial regions of control. Using actuation via an electron gun, issues arising from
focusing onto one region will be addressed. Perhaps most important, the mechanical response of
one region will be studied as the electron gun is focused onto other regions.

1.3 Research Plan

The above objectives will be met empirically, using two main sets of experiments, both
programmed with LabVIEW programming software. The first set of experiments involves
focusing the electron gun as well as possible and then altering the voltage on the back side of the
film in large (600-volt) and small (<200-volt) increments.
The second set of experiments involves focusing the electron gun onto each of five spatial regions with varying electron energies and measuring the response of the region closest to the cantilevered support. For each region, seven different electron energies will be used: 800-1400 electron volts in 100-volt increments. For each electron energy and region, the voltage on the back side of the film will be incremented in 4-volt increments from 0 to –600 V, then from –600 to +600 V, and finally from +600 V back to 0 V. The data collected will thus be a hysteresis loop describing the response of the region nearest the fixed support to the combination of altering voltage on the back of the film and focusing the electron gun onto the given region. Each hysteresis loop will be run five times for a given region of focus and electron energy to see how repeatable the data sets are. Thus the second set of data results in 175 data plots, all of which are shown in Appendix B.

1.4 Thesis Overview

In the following, Chapter 2 presents background information for the research. It first describes the basics of piezoelectricity and electron gun control of a thin film piezoelectric material. It then describes creation of piezoelectric bimorphs and some theory behind bimorph mechanics. Chapter 3 describes the experimental apparatus. In Chapter 4, issues arising from attempting to focus the electron gun onto one spatial region are discussed. These issues include covering the film with phosphor to see the “spot” of electrons, optimizing the electron spot size, how the spot moves as certain control variables are altered, and how to incorporate this movement into the controls. Chapter 5 discusses how focusing the electron gun onto one region influences the other regions. Here, such topics as charge-up effects, the influence of electron energy, the influence of control voltage, and secondary electron contribution are discussed. Finally, the conclusions and future work are given in Chapter 6.
CHAPTER 2

Background

2.1 Piezoelectric Basics

Piezoelectric materials have the unique property that material strain induces a build-up of electric charge on the material surface. This charge build-up correlates directly to an electric potential, or voltage, across the material. This effect is known as the direct piezoelectric effect. The converse of this effect, known as the converse piezoelectric effect, is when an applied charge or voltage results in material strain. Both effects have their useful applications. The direct piezoelectric effect is used in sensor applications, such as a strain gauge on a material to be strained. When the material strains, it also strains the adhered strain gauge, which then sends a voltage to the strain gauge controller. The controller can then calculate how much the material strained using the relationship between voltage and strain.

The converse piezoelectric effect is used in controls and actuator applications, such as in an ultrasound machine. As the doctor moves the ultrasound device over the pregnant woman’s abdomen, a block of piezoelectric material in the device is vibrating at ultrasonic frequencies due to the electric signal being sent to it. This converse piezoelectric effect is that which is used in this research—an electric signal will be sent to the thin film, and it will strain accordingly.

2.2 Non-Contact Actuation

Typically deformable mirrors are actuated by placing electrodes on either side and applying a voltage difference. For actuation of multiple regions, however, this can require hundreds of individual electrodes and wire leads, depending on the number of individual regions. Moreover, for a thin film mirror, this can cause deformation of the mirror surface, or more “bumpiness”.

To remove the need for so many leads, this research uses an electron gun to actuate each region individually. Instead of applying voltages, individual charges are applied by firing electrons at one side of the film. The other side is coated with a single electrode that is held at a certain
voltage via one wire lead. In previous research done at the University of Kentucky, this voltage was called the backpressure voltage. In this work, it is hereon referred to as the control voltage. Figure 1 is a not-to-scale picture of this process.

![Figure 1](image)

**Figure 1. Schematic of electron gun firing on thin film, with control voltage applied to back.**

### 2.3 Creation of Piezoelectric Bimorphs

Below is a figure of the piezoelectric bimorph. The bimorph is made of two 52 um-thick films of polyvinylidene fluoride (PVDF) oriented so their poling directions are in opposite directions. Adhering the two strips together is a ~28 um-thick layer of epoxy, making the overall average bimorph thickness ~132 um. Because the bimorph was to be cantilevered, it was made longer than the intended active surface—the rest of the film was fixed between two pieces of glass to act as a mount. Excluding the part of the film that was inside the mount, the film is 67 mm long by 22 mm high by 132 um thick. The outer faces of each PVDF strip are covered with conductive paint to act as electrodes. On the side facing away from the electron gun (hereon referred to as the back side), the entire surface is coated with a conductive paint, except for a 1 mm border of clean surface. On the side facing the electron gun (hereon referred to as the front side), the surface is coated the same as the back side, but here the conductive paint is divided into six equal regions along the length of the film (see Figure 2 below). In order from the fixed support, the regions are labeled Region 1, Region 2, Region 3, Region 4, Region 5, and Region
6, where Region 6 is the closest to the free end. However, Region 6 was not studied in this research, and is not discussed further than mentioning it here.

![Diagram showing PVDF thin film bimorph with dimensions and labels.](image)

Figure 2. Front and back isometric views of the PVDF thin film bimorph.

Each conductive region is 10 mm long by 20 mm high, with a 1-mm gap between each region and a 1-mm border around the edges of the film. The border and gaps were made by wiping off the conductive paint with acetone. Straight edges were ensured by placing Kapton™ tape where the paint would remain.

