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MODELING AND FABRICATION OF LIGHTWEIGHT, DEFORMABLE MIRRORS SUBJECTED TO DISCRETE LOADING

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ABSTRACT OF THESIS

MODELING AND FABRICATION OF LIGHTWEIGHT, DEFORMABLE MIRRORS SUBJECTED TO DISCRETE LOADING

The push towards larger diameter space telescope mirrors has caused the space industry to look at lightweight, deformable alternatives to the traditional monolithic mirror. One possible solution to the dilemma is to use the piezoelectric properties of certain materials to create a lightweight, deformable mirror. Current piezoelectric deformable mirror designs use individual actuators, creating an immensely complex system as the mirrors increase in size. The objective of this thesis is to aid in the design and development of lightweight, deformable mirrors for use in space based telescopes. Two topics are considered to aid this development. A doubly curved, lightweight, bimorph mirror is investigated. The fabrication method entails forming a thin film piezoelectric polymer into a doubly curved shape using a specially designed forming machine. The second topic entails the finite element modeling of a composite mirror substrate with a piezoceramic actuator backing. The model is generated using a meshing program designed to generate off-centered spot loads of electric potential. These spot loads simulate the actuation due to an electron gun. The effects of spot location and size on mirror deformation are examined.

Keywords: piezoelectric, deformable mirror, electron gun, finite element, carbon-fiber composite

Michael E. Roche
August 10, 2001

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MODELING AND FABRICATION OF LIGHTWEIGHT, DEFORMABLE MIRRORS SUBJECTED TO DISCRETE LOADING

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August 10, 2001
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MODELING AND FABRICATION OF LIGHTWEIGHT, DEFORMABLE MIRRORS SUBJECTED TO DISCRETE LOADING

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

Michael E. Roche

Lexington, Kentucky

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

Lexington, Kentucky

2001

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CHAPTER 1
Introduction

1.1 Introduction to Piezoelectric, Deformable Mirrors
The quest to see further into the depths of the universe has been an ongoing effort since man first gazed at the moon. Until recently, man’s vision of space has been blurred by Earth’s atmosphere. Adaptive optics techniques help solve some of the problems introduced by atmospheric wavefront distortion, but do not completely eliminate the problem. In order to achieve a completely clear vision of the universe, telescopes must be placed in orbit, free of Earth’s atmosphere.

This was done with great success in the case of the Hubble Space Telescope (HST). The images from HST have enlightened the scientific world and opened a new chapter in astronomy. However, the HST project was a very costly endeavor, with launch costs being a significant portion of the expense. The primary mirror on HST is a solid piece of polished glass coated with a thin layer of aluminum, 2.4-m in diameter and weighing 826-kg. The size constraints of the Shuttle’s cargo bay and the cost of launching an article this massive into orbit limit the size of the mirror for any subsequent space-based telescopes. This problem will only worsen in the future, as one of the proposals for NASA’s proposed Next Generation Space Telescope (NGST) employs a 8-m diameter primary mirror (Stockman 1997). It is impractical to consider manufacturing and launching a monolithic mirror of this size or larger with the necessary optical tolerances. Therefore, it is necessary that the mirror be constructed out of lightweight materials and be disassembled into numerous parts and then deployed in space. An active control system would be required to achieve the desired optical accuracy with such an assembly. The use of lightweight, deformable mirrors employing piezoelectric actuators for surface control is the solution considered in this thesis.

Jacques and Pierre Curie first discovered the piezoelectric property of certain materials in 1880. Piezoelectric materials have the property that when a strain is applied, an electric charge/voltage is produced. This is called the direct piezoelectric effect. In addition, when an electric charge/field applied, strain is induced. This is called the converse piezoelectric effect. The direct effect is typically employed in sensor applications, while the converse effect is utilized for actuation and control applications.
The common directional notations applied to piezoelectric materials are shown below, with reference to the typical poling direction. This will be the direction notation referenced in this thesis.

![Typical Poling Direction](image)

Figure 1.1: Definition of Direction Notation.

The use of piezoelectric actuators to control the surface of plates, shells and mirrors is not a new concept. The field of adaptive optics has used stack and bending moment actuators for years as methods of controlling the surface shape of Earth-based telescope mirrors. Most current designs employ discrete actuators for control. For example, a recent design of a 51-cm diameter adaptive optics mirror has 3000 PZT-5H ceramic tube actuators to supply sufficient surface control (Langlois et al. 1999). This control system is designed for a mirror approximately \( \frac{1}{250} \)th of the area of the 8-m diameter mirror proposed for the NGST. Obviously, this system becomes immensely complex as the size of the mirror and desired spatial resolution of control increases. The impracticality of having thousands of individual electrodes and accompanying wires blanketing the back of a large, space-based mirror drives the interest in methods that would allow shape control of larger mirrors with less hardware.

One promising solution to this dilemma uses an electron gun to control a large area, while maintaining a high spatial control resolution. Electron gun control could be used for changing the focal length, correcting aberrations, compensating for thermal deformations or correcting any manufacturing defects in the mirror surface. The gun can be set to only effect a very localized area, scan in a line or any other desired geometry, or “flood” the entire area with electrons. This type of flexibility gives the electron gun control technique significant versatility over traditional methods.
schematic comparing the electron gun technique to traditional methods is shown in Figure 1.2.

Figure 1.2: Comparison of Traditional vs. Electron Gun Actuated Mirror.

The fixed position linear actuators and the added weight of the rigid support structure make the traditional deformable mirror method increasingly impractical for new design concepts. The electron gun concept allows for a lightweight mirror to be constructed with the advantage of having a versatile control system with high spatial resolution.
1.2 Objectives
The objective of the thesis as a whole is to aid in the design and development of lightweight, deformable mirrors for use in space based telescopes. The solution investigated considers piezoelectric materials in combination with electron gun actuation.