Once created, the film was mounted between two pieces of glass that would act as the fixed support for the cantilevered film. Glass was used because it is inexpensive, readily available,
and an excellent dielectric. A picture of the mounting system can be seen in Figure 3 below. Note that the film mounted in this figure is not the film described above, but an older film. The glass has been colored purple for high visibility and always faces away from the electron gun, toward the chamber view port and the Keyence Laser Sensor. Also, the edge of the bimorph has been artificially colored black in this image using computer software to make it more discernable.

![Figure 3. PVDF thin film bimorph in glass mount (Martin 2001).](image)

### 2.4 Bimorph Mechanics

Figure 4 is a cross-section of a PVDF bimorph subject to electric field $E_3$. The figure (Martin 2001) shows the internal forces that develop from $E_3$ and the labeled polarization directions of the PVDF strips. The values of the PVDF thickness $t_p$, glue thickness $t_g$, total thickness $h$, and cantilevered length $L$ were given in Section 2.3. The silver electrode side is where the control voltage is applied, and the electron gun side is where the electrons strike the regions. Because the glue is not piezoelectric, it causes no internal forces when encountered by $E_3$. However, the internal forces created by the PVDF are a function of the distance from the neutral surface, which for this structure, lies at the geometric central surface of the glue layer. This assumes the
bimorph has no initial curvature—if it did, the neutral surface would shift toward the center of curvature of the film.

\[ M = 0.25 \left( h^2 - t_g^2 \right) b e_{31} E_3(x) \]  

(1)

It is desirable to see how much transverse deflection \( u_3(x) \) can be observed with this bimorph. For a given region, the electric field \( E_3 \) is constant (neglecting end effects) and it can be assumed that the glue layer thickness \( t_g \) is constant. Transverse deflection can be found by combining equation (1) with the elementary beam equation:

\[ \frac{d^2}{dx^2} (u_3(x)) = \frac{M}{Y I} \]  

(2)

where \( Y \) is the elastic (or Young’s) modulus of the material and \( I \) is the area moment of inertia.

Finally, the equation for \( u_3(x) \) is (Martin 1998):

\[ u_3(x) = 1.5 \left[ e_{31} E_3 \left( h^2 - t_g^2 \right) / (Y I^3) \right] x^2 \]  

(3)

Here, all values are known except the electric field strength \( E_3 \). If the bimorph were actuated using a known voltage, \( E_3 \) could be easily found using the equation for capacitors \( E_3 = V/h \).
However, in this research the bimorph is actuated by applying individual electrons. The only way to find the effective electric field due to electron actuation is by actuating the surface with electrons and the control voltage, measuring $u_3$, and then actuating the surface with direct voltages via wire leads until the same $u_3$ is found. From this, the electric field due to direct voltage application can be found, which must be the same electric field caused by the electrons on the surface interacting with the control voltage. This information is important for focusing the electron gun beam onto each region, as will be shown later in this research.

2.5 Previous Work

This work is a continuation of previous research performed at the University of Kentucky and Sandia National Laboratories. Other research includes work by Dr. John A. Main, Dr. Jeff W. Martin, Dr. Philip C. Hadinata, Dr. Haiping Song, and Dr. George C. Nelson. This work uses the same material, polyvinylidene fluoride (PVDF), and experimental setup as that used by Martin, and so is most closely linked with his work. However, this work uses the same model electron gun, Kimball Physics EFG-7, as the other research, so the electron gun variables and beam profile are comparable. This is important, because the electron beam profile found by Hadinata in 2001 is later compared to the film response in this work.

It is important to note how this work differs from previous work. Previously, a PVDF film was covered with one large electrode on each side of the film and actuated (Martin 2001) and a lead zirconium titanate (PZT) film was left bare on the electron gun side and actuated (Hadinata 2001 and Song 2002). Martin’s work found that to keep charge built up on the surface for as long as possible after turning off the electron gun, the optimum electron energy was 1400 eV. It also showed that minimum hysteresis occurred when using 1200 eV electrons. Hadinata focused the electron gun onto a spot and measured film strain at several places using strain gauges. The strains at locations other than where the beam was focused were found to be unpredictable.

This work finds a scenario where film responses at locations other than where the beam is focused are in fact predictable. It also determines secondary electron contribution for this scenario. These two results provide crucial information that can later be used for the mirror
characteristics, such as spatial resolution, and the control system characteristics, such as electron energy and voltage on the back side of the film. These in turn will help to reach the final goal of producing a controllable thin film.
CHAPTER 3

Setup

3.1 Experimental Apparatus

The series of experiments comprising this research were conducted during the summer of 2003 at Sandia National Laboratories in Albuquerque, New Mexico. These experiments were run using the experimental apparatus previously designed and constructed by Dr. Jeff Martin. The only changes made to the setup were the use of different films, the addition of a black and white camera controlled by National Instruments IMAQ software for LabVIEW programming software, and a newly-developed system control program also created using LabVIEW. The setup can be seen in Figures 5 and 6 below.
Figure 5. Electron gun controlled PVDF thin film bimorph system.
Figure 6 shows a schematic of the top view of the setup used in this research, and Figure 6 is a picture of the actual setup (Martin 2001). Shown are the vacuum chamber, chamber door (for accessing the vacuum chamber interior), thermocouples (for measuring pressure), Nitrogen supply line (for refilling the chamber when making alterations or repairs), ion gauge (for measuring pressures below 1.0E-4 Torr), ion pump and ion pump valve (for rapid reduction of pressure once below 5.0E-6 Torr), electron gun, laser displacement sensor (for measurement of the film), and X-, Y-, and Z-stages (for moving the laser sensor). The vacuum chamber and the optical table are grounded for safety; grounding the chamber, moreover, serves the second purpose of a secondary electron collector—secondary electrons will be discussed later.