Chapter 2 presents a thorough literature review of the topics considered within this thesis. The objective is to present a comprehensive overview of the background as well as the state of the art in the field.

The fabrication of a piezoelectric polymer (PVDF) bimorph mirror is presented in Chapter 3. The objective of this section was to investigate the ability to plastically deform a PVDF bimorph into a doubly curved dome or paraboloid. A machine was designed to deform the mirror in the 1-2 plane, creating a doubly curved bimorph from previously flat specimens.

The objective of Chapter 4 is to detail the relevant piezoelectric theory and formulate the elastic stiffness matrix and the piezoelectric stress matrix for PZT-5H. In addition, a verification model consisting of a PZT-5H bimorph beam is presented to verify that the matrices were calculated and input in ANSYS correctly.

The information presented in Chapter 4 is used directly within the following two chapters. The objective of Chapters 5 and 6 are to successfully model a composite mirror developed at NASA Langley Research Center for use in space telescopes. Chapter 5 details the mirror and the methods employed to perform the modeling, while Chapter 6 presents the results of the modeling study. The mirror consists of a six-layer, carbon fiber composite mirror substrate with a layer of piezoceramic (PZT-5H) adhered to the back. The composite mirror substrate gives the structure the rigidity necessary while the PZT-5H layer is used as an actuator to provide surface control. A unique meshing method allows for circular spot loads of electric potential to be applied anywhere on the mirror surface creating a localized electric field. These spot loads simulate electron gun actuation. Local and global effects of the loading are investigated, as well as the effects of spot diameter and location on transverse displacement.
CHAPTER 2
Literature Review

2.1 Background of Deformable Mirrors
The ability to control the surface profile of plates and shells has been studied for many years. A strong interest in deformable mirrors developed in the 1960’s. Robertson et al. developed an early active optics system in 1966. A 0.508-m diameter mirror was constructed, composed of three segments. Piston actuators were used to control the position and tilt of each segment. The segments in this early design were moved as rigid bodies, but a later design also introduced by Robertson deformed the surface of a 0.762-m diameter, 0.0127-m thick spherical glass mirror (1970). Equally spaced actuators, totaling 58, were used to correct any manufacturing irregularities in the mirror surface. Robertson calculated the actuator configurations needed to provide the correction with the finite element method.

Other early designs included changing the focal length by changing the tension in a spring attached to back of a mirror, or alternatively, a differential screw (Ahlborn and Mikoshiba 1973). This design provided a change in focal length from 1.3-m to infinity. Another concept used hydrostatic pressure to deform the mirror while maintaining image quality (Bin-Nun and Dothan-Deutsch 1973).

These designs worked well to prove the feasibility of deformable mirrors, yet lack high control resolution. Also, the response time is too slow for real-time correction. In 1977, Grosso and Yellin created membrane mirrors from titanium and nickel, between 0.5 and 1.5-µm thick. Actuation was achieved by using a region of electrostatic actuators, consisting of conducting pads. An advantage of this method is the fast response time of the materials to the applied voltage.

A subsequent design in 1982 by Merkle et al. combined electrostatic and piezoelectric actuators in an adaptive optics mirror design. The mirror is an electrostatically deformable membrane set at ground potential with an array of 63 electrodes with controllable voltages.
2.2 Piezoelectric Actuation of Deformable Mirrors

The use of piezoelectric actuators for controlling the mirror surface began shortly after the earliest adaptive mirrors were developed. Piezoceramics were the first piezoelectric actuators considered. In 1974, Feinleib et al. designed a flat, monolithic piezoelectric mirror for use in wavefront correction in adaptive optics. However, the design provided a low degree of resolution since any applied voltages deformed the entire surface and it was difficult to avoid thermal distortions.

Next, designs of doubly curved, piezoelectrically actuated mirrors began to emerge. A promising design applied a layer of piezoceramic (PZT-5H) to the back of a thin (0.6-mm), spherical glass mirror. The mirror was designed with the control of optical instruments in mind. This arrangement achieved a focal length variation from infinity to about 3-m with the single actuator setup (Adelman 1977).

To achieve a greater degree of control resolution, researchers began to investigate using multiple electrodes to control more discrete areas. In 1979, Steinhaus and Lipson epoxied a layer of piezoceramic (PZT) to the back of a thin glass mirror. They placed a continuous electrode at the interface and painted an array of twelve electrodes on the back side. This design allows for more discrete areas to be actuated and it took a relatively low operating voltage to achieve significant deformations, about 70-V to achieve a wavelength of light of distortion.

The piezoelectric polymer, polyvinylidene fluoride or PVDF, is an attractive piezoelectric material due to its high piezoelectric response, flexibility, and durability. In 1980, Sato et al. made a deformable mirror by bonding PVDF (30-µm thickness) to the back side of a thin, square glass plate (22-mm x 22-mm x 0.12-mm). Silver evaporation was used on the other side of the glass to act as the mirror. Mono-oriented PVDF was used (the piezoelectric constant is much higher in manufacturing stretch direction); therefore, the mirror essentially acted as a singly curved reflector when actuated.

A possible application for PVDF is the control of gossamer space structures, particularly reflectors and mirrors. There is one considerable criticism of PVDF for these types of applications. According to Simpson et al. in “Novel Piezoelectric Polymides”, “One of the limiting aspects of PVDF is its lack of piezoelectric activity at elevated temperatures” (1995). The maximum service temperature for PVDF is 80°C.
Above this critical temperature, the material loses the dipole orientation induced by the poling process, thereby losing its piezoelectric properties. This limitation could severely hamper the use of PVDF in the harsh temperatures of space, which can range between -150°C and 120°C depending on whether the object is in darkness or sunlight.

Simpson et al. show the development of a new class of polymers, polyimides, that posses a “strong piezoelectric response and polarization stability at temperatures in excess of 100°C.” The piezoelectric constants of the polyimide samples actually increased with increasing temperature up to approximately 100°C, then leveled off. PVDF may not be ideal for practical application in all space structures, but it offers a low cost material used for the testing of the concepts and the development of control schemes for such structures.

Utku et al. considered “Shape Control of Inflatable Reflectors” (1995). Controlling the inflatable reflector shape is critical “where accurate shape must be maintained on-orbit to the order of a hundred microns RMS and where adjustments of shape must be made in response to unavoidable manufacturing errors, thermal loads, and geometry changes due to aging of the material.” A canopy style inflatable reflector was considered and assumed to be a thin shell of revolution. The equations of strain were solved for in terms of the critical parameters of the reflector, such as radius and focal length. Suggestions were then made as to possible solutions to the shape control problem, such as piezo film actuators or shape memory alloys.

There has been significant work with the concept of bimorph piezoelectric mirrors. The bimorph is similar in concept to a bimetallic strip in a common household thermostat. In a bimetallic strip, the different coefficients of thermal expansion of the two metal pieces causes the strip to bend. The poling orientations of the two layers of PVDF are oriented opposite of one another in the piezoelectric bimorph. When an electric field is applied across the entire bimorph, one side expands and the other side contracts, creating a curvature due to the induced moment. See Figure 2.1 for a schematic of the bimorph.
The bimorph arrangement has been used with both PVDF and piezoceramics. When using PVDF, generally the more commercially available unidirectional PVDF is used to make a singly curved mirror. However, there is copolymer PVDF (piezoelectric constants are equal in the 1 and 2 directions) available that could be used to make a doubly curved mirror. Piezoceramics, such as the PZT family, have the same piezoelectric constant in the 1 and 2 directions but a separate constant in the 3 or thickness direction. This property allows for mirrors of double curvature to be formed.

In 1992, Ikramov et al. considered a cooled copper adaptive mirror with a double bimorph structure intended for the compensation of large-scale optical aberrations. A piezoceramic was used with 19 controlling electrodes. The major shortcomings of this design were the presence of thermal deformations; however, it is noted that the nature of the deformable mirror itself could compensate for these deformations. Another bimorph design used PZT with a continuous, grounded electrode between the layers with continuous electrodes deposited on either side of the bimorph (Susini et al. 1995). The necessary actuation voltage was applied to the outer two electrodes. An ANSYS finite element model was generated that matched well with experimental results.

Safronov presented a detailed study of adaptive optics mirrors actuated by piezoceramic bimorphs (1998). One of the advantages of bimorphs discussed is that mounting sites for the actuation hardware are not needed, since the actuation is due to the bending moment induced within the bimorph. The actuators are attached directly to the back of the mirror plate. This greatly reduces the weight of the system, a critical parameter for space-based applications. Another advantage of the bimorph is the simplicity of the design. The nature of the bimorph reduces the complexity of the mirror design, since hundreds of discrete actuators are often needed in large mirror designs.

![Figure 2.1: Bimorph Description.](image)
A mosaic technique is introduced where an array of hexagonal piezoceramic bimorphs are attached to the back surface of the mirror plate. Nearly the entire surface of the mirror is covered, except for small areas around the outer edges of the mirror. This technique allows for the consistency of a uniform piezoelectric actuator to be more easily applied to curved mirrors. Within the study, a 3.3-m bimorph mirror design was modeled via the finite element method with promising results. The finite element model generated displayed the advantage of the bimorph mirror in compensating for defocusing problems and spherical aberration.

2.3 Non-Contact Actuation

Limited work has been done researching “non-contact” actuation of piezoelectric materials. The non-contact method eliminates the numerous control electrodes attached to the back of the mirror, simplifying the system. Electron gun control is an example of this type of actuation. Brown and Sivyer pioneered research in the field with U.S. Patent #3,899,709 (1975). Electron gun actuation was used to excite a piezoelectric quartz transducer within a cathode ray tube.

Hubbard considered electron gun actuation of piezoelectric materials for use in deformable mirrors with U.S. Patent #5,159,498 entitled “Active Mirror Assembly,” in 1992. A PVDF bimorph was used as the mirror actuator. An electron gun was used to provide the charge distribution on one side and a uniform electrode applied to the other side of the mirror providing a reference potential, referred to as the “backpressure voltage.”

Martin and Main performed experimental work using a 1-D bimorph design in 1998. The bimorph was two layers of unidirectional PVDF with a layer of insulating epoxy sandwiched between. The bimorph had an electrode deposited on one side with a constant potential applied, while the other side was bare. The bare side was then bombarded with electrons from an electron gun, creating an electric field across the thickness of the bimorph; hence, causing the bimorph to bend.

Experimental work on the response of PZT-5H when bombarded with electrons has also been performed. In 1998, Nelson performed experimental studies of PZT-5H under electron bombardment to examine the effect of varying the backpressure voltage.
on piezoelectric response. In addition, a control method was formulated from these findings, resulting in United States Patent #6,188,160 (Main and Nelson 2001).

Hadinata and Main considered the strain response of a PZT-5H plate (7.5-cm x 5-cm x 1.975-mm) subjected to various backpressure voltages and electron fluxes (1999). Backpressure voltages were stepped up from 0 to 100-V and also stepped down from 0 to –100-V. Flood, line and spot loads were examined using these various backpressure voltages with fixed–free boundary conditions. Nine strain gages were applied in a 3 x 3 array on the electroded side of the piezoceramic. Strain measurements were taken and from this data time constants were evaluated. When the backpressure voltages were stepped-up from 0 to 100-V, the time constant was approximately one-second. However, when the voltage was stepped down from 0 to –100-V the time constant was nearly one minute. It is shown that the “changes in the structure remain after the input signals were removed, indicating that there is some potential for energy-efficient static strain control in adaptive structures using this method.” This finding indicates that the input would not need to be a constant correction method, thereby saving energy.