As shown in Figure 5, electrons leaving the electron gun will normally do so in a conical shape. However, there are five electron gun variables that can be controlled from the computer console: electron energy (in electron volts), X-deflection voltage, Y-deflection voltage, focus voltage, and grid voltage (these four voltages are negatively biased to repel electrons). The electron energy is a measure of how much kinetic and potential energy each electron has. The X- and Y-deflection voltages shift the cone of emitted electrons from side to side and up and down. The focus voltage causes the cone of emitted electrons to narrow (until a certain voltage, when the cone...
will grow again). The grid voltage is a negative voltage that repels electrons, and as such, it acts like a filter, repelling more electrons as the voltage increases, resulting in fewer electrons emitted from the electron gun. The proper grid voltage can mean the difference between a functioning and non-functioning sample, because focusing the beam to a single point on the sample will act like a magnifying glass in direct sunlight, burning a hole through the sample.

Inside the vacuum chamber, the PVDF thin film bimorph intercepts the electrons from the electron gun. Depending on the control voltage, the incident electron beam results in the bimorph bending either toward or away from the electron gun. The bending direction is simply a property of how the electric dipoles inside the PVDF bimorph are oriented, as shown in Figure 7. A positive control voltage causes the sample to bend away from the electron gun, while negative voltage causes it to bend toward the electron gun.

![Figure 7. Bimorph bending under applied voltage difference.](image)

The transverse displacement at a discrete location along the bimorph’s length is measured by the Keyence Laser Sensor. As seen in Figure 8, the sensor sends a laser signal into the chamber, which bounces off the sample at nearly all angles. However, only the photons bouncing off at a certain angle will make it back to the sensor window, thus allowing the sensor to determine how far away the sample is at that location. To measure the entire contour of the film, then, one would have to measure the location of every point on the film. Because the film shape is always receiving or losing electrons on the surface, it is not possible to measure the entire contour of the film at one time in this manner.
However, it is possible to measure the film contour over a period of time. The X, Y, and Z motors are connected to worm gears that move the X, Y, and Z stages in their respective directions (Figure 9). This allows the user to specify a location where the transverse displacement of the bimorph is desired, and have the laser sensor move to that location. Creating nested “For Loops” then allows the displacement to be taken along the bimorph’s surface and the contour of the whole sample to be known. When this capability was utilized, only the X stage was moved to measure points along the length of the film, from region to region. The Y and Z stages were only moved for access to the chamber door. Preliminary experiments utilized this capability to measure the film contour, but the data presented herein did not require it. Rather, the laser sensor was kept at one location for most experiments.
To get the vacuum chamber to the proper vacuum level, a Varian© Turbo Mini Pumping Station was used (Figure 10). The Diaphragm Pump, also known as a roughing pump, would lower the chamber pressure to 1.0E-3 Torr, after which the turbo molecular pump would lower the chamber pressure to the electron gun operating range of < 5.0E-6 Torr.

![Varian© Turbo Mini Pumping Station (Martin 2001).](image)

Once the chamber was below 1.0E-4 Torr, an ion gauge was turned on to more accurately read the chamber pressure at low pressures (Figure 11). The digital readout on the ion gauge controller (Figure 12) allowed the user to know when it was safe to turn on the electron gun. Once the electron gun was on, if the pressure ever spiked above 5.0E-6 Torr, the ion gauge controller would trigger the electron gun power supply to set all voltages and currents to zero.
The electron gun power supply (Figure 12) was used to control all voltages and currents in the electron gun. It was used to set the cathode current, grid voltage, focus voltage, X- and Y-deflection voltages, and electron energy.

The Kepco Voltage Amplifier (Figure 12) was used to set the control voltage on the back side of the film. Its maximum voltage range was –1000 to 1000V, but the operating control voltage range on the film was only –600 to 600V.
The cathode current in the electron gun is not an accurate measure of electrons actually emitted from the electron gun, because the vast majority of electrons either hit the interior walls of the electron gun (which was grounded) or were stopped by the grid voltage. Therefore a Faraday Cup was placed on the tip of the electron gun and could be controlled to cap off the electron gun for a few seconds to measure the actual electron beam current. Because the stream of electrons heats up the Faraday Cup considerably, it could only be used every five to ten minutes. This time limit was only really necessary when finding the proper electron gun settings for focusing on each region of the thin film, when it was vital that the beam current not be great enough to burn a hole in the film. The Faraday Cup current was displayed on a pico-ammeter, showed in Figure 13. Figure 13 also shows the computer workstation for all of the control programming using LabVIEW software.

![Figure 13. LabVIEW workstation, controller, and Faraday Cup pico-ammeter (Martin 2001).](image)

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CHAPTER 4

Focusing Onto One Region

4.1 Optimizing the Spot Size

When focusing the electron beam onto the film, it is impossible to perfectly focus the electrons to one point. In fact, because electrons, like photons, have particle-wave duality, the primary electrons leaving the electron gun exhibit a diffraction pattern (Hadinata 2001), as shown in Figure 14. Instead of showing the contour across the film surface, Figure 14 shows the contour as functions of X and Y deflection voltages, which correlates to an angular spread emanating from the electron gun tip. This allows the plot to not depend on the distance from the e-gun tip to the film surface.