Tzou and Chou also considered non-contact control of piezoelectric materials, but used an approach other than an electron gun (1996). Illumination from a high intensity light source was used as the actuating device. Tzou and Chou state, “it is known that certain classes of semiconductive solid-state materials and ferroelectric materials are light sensitive, and they exhibit complicated opto-thermo-electromechanical behavior when subjected to irradiating lights.” Two layers of these materials were laminated in a bimorph fashion, with the polarities of the two layers opposite. Irradiating the surface with a high-energy light source induces a deformation due to the combination of the “photovoltaic effect and the converse piezoelectric effect.”

Tzou and Chou strengthen the argument for non-contact control by stating that hard-wired connections attract electrical noise, contaminating sensor/actuator control voltages. Additionally, hard-wired connections are stated to be not desirable or feasible in hostile environments. The hostile environment of space would seem to be an ideal application for non-contact control methods.
2.4 Composite Materials Used in Deformable Mirrors

The push for accurate, lightweight mirrors has caused the space industry to look towards reinforced composites as a solution. The high strength-to-weight ratios of composite structures make this type of material seemingly ideal for the construction of space telescope mirrors. However, the high level of accuracy required for optical instruments can not be met with the current manufacturing processes of composites. Therefore, it is necessary to control the surface of the mirror. This can be done with all the same methods previously discussed. In addition, piezoelectric actuators can be embedded between layers of composite laminate.

Significant work has been done to reduce the areal density of composite mirrors. Chen et al. have researched the field of lightweight composite materials extensively in recent years. Lightweight is defined by this group as having an areal density of 5-kg/m², whereas HST has an areal density of 180-kg/m², and NGST has an areal density goal of 15-kg/m² (Chen 2000). Composite mirrors have inherent manufacturing irregularities, causing aberrations in the final mirror, including astigmatism, coma, and spherical aberration. These aberrations are caused by the fact that each composite layer exhibits its own unique stiffness and thermal expansion coefficient. There are also non-zero tolerances when laying up the angles of the individual plies to make the quasi-isotropic final product. Although, it has been shown that a small number of moment actuators can correct low order aberrations (Chen 1998). Applying a layer of piezoelectric material to the back of the structure could supply the moment necessary for correction.

Controlling composite structures using piezoelectric materials has been studied thoroughly. This is of interest for damping vibrations in structures, negating thermal deformations, and in this case, maintaining the surface profile of an optical mirror. Kyu Ha et al. wrote a finite element code for the analysis of fiber-reinforced composites containing distributed piezoceramics under static and dynamic loading (1992). The code was written so that either a mechanical or electrical input could be provided. Another extensive study deals with composite structures containing embedded actuators (Koconis et al. 1994). This study emphasizes shape control rather than vibration control, much like the work presented here. Solutions for six structural
elements are presented: straight beam, curved beam, rectangular plate, circular plate, rectangular shell and circular shell. The method is provided for the voltages known and the shape desired, as well as shape known, necessary voltages required.

A recent design of a deployable space based telescope mirror uses six composite mirror panels deployed about a central fixed mirror panel (Lake et al. 1999). The mirror has an effective area of a 1.8-m diameter monolithic mirror. According to the authors, the mirror could be adapted to an image-quality mirror with the addition of an active control system. In 1999, Paradies and Hertwig analyzed two different composite mirror arrangements. They considered a planar adaptive mirror and a doubly curved sandwich mirror with PZT patches integrated into the layers as actuators. Finite element models were created in NASTRAN 67, I-DEAS VI, and ANSYS 5.3 using triangular and quadrilateral shell elements. The piezo actuators were added in the proper areas as an additional layer of shell elements. A thermal analogy between piezoelectric effect and thermal expansion was used rather than piezoelectric elements.

2.5 Finite Element Modeling of Composites and Piezoelectric Materials
Many of the papers already cited demonstrate the use of the finite element method to solve structural problems using composites and piezoelectric materials. Finite element modeling has been used with success in modeling of piezoelectrically actuated structures for years. Often the thermal analogy is employed to simplify the solution. A limitation to thermal modeling is apparent in the work of Tauchert (1991). The piezothermoelastic behavior of materials is considered for laminated plates. Tauchert considered an eight layer graphite/epoxy (carbon fiber reinforced composite) plate with a layer of PVDF piezoelectric polymer adhered to the laminate. Free and simply supported boundary conditions are considered. The laminate is subject to both thermal and electric fields. In Tauchert’s problem, using the thermal to piezoelectric analogy would be difficult since the thermal coefficient of expansion of the graphite/epoxy layer would be set to zero to solve the problem.

Hwang and Park presented a study on the modeling of piezoelectric sensors and actuators (1993). A PVDF bimorph beam (100-mm x 5-mm x 1-mm, with each layer of PVDF being 0.5-mm thick) was also examined with the static deflections at the nodes
calculated. The bimorph beam was given cantilever boundary conditions at one end. The finite element method was used to calculate the deflections at several nodes for input voltages varying from 0 to 200-V. It was found that the tip deflection changed linearly with the applied voltage up to a maximum deflection of approximately 62-µm. This matched well with previous experimental work (Tseng 1989). Additionally, a vibration analysis of a laminated composite plate with a piezoelectric sensor/actuator combination is considered. The composite plate consisted of 6 layers of graphite epoxy in a symmetric lay-up. PZT sensor/actuator pairs were applied in a sandwich manner. A finite element code was written to solve the vibration control problem of such a setup.

In 1998, Kapania et al. presented a FEM solution to a hexagonal, 8 layer graphite/epoxy mirror substrate, with a ninth layer of PVDF added for actuation. The purpose of the study was to control the thermal deformations with piezoelectric actuation. Triangular shell elements were used with 6 degrees of freedom. As a verification of that model, a piezoelectric bimorph cantilever beam was presented, similar to the study at hand. The results were in agreement with Tzou and Tseng’s analytical and theoretical solution for the piezoelectric bimorph cantilever beam (1990).

In 1999, Vecchio et al. used ANSYS to model a thin glass mirror using a combination of shell and brick elements, similar to the models generated in this study. However, Vecchio et al. actuated the deformable mirror with electromagnetic actuators rather than piezoelectric actuators. The glass mirror was modeled using shell elements, while the magnets were modeled with brick elements. Both static and dynamic analyses were performed.

Another study modeling piezoelectrically actuated deformable mirrors looked at two different cases both using piezoceramic tube actuators (Winsor et al. 1999). Flat mirrors of 200 to 500-µm thickness were considered. The first design uses a vacuum drawn within the tubes to create suction that keeps the mirror in place on top of the piezoceramic tube actuators. The second design epoxied precision ball bearings atop the tube actuators, and then the mirror was rigidly epoxied to the ball bearings. The Algor Finite Element Analysis software was used for this project. The FEA results for the ball bearing configuration were very promising, while the vacuum design caused dimples to occur wherever the tube actuators resided. This study demonstrates a
severe drawback of using actuators such as piezoceramic tube actuators or linear piston style actuators. A robust mounting surface for the actuators is necessary, greatly increasing the weight of the system. This limits the practical size of a mirror of this style that can be economically launched into space.
CHAPTER 3
Manufacture of Bimorph, Deformable Membrane Mirrors

A method of manufacturing a lightweight, deformable mirror is investigated. The ability to form a doubly curved PVDF membrane mirror would allow for an extremely lightweight, deformable mirror design.

The manufacture of the doubly curved membrane mirror took these stages:

1. Verify that it is possible to pole ordinary, unpoled PVDF with simple laboratory equipment. Also determine the approximate piezoelectric constant of material.
2. Pole a curved, previously unpoled PVDF dome of paraboloid shape. Adhere poled PVDF dome to back of aluminized Mylar dome and attempt to actuate with electron gun.
3. The focus turned towards cold forming of previously poled PVDF into a doubly curved shape. A machine was designed to stretch a PVDF bimorph structure into a permanently curved surface.

3.1 Poling Unpoled PVDF
The initial objective in this portion of the research was to prove that unpoled piezoelectric material, namely PVDF, could be sufficiently poled with simple laboratory equipment. A flat, rectangular, unpolarized PVDF sheet (19.6-cm x 12.7-cm x 55-μm) was placed between two 1.27-cm thick Blanchard ground and polished steel plates. The top plate was grounded while the bottom plate was wired to a DC power supply. After numerous trials, 0.55-kV was chosen to be the best voltage. This voltage allowed for the PVDF to reach the proper poling temperature without arcing through the material and short-circuiting the process and ruining the sample. An insulating Kapton sheet was placed over the setup to ensure safety.

A halogen heat lamp was used to heat the setup to the critical poling temperature of PVDF. The temperature was maintained at 105-110°C. The poling temperature is the temperature at which the molecules within the PVDF are free to align with the applied electric field. Holes (approximately 0.5-in deep) were drilled at various locations around the perimeter of the grounded plate and a thermocouple was used to measure
the plate temperature and guarantee a uniform, consistent temperature. Adjusting the height of the heat lamp compensated for any variations in temperature. The applied temperature and electric field was maintained on the PVDF for 1.5 hours. The heat lamp was then turned off and the PVDF was allowed to cool to room temperature while the electric field was held constant. Figure 3.1 shows the poling setup, with the 3-direction corresponding to the poling direction.

After poling the PVDF, a rectangular sample was cut from the center of the sheet and an insulating, quick-cure epoxy was used to adhere the PVDF to the aluminum bar shown in Figure 3.1. A smaller, rectangular piece of aluminum foil was then adhered to the top surface of the PVDF in a similar manner. Great care was taken to ensure the epoxy layer was as thin and uniform as possible. Next, a thin wire was taped to the aluminum foil using ordinary scotch tape and a positive lead was clipped to the opposite end of this wire. A ground wire was then clipped to the aluminum bar. A BNC cable was used to connect these leads to an oscilloscope. The poling of the PVDF was tested by flicking the end of the aluminum bar and observing the sinusoidal output voltage due to the induced strain in the PVDF, which is seen in Figure 3.2.
It was successfully proven that unpoled PVDF could be poled with simple laboratory equipment. Focus now turned to performing the same procedure to a doubly curved PVDF dome.

### 3.2 Poling Doubly Curved PVDF

The detailed experimental procedure for poling the PVDF dome is outlined, as well as the procedure for testing electron gun actuation. The test article is a 17-cm diameter, 55-µm spherical PVDF dome with a 15.75-cm radius of curvature. The PVDF dome was manufactured by United Applied Technologies in Huntsville, AL.
Figure 3.3 shows the apparatus used to pole the PVDF. The materials were assembled in the following order, starting from the bottom: rubber insulated convex bottom piece, aluminized “hot” poling surface, PVDF dome, Kapton insulating material, and steel grounded poling surface. These items were then clamped together to ensure a uniform distance between the poling surfaces during the poling process. An electric field was then applied using a DC power supply. The same voltage/temperature combination was used to pole the doubly curved PVDF as the flat. The PVDF was allowed to cool to room temperature with the field still applied before disassembly. A digital multimeter and a thermocouple were used to ensure a constant electric field and temperature throughout the poling process. Figure 3.4 shows the poling setup.

![Poling Setup for PVDF Dome.](image)

The poled PVDF sample was adhered to an aluminum beam and tested for piezoelectric response in the same manner as detailed in Section 3.1. The piezoelectric constant calculated was approximately 20e-14 m/V, or about 1/100th of the manufactured PVDF piezoelectric constant. Higher voltages were attempted to increase the constant, but the system became very unstable. The electric field would become too great and arc through the PVDF, destroying the sample.