![Figure 14. Primary electron distribution pattern (Hadinata 2001).](image)

Although the grid voltage in conjunction with the focus voltage can be used to remove most of the surrounding haze, primary electrons will always strike more than one region, some receiving more electrons than others.
To see where the electrons strike the surface, the front side of the film was coated with phosphor, which gave off blue light when struck by electrons. This light was visible to the naked eye only when the electron beam current density on the film surface was great enough. For example, 20 electrons striking the surface would not give off enough light to be seen. But once the beam current was large enough, the electron haze could be seen. This allowed the user to increment grid and focus voltages until the smallest and faintest spot was seen. For these experiments, the optimal beam current was $\sim 1 \pm 0.5 \mu\text{A}$.

Raising the grid voltage creates a greater negative charge to slow down or repel the electrons leaving the electron gun cathode. It will prevent all electrons having up to a certain energy from leaving the electron gun (see Figure 15).

Electrons with energy greater than the specified energy will still strike the surface, making it impossible to remove all of the haze. To get very close to removing the visible haze, this critical energy value can be shifted up so only the highest energy electrons can hit the film (see Figure 16).
This method removes most of the visible haze when the electrons are focused as well as possible. However, too much or not enough focusing will also cause problems, as shown in Figure 17 below.

It is important to keep in mind that Figure 17 depicts the visible haze—it cannot be assumed that the visible haze represents all electron interactions with the surface. It must be assumed that there is a haze of electrons always striking the whole film, because it cannot be proved otherwise in this research. Furthermore, secondary electrons, or electrons escaping the film surface, are likely to land on other regions of the film as well. The physics of this setup make it impossible to prevent electrons intended for actuation of one region from striking another.
4.2 Spot Movement

Focusing the optimal electron spot to the desired position depends on many variables: grid, focus, X-deflection, and Y-deflection voltages; electron energy; and control voltage. The X- and Y-deflection voltages were set such that the central electron spot would strike the centroid of each region, while the grid and focus voltages focused the electron beam as much as possible. All of these values are dependent on the electron energy and control voltage—though not at first apparent, the control voltage affects the electron energy, because it will cause primary electrons to be either attracted to or repelled by the film. Thus the electron energy set by the electronics is not necessarily the final electron energy when the primary electrons strike the film; they may have sped up or slowed down between leaving the electron gun and reaching the surface.

For example, an optimal electron spot for 1200 eV and 0 control volts will change when the control voltage is abruptly changed to +600 V. A black and white filtering camera connected to a PC was used to get actual footage of the spot changing location. It was set to take a series of images as rapidly as the electronics would allow (it was programmed to take the images with no time delay between them, but this computer system had considerable data-taking delay). Figure 18 shows two images of the film, one immediately before changing the control voltage to +600 V, and one immediately afterward. Figure 19 shows the same thing for a different film. It can be seen for both films that the emitted phosphorescent spot of light gets brighter and moves slightly. It gets brighter because the primary electrons gain energy when the control voltage increases, so more electrons reach the film and with more energy. The spot moves slightly because the X- and Y-deflection voltages, which should have been altered to compensate for the energy change, were not altered in this experiment.

![Figure 18](image1.png)  ![Figure 18](image2.png)

Figure 18. Small film before (a) and after (b) changing control voltage from 0 to 600V.
Figure 19. Large film before (a) and after (b) changing control voltage from 0 to 600V.

Since a sequence of images in this paper would not adequately display the spot movement, a plot of the spot was made in Figure 20 below. Here the X- and Y-axes are physical dimensions of the film surface itself, and the plot shows how the spot moved in time—X and Y are both functions of time here.

Figure 20. Movement of phosphor spot as control voltage changed from 0 to 600 V.
This plot shows data for two different films. The blue/green plot is the spot movement for the film discussed in Chapter 2. The brown/orange plot is the spot movement for an identical film except the height of the film is 6 cm and has only one region along its length of 12 cm. The blue and brown lines represent the movement of the spot when the control voltage was abruptly changed from 0 to 600 V. The green and orange lines represent the movement of the spot as the control voltage was kept constant at 600 V; in other words, they show transient data of how the spot tended toward its steady-state position. The relative slopes of these four curves are not significant in this data, because the spots were initially focused at very different X and Y locations; therefore when the voltage was changed, the spots would not necessarily move in the same direction. Also, the relative positions have no significance here, as they have been shifted to optimally fit on the same plot.

Two important observations can be found from Figure 20. First, the length of the brown line is greater than that of the blue line. Second, the length of the orange curve is much greater than that of the green curve. Both observations can be attributed to end effects—because the first film was only 20 mm tall while the second film was 60 mm tall, it can be assumed that the electric field lines around one film were very different from those around the other film. It seems that end effects limit the movement of the spot. This distinction may help in deciding if a thin film mirror controlled using this approach should leave a rim of “inactive” material to prevent end effects.

**4.3 Focusing Incorporated into the Controls**

The fact that the location and size of the electron spot on the film was dependent on several variables meant that equations had to be found for programming the controls. The independent variables used were electron energy and control voltage—these were set to a certain value, and then the other variables were altered until the optimal spot size and location were obtained. Then control voltage was incremented between –600 V and +600 V, and again the dependent variables were altered, resulting in one equation. The electron energy was changed to its next value, and the whole process was repeated. The relationships found were not exactly linear, but very nearly
so, so a linear regression was used to find an equation. This meant that the spot would change slightly; however, later observations showed that the spot change was nearly inconspicuous, and would not cause issues with the control. Once these relationships were programmed into the controls, the electron spot would remain nearly optimal for each new electron energy and/or control voltage.
CHAPTER 5
Multiple Regions

5.1 Affect of All Regions on Region 1

The following set of experiments was designed to see how one region of the film is affected by the other regions. Clearly actuating one region will affect the displacement of all regions closer to the free end. But it was unclear how such actuation would affect the regions between the fixed end and the actuated region. From elementary beam theory, these regions should be unaffected, assuming the piezoelectric effect can be modeled by application of a pure moment. However, such analysis does not account for the distribution pattern of primary electrons, nor does it account for secondary electron emission—where these electrons land and how they would influence other regions that were not meant to be actuated. The goal of these experiments was to see how Region 1 was influenced when focusing the electron beam spot to each of Regions 1 – 5 in turn.