The PVDF dome was adhered to an aluminized Mylar dome of matching dimensions after verifying that the PVDF was poled. A general purpose, insulating epoxy was used to glue the two pieces together. The PVDF dome was adhered to the
convex side of the Mylar dome, with the aluminized side on the concave surface. Again, great care was taken to ensure a thin, uniform layer of epoxy free of air pockets. The finished dome can be seen in Figure 3.5. The Teflon disk in the center stiffens the mirror, helping to hold its intended shape.

![Figure 3.5: Finished PVDF/Mylar Dome.](image)

The next step entailed placing the finished dome in a vacuum chamber. The piece was tested for sufficient piezoelectric response using a backpressure voltage lead attached to the aluminized surface and an electron gun to spray the PVDF surface, achieving a localized electric field, thus inducing strain.

Input parameters were varied to actuate the mirror, with the assistance of George Nelson, Mechanical Engineering Graduate Student at the University of Kentucky. The backpressure voltage was varied –1000-V to 1000-V, with 2500-eV actuating the bare side of the PVDF. However, the Keyence Laser Displacement Sensor, Model LK-503 with the LK-2503 controller was not able to detect a measurable response. The sensor is capable of detecting distance variations as small as 10-µm.

### 3.3 Stretching of PVDF Bimorph

The research took a new approach after proving that the doubly curved mirror did not have sufficient piezoelectric response to generate measurable deflections. The method developed takes previously poled PVDF and laminates two sheets together. A machine
then stretches or forms the laminate into a curved profile. First, it was necessary to determine the effect on the piezoelectric constant of inducing strain into poled PVDF. A piece of 75-µm, uniaxially poled PVDF was subjected to 7.5% strain in the 1-direction (manufacturing stretch direction). The stretched specimen’s piezoelectric constant was compared to the unstretched specimen using the same aluminum beam method described previously. The piezoelectric response curve of the stretched specimen was superimposed on the unstretched response curve and no difference was noticed (see Figure 3.6). The unstretched sample corresponds to the solid line, while the stretched sample is the dashed line. Therefore, it was concluded that the PVDF could be stretched into the doubly curved profile without significantly effecting the piezoelectric response.

![Effect of Strain on Piezoelectric Response](image)

**Figure 3.6: Effect of Strain on Piezoelectric Constant.**

The forming process cold-forms the PVDF material by stretching it over a 2.25-in diameter Teflon mandrel with a two-inch radius of curvature. The machine used to apply the forming force employs a jackscrew to move the material over the Teflon mandrel. The PVDF is clamped between two steel plates; one of the plates has an o-ring groove, where the o-ring is used to keep the material from slipping. Figure 3.7 shows a schematic of the machine designed and built to perform the forming operation. Figure 3.8 is a picture of the final machine.
Figure 3.7: Forming Machine Schematic.
To make the bimorph, two pieces of PVDF are cut to a diameter of 4.5 in. One piece of PVDF has a silver-ink electrode on both sides, the other has no electrodes. One electrode of the two-sided PVDF is removed by gently swabbing away the silver-ink with acetone. Next, the electrode side of the PVDF is placed face down on a plate of glass, then a general purpose, insulating epoxy is layered on the non-electrode side. The non-electrode piece of PVDF is then placed on top of the epoxy layer and a glass stirring rod is used to squeeze out any excess epoxy and eliminate any air bubbles. This was repeated until the epoxy layer was extremely thin and free of any voids.

In order to create the bimorph, the PVDF layers must be oriented in a particular manner. The poling orientation of the two layers had to be placed opposite of one another. The 1-direction of each layer must be 90° to the other. Figure 3.9 details the lay-up.
Any excess epoxy is removed and the bimorph is placed within the machine to be stretched. The bimorph is stretched before the epoxy has cured to allow the epoxy to flow while the material is deformed. A simplified cross section of the forming process is shown in Figure 3.10 with arrows indicating the direction of applied force.
The bimorph was stretched 0.4-in, as measured from the highest point on the mandrel. Several epoxies were used, with cure times varying from 1-hr to 15-days. The bimorph was left in the machine to cure for twice the curing time of the epoxy, ensuring that the epoxy has completely hardened. The final result is a deformed PVDF bimorph as shown in Figure 3.11. The strain induced in the mirror was calculated to be 4.5%, less than the 7.5% induced in the uniaxially stretched test case.

![Figure 3.11: PVDF Bimorph with Induced Curvature.](image)

The mirror was to be placed in the vacuum chamber and actuated with the electron gun actuation method. However, the final mirror would not hold its shape. The mirror would gradually lose its curvature over the span of several days, despite leaving the mirror in the forming machine for twice the epoxy cure time. The procedure was attempted numerous times, with eight different brands and types of epoxy. The same disappointing result occurred each time, with the time taking to relax to an undeformed state varying.

The probable explanation of the failure lies in the reason a bimorph needs to be formed, the orthotropic nature of the PVDF material. The bimorph needed to be formed with the two pieces of PVDF oriented 90° to each other because of the difference in the piezoelectric constants in the 1 and 2-directions. However, mono-oriented PVDF also exhibits highly orthotropic mechanical properties. Young’s modulus in the 1-direction is
2.5-GPa, while the Young’s modulus in the 2-direction is 0.22-GPa. Similarly, the yield stress in the 1-direction ($\sigma_{s1}$) is 455-MPa, whereas the yield stress in the 2-direction ($\sigma_{s2}$) is 44-MPa. It is believed that this drastic difference in yield stress caused the forming method to fail. As the material was stretched and the 2-direction reached failure, the 1-direction had not even approached its yield point. Although the ultimate strength ($\sigma_u$) is not known, this drastic difference in the modulus and yield points of the 1- and 2-directions lead to this conclusion. Therefore, when the forming force was released, the 1-direction of each layer began to return to its unstrained state. The epoxy probably slowed the return, but the poor strength properties of epoxy in shear allowed the bimorph to return to its original flat profile. Figure 3.12 demonstrates the possible cause of failure.

\[ \begin{align*}
\sigma_{y1} &= 455 \times 10^6 \\
\sigma_{y2} &= 44 \times 10^6 \\
Y_1 &= 2.5 \times 10^9 \\
Y_2 &= 0.22 \times 10^9 \\
\end{align*} \]

Figure 3.12: Stress-Strain Plot for the 1- and 2-directions of Mono-Oriented PVDF.
3.4 Discussion

It was successfully proven that PVDF can be poled using ordinary laboratory equipment. However, the piezoelectric response was not great enough to measurably actuate a PVDF/Aluminized Mylar mirror via electron gun actuation and backpressure voltage.