The Keyence laser displacement sensor was set up to measure the displacement of the far edge of Region 1 (i.e. the edge not fixed, adjacent to Region 2). Hereon this point will be referred to as Point 1. Originally, the center of Region 1 was measured, but this choice was altered so more deflection could be observed. Indeed, by elementary beam theory, Point 1 should experience four times the displacement of the center of Region 1 because it is twice the distance from the fixed support as the center of Region 1 is. A program was written in LabVIEW to set the control voltage, then fire electrons at a given region for a set time of 400 ms, and finally take several measurements of the displacement of Point 1. The time of 400 ms was chosen because it is the time it takes for noticeable actuation to begin (Hadinata 2001 and confirmed in this research). This sequence was run in a “for loop” while the control voltage was incremented in 4-volt increments from 0 to –600 V, –600 to +600 V, and finally +600 to 0 V. This process was run five times for each electron energy level, from 800 to 1400 electron volts in 100 eV increments. It was chosen to go to negative voltage first and then increment into positive voltage because when using positive voltage, the charge built up on the surface remains much longer than for
negative voltage. Thus it was believed that by using negative voltage first, more displacement would be observed.

Before continuing the discussion of the data collected, five figures must be described that will be used throughout the following. For each data set given, one or more additional figures will be shown to visually describe where the primary electron peak was focused and where measurement occurred. The measurement location, indicated by an “M” in the figure, will always remain the same (Point 1), while the actuation location, indicated by an “X” in the figure, will change for each data set. Figure 21 shows all five scenarios and describes where the primary electron peak was focused.

![Figure 21: Actuation (X) and Measurement (M) for each scenario.](image)

Now, continuing the discussion of data collected, a sample of the data is shown in Figure 22a below. Here Region 3 is being actuated with 1200 eV electrons while the displacement of Point
1 is measured. This data has considerable noise, because several measurements were taken at each increment. To reduce the noise in the data, the average displacement at each control voltage was found and plotted verses control voltage. Also, to more effectively see the hysteresis loop, the plot was colored blue when the control voltage was decreasing and red when the control voltage was increasing. The same plot from Figure 22a was refined with these techniques and is shown in Figure 22b below. Note the actuation (X) and measurement (M) locations indicated in the figure in the top right corner.

**Actuation (X) and Measurement (M):**

![Figure 22. a) Raw data and b) refined plot examples of inter-region interaction.](image)

The improvement in clarity from Figure 22a to b is obvious. In the raw plot, it is difficult to distinguish whether the top of the second “loop” continues from the top or bottom of the first loop. By refining the data, it is clear that it continues from the top of the first loop. This is one justification for the refinement of the data; it is not always advantageous to alter raw data, but in this case it is. This refinement also distinctly shows when the control voltage is increasing or decreasing, making the hysteresis determination evident. Because of these advantages, the raw data is not presented hereon; rather, the rest of the data presented has been refined using the method described above.
5.2 Charge-Up Effects

The five plots shown below are all plots of transverse displacement of Point 1 verses control voltage while Region 1 was actuated with 800 eV electrons. The purpose of showing all five plots is to see how time influences the data—time is the only change from one plot to the next. Figure 23a (RunAvg00) was run first, and is quite different from the rest because no charge had yet been applied to the surface before this data was taken. Figure 23b – e (RunAvg01 – RunAvg04) all look very similar. Thus there is clearly a charge-up effect taking place here. Also, one very subtle trend is that the plots slowly shift to the left. In Figure 23b, the center of the peak occurs at a control voltage of -200 V. However, by Figure 23e, this peak has gradually moved to -230 V. This same tendency occurs for all electron energies used and when actuating all five regions.

![Figure 23a](image1)

![Figure 23b](image2)

Figure 23. Displ. vs. control voltage when actuating Region 1 with 800eV electrons.
Figure 23 (cont’d). Displ. vs. control voltage when actuating Region 1 with 800eV electrons.

This trend can be explained by considering the electric fields that are built up on the film. The shift to the left means that to obtain the same displacement, a lower control voltage is needed. Lower control voltage means more negative charges on the back of the film. To get the same displacement, however, the electric field through the film must be the same. Therefore there must be more negative charges on the front of the film as well. In other words, the number of electrons that can be held on the film surface (both front and back) increases gradually with time as the film is continuously actuated.
5.3 The Affect of Electron Energy

The following plots show the effect of changing electron energy while actuating the same region, Region 1 (the only variable between plots is electron energy). These plots are each RunAvg04 (refer to previous plots), or the last of five plots taking the same data. Note that from figure to figure, the vertical scale is not the same; the axes were scaled automatically to see the most data in the allotted space. This is important because the total range of motion for each figure are not the same—as will be shown, the range of motion generally increases with electron energy when focusing the electron beam onto Region 1.

Figure 24. Displ. vs. control voltage when actuating Region 1 with various eV electrons.
Figure 24 (cont’d). Displ. vs. control voltage when actuating Region 1 with various eV electrons.

Figure 24 shows that as electron energy is increased between 800 and 1400 eV, the hysteresis loops become tighter; in other words, hysteresis becomes less prominent as electron energy increases toward 1400 eV. Such a trend indicates that controllability becomes more plausible as electron energy increases toward 1400 eV, because the controller will have to “jump around” less to reach the desired position.

Similar plots were obtained when actuating each of the five regions, and once again measuring the response at Point 1. The minimum, maximum and range values of these plots were obtained, entered into a table, and graphed to more easily compare the effect of each region’s actuation on Region 1 (see Table 1, Figure 25 and Figure 26 below).
Table 1. Minimum, maximum, and range for each plot of displ. vs. control voltage.

<table>
<thead>
<tr>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 3</th>
<th>Region 4</th>
<th>Region 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>eV</td>
<td>min</td>
<td>max</td>
<td>range</td>
<td>min</td>
</tr>
<tr>
<td></td>
<td>(µm)</td>
<td>(µm)</td>
<td>(µm)</td>
<td>(µm)</td>
</tr>
<tr>
<td>800</td>
<td>-42</td>
<td>72</td>
<td>30</td>
<td>-149</td>
</tr>
<tr>
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<td>15</td>
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<td>-151</td>
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<td>138</td>
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<td>-163</td>
</tr>
<tr>
<td>1400</td>
<td>-221</td>
<td>-17</td>
<td>204</td>
<td>-169</td>
</tr>
</tbody>
</table>

Actuation (X) and Measurement (M) locations:

![Actuation (X) and Measurement (M) locations](image)

Figure 25. Displacement range vs. electron energy for each region.
Actuation (X) and Measurement (M) locations:

![Diagram of actuation and measurement locations]

Displacement Range of Region 1 Far Edge vs Region Number for each Electron Energy

Figure 26. Displacement range vs. region for each electron energy.

It is evident from these plots, particularly Figure 25, that the displacement of Point 1 is affected most by actuation of Region 1 directly. This first observation is the most obvious trend, and clearly to be expected. However, this is only the case once the electron energy exceeds 1000eV, which is not necessarily to be expected. In fact, actuating Region 3 with 800eV electrons seems to affect the displacement of Point 1 more than actuating Region 1 directly with 800eV electrons.

This striking result is not the only unexpected result—the displacement of Point 1 seems to be influenced similarly by all regions; that is, for some energies, Region 5 has as much influence on the displacement of Point 1 as Region 2 does. For 1000 – 1400eV electron energies, Point 1 moved more when Region 5 was actuated than it did when Region 2 was actuated. This is counterintuitive for engineers that are used to linear systems where superposition applies. If
superposition were applicable, Region 2 would have a much greater influence on the displacement of Point 1 than Region 5 would.

These results can be attributed to the primary electron distribution pattern in Figure 14 in Chapter 4. From Figure 26, it seems that the main peak in the diffraction pattern shifts as the electron energy changes. For example, the main peak for 800 eV electrons seems to occur not at Region 1 but ~22 mm away, at Region 3. The main peak for 900 eV electrons has shifted to occur at Region 2. All other energies have their main peak at Region 1, but seem to also have secondary peaks in other regions. For example, a secondary peak occurs at Region 3 for 1000 and 1100 eV primary electrons. The secondary peak for 1200 eV electrons occurs somewhere between Regions 3 and 4, while that for 1300 and 1400 eV moves out even further to Region 4.

When considering how secondary electrons influence this data, it is helpful to compare this to electric field lines in a capacitor (see Figure 27). Here, an electron placed close to the plates will be more influenced by the electric field than an electron placed far away.

Consider now an electron on the surface of this capacitor that is given energy by an electron that strikes the surface. It will not follow the electric field lines. These lines show the path an electron will take if it’s placed in this electric field at rest. However, it will follow a magnified version of this path, since the only difference is that this electron has some initial kinetic energy.
An electron leaving the surface will follow an even larger path. The distance a secondary electron travels without being intercepted depends on its kinetic energy when leaving the surface.

Consider the same situation, but now place an insulating block somewhere in this field (see Figure 28). The electric field lines do not change (assuming no charge builds up on the surface).

![Figure 28. Electric field lines around parallel-plate capacitor with insulator in field.](image)

An electron having energy in a certain range will follow the electric field lines that strike this insulating block. If the electron has too much or too little energy, it will miss the insulator. This is the same situation that secondary electrons leaving the PVDF film find themselves in. A secondary electron leaving the center of Region 3 with a certain energy will follow the electric field lines until it is intercepted by an object, say Region 2. But another electron with a certain greater energy leaving the same spot will travel further, striking Region 1.

Given an even distribution of electron energies leaving the center of Region 3, the probability of an electron striking Region 1 is equal to the probability of an electron striking Region 5, because it has equal surface area and is an equal distance away. Because they are closer to Region 3, Regions 2 and 4 are more likely to be struck by such electrons than Regions 1 and 5.

This idea is the same as that used for radiation calculations—radiation leaving one surface and striking another surface depends on the incident body’s surface area and distance from the source.
of the electromagnetic wave, as well as the electromagnetic field lines. This is also true of secondary electrons.

But the electrons leaving the center of Region 3 do not have an even distribution of energies. The secondary electron energies depend on the energies of the primary electrons striking the PVDF film. These primary electrons have a Gaussian distribution of energy, with the mean value as that proscribed by the control system, as discussed in Chapter 4. Thus the secondary electrons will also have a Gaussian distribution of energy, with the mean value considerably less than that of the primary electrons. So a secondary electron leaving Region 3 may be more likely to reach Region 5 than to reach Region 4, based on its energy. Both the secondary and primary electrons influence the data shown in Figures 25 and 26.