Numerous samples of the doubly curved PVDF bimorph were created, using several types of epoxy as the laminate adhesive. None of the samples would maintain the curved shape after the pieces had been formed. The probable reason for the failure lies in the vast differences between Young’s moduli and yield stress in the 1- and 2-directions of the material.
CHAPTER 4
Linear Piezoelectric Theory and Matrix Formulation

4.1 Definitions
The material properties used herein were defined using the American National Standard: IEEE Standard on Piezoelectricity, Std 176-1987. The following symbol definitions were taken from the standard.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>cijkl, cpq</td>
<td>Elastic stiffness constant</td>
<td>N/m²</td>
</tr>
<tr>
<td>dijkl, dip</td>
<td>Piezoelectric strain constant</td>
<td>m/V</td>
</tr>
<tr>
<td>eijkl, eip</td>
<td>Piezoelectric stress constant</td>
<td>C/m²</td>
</tr>
<tr>
<td>Di</td>
<td>Electric displacement</td>
<td>C/m²</td>
</tr>
<tr>
<td>E (superscript)</td>
<td>At constant electric field</td>
<td>-</td>
</tr>
<tr>
<td>E_k</td>
<td>Electric field component</td>
<td>V/m</td>
</tr>
<tr>
<td>S (superscript)</td>
<td>At constant strain</td>
<td>-</td>
</tr>
<tr>
<td>Sij, Sp</td>
<td>Strain component</td>
<td>-</td>
</tr>
<tr>
<td>Tij, Tp</td>
<td>Stress component</td>
<td>N/m²</td>
</tr>
<tr>
<td>Yi</td>
<td>Young’s Modulus</td>
<td>N/m²</td>
</tr>
<tr>
<td>Gij</td>
<td>Shear Modulus</td>
<td>N/m²</td>
</tr>
<tr>
<td>νij</td>
<td>Poisson’s Ratio</td>
<td>-</td>
</tr>
<tr>
<td>εij, εp</td>
<td>Permittivity component</td>
<td>F/m</td>
</tr>
</tbody>
</table>

4.2 Linear Piezoelectric Equations
ANSYS uses the form of the constitutive piezoelectric equations shown below, taken from ANSI/IEEE Std.176-1987.

\[
T_{ij} = c^{E}_{ijkl}S_{kl} - e^{*}_{kj}E_k
\]

Equation 4.1

\[
D_i = e_{ijkl}S_{kl} + ε^S_{ij}E_k
\]

Equation 4.2
Matrix notation consists of replacing $ij$ or $kl$ with $p$ or $q$, where $i, j, k, l$ take the values of 1, 2, 3 and $p, q$ take the values 1, 2, 3, 4, 5, 6. Table 4.2 further explains the notation. A third column is added showing the variation of the ANSYS definition of $p$ and $q$.

Table 4.2: Matrix Notation (ANSI/IEEE Std. 176-1987).

<table>
<thead>
<tr>
<th>$ij$ or $kl$</th>
<th>$p$ or $q$</th>
<th>$p$ or $q$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IEEE Standard</td>
<td>ANSYS</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>33</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>23 or 32</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>13 or 31</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>12 or 21</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

Using this notation, Equations 4.1 and 4.2 are the following.

$$T_p = c^{E_{pq}}S_q - e^{E_{kp}}E_k$$

Equation 4.3

$$D_i = e_{iq}S_q + \varepsilon^{S_{ik}}E_k$$

Equation 4.4

Equation 4.3 demonstrates the electrical-mechanical coupling of piezoelectric materials. The total stress in the material is composed of the mechanical component, $c^{E_{pq}}S_q$, and the electrical component, $e^{E_{kp}}E_k$.

To input the required data into ANSYS, a simple calculation must be performed. The ANSI/IEEE Std 176-1987 defines the piezoelectric constant as follows.

$$e_{ip} = d_{iq}c_{qp}$$

Equation 4.5

The piezoelectric strain constant matrix, $[d]$, is defined by Equation 4.6:

$$[d] = \begin{bmatrix}
0 & 0 & 0 & 0 & d_{15} & 0 \\
0 & 0 & 0 & d_{24} & 0 & 0 \\
d_{31} & d_{32} & d_{33} & 0 & 0 & 0
\end{bmatrix}$$

Equation 4.6

Piezoelectric strain constant values are typically found in product literature.
The piezoelectric stress constant matrix, \([e]\), takes a similar form:

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & e_{15} & 0 \\
0 & 0 & 0 & e_{24} & 0 & 0 \\
0 & 0 & e_{31} & e_{32} & e_{33} & 0 & 0
\end{bmatrix}
\]

*Equation 4.7*

The most general form of the stiffness matrix contains 21 independent constants for an anisotropic material. The entire stiffness matrix is shown in Equation 4.8:

\[
\begin{bmatrix}
    c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\
    c_{22} & c_{23} & c_{24} & c_{25} & c_{26} &  \\
    c_{33} & c_{34} & c_{35} & c_{36} &  \\
    c_{44} & c_{45} & c_{46} &  \\
    c_{55} & c_{56} &  \\
    c_{66} &  
\end{bmatrix}
\]