5.4 Locations of Predictability

One goal of this research is to determine if piezoelectric thin films can be used for lightweight deployable mirrors. As such, it is helpful to get an idea of what the spatial resolution of such a mirror would need to be. Though the following data does not determine the spatial resolution of a piezoelectric thin film mirror, it does indicate possibilities regarding spatial resolution.

Figure 29 shows the response of Point 1 to actuation of Region 4 with the indicated electron energies. Because it was decided earlier in this analysis that only electron energies above 1000 eV were desirable, the plots below are for 1100 – 1400 eV only.
Figure 29. Displacement of Point 1 when actuating Region 4.

The most important aspect in all four plots is the response when negative control voltage is applied—it is quite small compared to the response when positive control voltage is applied. To see the range of motion of Point 1 when actuating each region with only negative control voltage, a table and plot were created (see Table 2 and Figure 30 below).
Table 2. Range of motion of Point 1 when actuating only with negative control voltage.

<table>
<thead>
<tr>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 3</th>
<th>Region 4</th>
<th>Region 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>eV</td>
<td>min</td>
<td>max</td>
<td>range</td>
<td>min</td>
</tr>
<tr>
<td>1100</td>
<td>-53</td>
<td>4</td>
<td>57</td>
<td>-129</td>
</tr>
<tr>
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</tr>
<tr>
<td>1400</td>
<td>-146</td>
<td>-17</td>
<td>130</td>
<td>-140</td>
</tr>
</tbody>
</table>

Actuation (X) and Measurement (M) locations:

![Diagram of Actuation and Measurement Locations](image)

Figure 30. Range of motion of Point 1 when actuating only with negative control voltage.

It is clear from Figure 30 that overall, Point 1 responds the most when Region 1 is actuated. Perhaps a more important finding, however, is that Point 1 responds the least for electron energies of 1100 – 1400 eV when Region 4 is actuated. It seems, in fact, that 1400 eV is the best electron energy to use for this purpose because it yields the greatest response (130 µm) to Region
It is useful to also compare the primary electron profile to the film response. The data for Figure 14 in Chapter 4 was found using the same model of electron gun (Kimball Physics EFG-7) as the data in this research. From Figure 14, the minimum number of primary electrons occur at a ring of radius ~25 deflection volts away from the central peak (here the electron energy was 400 eV). From the data in Figure 30, the minimum film response occurs at approximately Region 4. The difference in X-deflection voltage between Region 1 and Region 4 for this experiment was 4.1 – 5.6 volts for electron energies of 1000 – 1400 eV respectively. At first glance, it seems that these results differ by a factor of ten. However, Figure 14 was created using a power supply sent to a controller that had a built-in gain of 1/10, then to the electron gun inputs. This was verified by the creator of Figure 14, Dr. Hadinata, because the maximum allowable deflection voltages into the electron gun were +/-10 V. Thus the 25 deflection volts in Figure 14 actually occurred at 2.5 volts. Now, considering a nearly linear relationship between electron energy and deflection voltage, the uncertainty in determining where the minimum number of electrons occurs, and the range of minimum film response, it follows that the minimum film response occurs where least primary electrons strike the film.

This result leads to a significant conclusion: given electron energy between 1100 and 1400 eV and negative control voltage, two locations have been discovered where the film response is predictable. The first location is where the primary electron peak is focused—the response here has been predictable in previous works as well (Hadinata 2001), so this finding is not surprising. A more significant finding, however, is that another location has been found where film response is predictable. In this work, the location of predictability is ~33 mm away from where the primary electron peak is focused, where very little response occurs. In fact, since the region is 10 mm wide, there is a ring of predictability about the central focal point of average radius 33 mm and thickness of 10 mm. In previous works, such a location could not be found. It was previously believed that the uncertainty in response, attributed mainly to secondary electron emission, made predictability impossible. And for other experimental setups, that was indeed the
case. This work has simply found a setup that allows the controller to know more locations of predictable response.

This predictability is indicative of another strong conclusion: secondary electron emission does not have a significant impact on film response at these locations of predictability. Indeed, the nature of secondary electrons is such that any influence by them on film response creates unpredictability. It follows, then, that predictability of film response indicates that secondary electrons influence the film response very little. Thus, any application using this setup need not utilize alternate methods of capturing secondary electrons (recall from Chapter 3 that the vacuum chamber was grounded, which may act as a secondary electron collector).
CHAPTER 6

Conclusions and Future Work

6.1 Conclusions

The following conclusions can be drawn from the data presented: (1) When directly actuating the region of interest, the PVDF film exhibits hysteresis, but that hysteresis becomes less pronounced as the electron energy increases between 800 and 1400 eV. Despite the hysteresis, however, the film seems controllable because at the higher electron energies, the hysteresis loops become tighter. (2) There is a charge-up effect when first actuating the film and finding a hysteresis loop. After this, the hysteresis loops are repeatable. (3) Edge effects play a significant role in the response of the film and focusing. Therefore mirror applications may need a rim of “inactive” material to avoid these end effects. (4) It is desirable to use electron energies greater than 1000 eV, where the response of the region of interest is greatest. At these energies, the response of other regions does not increase dramatically. (5) It is preferable to use only negative control voltage to get the desired response. (6) When using only negative control voltage and electrons with energy greater than 1000 eV, the response of Region 1 to actuation of Region 4 is minimal (~20 um) while other regions’ responses are typically at least double that amount. This leads to a ring of predictable film response with the center at the electron beam focal point, radius of ~33 mm, and thickness of ~10 mm. Such parameters could be used to determine the spatial resolution of a PVDF thin film bimorph mirror. (7) The minimum film response occurs where least primary electrons strike the film. (8) Given the conditions of the sixth conclusion, secondary electrons do not significantly contribute to film response.

6.2 Future Work

One limitation for performing this research was the inability to measure the whole contour of the film at once. Therefore a new measurement system, namely a Shack-Hartmann or Wavefront sensor, could be incorporated for future research.
Other future work includes the jump from static to dynamic analysis. All data taken here was done statically; however, the modes of vibration of a thin film will occur at frequencies much lower than those of a polished glass mirror, and to obtain clear images, it will be vital to prevent resonance of the film.

Further work includes testing of a larger PVDF thin film bimorph that is already fabricated to its bulk desired shape. Such testing would require new mounting and measurement techniques, as well as complicated algorithms of control. For example, a 0.5 m diameter spherically-curved thin film, separated into individual regions as done in this research, would increase the complexity of the control system by orders of magnitude.
APPENDIX A

LabVIEW Virtual Instrument

Diagram
User Interface

Controls

This program is designed for 1200 eV only.

Indicators

Closed Loop Control Time History

Keyence Reading (Microns)

PID Output (Vols)

Control Voltage (Vols)
APPENDIX B

Data for Chapter 5

Actuating Region 1

Figure A-1. Displacement vs. control voltage when actuating Region 1 with 800eV electrons.

Figure A-2. Displacement vs. control voltage when actuating Region 1 with 900eV electrons.
Figure A-3. Displ. vs. control voltage when actuating Region 1 with 1000eV electrons

Figure A-4. Displ. vs. control voltage when actuating Region 1 with 1100eV electrons.
Figure A-5. Displ. vs. control voltage when actuating Region 1 with 1200eV electrons

Figure A-6. Displ. vs. control voltage when actuating Region 1 with 1300eV electrons
Figure A-7. Displ. vs. control voltage when actuating Region 1 with 1400eV electrons
Actuating Region 2

Figure A-8. Displ. vs. control voltage when actuating Region 2 with 800eV electrons

Figure A-9. Displ. vs. control voltage when actuating Region 2 with 900eV electrons
Figure A-10. Displ. vs. control voltage when actuating Region 2 with 1000eV electrons

Figure A-11. Displ. vs. control voltage when actuating Region 2 with 1100eV electrons
Figure A-12. Displ. vs. control voltage when actuating Region 2 with 1200eV electrons

Figure A-13. Displ. vs. control voltage when actuating Region 2 with 1300eV electrons
Figure A-14. Displ. vs. control voltage when actuating Region 2 with 1400eV electrons
Actuating Region 3

Figure A-15. Displ. vs. control voltage when actuating Region 3 with 800eV electrons

Figure A-16. Displ. vs. control voltage when actuating Region 3 with 900eV electrons
Figure A-17. Displ. vs. control voltage when actuating Region 3 with 1000eV electrons

Figure A-18. Displ. vs. control voltage when actuating Region 3 with 1100eV electrons
Figure A-19. Displ. vs. control voltage when actuating Region 3 with 1200eV electrons

Figure A-20. Displ. vs. control voltage when actuating Region 3 with 1300eV electrons
Figure A-21. Displ. vs. control voltage when actuating Region 3 with 1400eV electrons
Actuating Region 4

Figure A-22. Displ. vs. control voltage when actuating Region 4 with 800eV electrons

Figure A-23. Displ. vs. control voltage when actuating Region 4 with 900eV electrons
Figure A-24. Displ. vs. control voltage when actuating Region 4 with 1000eV electrons

Figure A-25. Displ. vs. control voltage when actuating Region 4 with 1100eV electrons
Figure A-26. Displ. vs. control voltage when actuating Region 4 with 1200eV electrons

Figure A-27. Displ. vs. control voltage when actuating Region 4 with 1300eV electrons
Figure A-28. Displ. vs. control voltage when actuating Region 4 with 1400eV electrons
Actuating Region 5

Figure A-29. Displ. vs. control voltage when actuating Region 5 with 800eV electrons

Figure A-30. Displ. vs. control voltage when actuating Region 5 with 900eV electrons
Figure A-31. Displ. vs. control voltage when actuating Region 5 with 1000eV electrons

Figure A-32. Displ. vs. control voltage when actuating Region 5 with 1100eV electrons
Figure A-33. Displ. vs. control voltage when actuating Region 5 with 1200eV electrons

Figure A-34. Displ. vs. control voltage when actuating Region 5 with 1300eV electrons
Figure A-35. Displ. vs. control voltage when actuating Region 5 with 1400eV electrons.
BIBLIOGRAPHY


VITA

Benjamin Tyler Macke was born in Cincinnati, Ohio on January 2, 1979, but has lived in Kentucky his entire life. Ben graduated from Bishop Brossart High School in May of 1997 with honors. In May of 2001 he received his Bachelor of Science degree in Physics and Associate of Art degree in Mathematics from Thomas More College, graduating Magna Cum Laude. He has worked in the Dynamic Structures and Controls Lab at the University of Kentucky as a research assistant since November of 2000, and as a student intern at Sandia National Laboratories in Albuquerque, New Mexico since May of 2002. Ben’s professional interests include research and development, design, controls, and vibrations.