*Equation 4.8*

The stiffness matrix is found by calculating the compliance matrix, or a measure of the “softness” of a material. The compliance matrix is the inverse of the stiffness matrix. The relationship between the two is shown below, where \(\{\sigma\}\) represents the stress vector and \(\{\varepsilon\}\) is the strain vector.

\[
\{\sigma\} = [c]\{\varepsilon\} \\
\{\varepsilon\} = [s]\{\sigma\} \\
\therefore [c] = [s]^{-1}
\]

*Equation 4.9*

The final material property matrix that needs to be formulated is the permittivity matrix, \([\varepsilon]\), defined by Equation 4.10:

\[
\begin{bmatrix}
\varepsilon_1 & 0 & 0 \\
0 & \varepsilon_2 & 0 \\
0 & 0 & \varepsilon_3
\end{bmatrix}
\]

*Equation 4.10*
4.3 PZT-5H Material Definitions

PZT-5H is a transversely isotropic material with the 1-2 plane being the plane of isotropy; therefore, the stiffness matrix requires 5 independent constants. Note that $c_{66} = 0.5(c_{11} - c_{12})$. The stiffness matrix is shown below.

\[
\begin{bmatrix}
    c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\
    c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\
    c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\
    0 & 0 & 0 & c_{44} & 0 & 0 \\
    0 & 0 & 0 & 0 & c_{44} & 0 \\
    0 & 0 & 0 & 0 & 0 & c_{66}
\end{bmatrix}
\]

*Equation 4.11*

The compliance matrix, $[s]$, must be calculated for a transversely isotropic material to find $[c]$. The compliance matrix is calculated using common material properties.

\[
[s] = \begin{bmatrix}
    1 & -v_{21} & -v_{31} & 0 & 0 & 0 \\
    \frac{y_1}{y_1} & \frac{y_1}{y_1} & \frac{y_3}{y_3} & 0 & 0 & 0 \\
    -v_{12} & 1 & -v_{31} & 0 & 0 & 0 \\
    \frac{y_1}{y_1} & \frac{y_1}{y_1} & \frac{y_3}{y_3} & 0 & 0 & 0 \\
    -v_{13} & -v_{13} & 1 & 0 & 0 & 0 \\
    \frac{y_1}{y_1} & \frac{y_1}{y_1} & \frac{1}{G_{23}} & 0 & 0 & 0 \\
    0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\
    0 & 0 & 0 & 0 & \frac{1}{G_{12}} & 0 \\
    0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}}
\end{bmatrix}
\]

*Equation 4.12*
Table 4.3 summarizes the piezoelectric and mechanical properties of PZT-5H.

Table 4.3: PZT-5H Material Properties (Aura Ceramics).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_{31}, d_{32}</td>
<td>Piezo Strain Constant</td>
<td>-270</td>
<td>10^{-12} m/V</td>
</tr>
<tr>
<td>d_{33}</td>
<td>Piezo Strain Constant</td>
<td>580</td>
<td>10^{-12} m/V</td>
</tr>
<tr>
<td>d_{15}, d_{24}</td>
<td>Piezo Strain Constant</td>
<td>700</td>
<td>10^{-12} m/V</td>
</tr>
<tr>
<td>Y_1, Y_2</td>
<td>Young's Modulus</td>
<td>60</td>
<td>10^9 N/m^2</td>
</tr>
<tr>
<td>Y_3</td>
<td>Young's Modulus</td>
<td>50</td>
<td>10^9 N/m^2</td>
</tr>
<tr>
<td>G_{12}</td>
<td>Shear Modulus</td>
<td>25</td>
<td>10^9 N/m^2</td>
</tr>
<tr>
<td>G_{13}, G_{23}</td>
<td>Shear Modulus</td>
<td>20*</td>
<td>10^9 N/m^2</td>
</tr>
<tr>
<td>ν_{12}, ν_{21}</td>
<td>Poisson's Ratio</td>
<td>0.31</td>
<td>-</td>
</tr>
<tr>
<td>ν_{31}, ν_{32}</td>
<td>Poisson's Ratio</td>
<td>0.25*</td>
<td>-</td>
</tr>
<tr>
<td>ν_{13}, ν_{23}</td>
<td>Poisson's Ratio</td>
<td>0.3*</td>
<td>-</td>
</tr>
<tr>
<td>ε_1, ε_2, ε_3</td>
<td>Permittivity</td>
<td>279</td>
<td>10^{-10} F/m</td>
</tr>
</tbody>
</table>

*Note: Approximated Values

It must be noted that not all of the mechanical properties for PZT-5H could be found in any product literature or other reference sources. Therefore values for ν_{31}, ν_{32}, ν_{13}, ν_{23}, G_{13} and G_{23} had to be approximated. However, it is known that ν_{31}=ν_{32}, ν_{13}=ν_{23}, and G_{13}=G_{23} by the nature of the transversely isotropic material. Therefore, ν_{31}=ν_{32}=0.25 was used as an approximation. Then ν_{13}, ν_{23} were calculated from those values using the reciprocal relationship of Poisson’s ratios shown in Equation 4.13.

\[
\frac{ν_{ij}}{Y_i} = \frac{ν_{ji}}{Y_j}
\]

Equation 4.13

The remaining shear modulus, G_{13}, was approximated through the shear modulus properties of a piezoceramic (PZT-4) used in Verification Model 176 of the ANSYS Verification Manual. The ratio G_{12}/G_{13} for that material was used to calculate G_{13} for PZT-5H. This is assumed valid because of the similar mechanical properties of the material in the verification case.
After calculating the compliance matrix for PZT-5H using the material properties outlined in Table 4.3, the inverse is taken and the final stiffness matrix is found and shown below. The resulting piezoelectric matrix, \([e]\) is then found by Equation 4.5.

\[
[c] = \begin{bmatrix}
7.8456 & 3.2655 & 2.7778 & 0 & 0 & 0 \\
3.2655 & 7.8456 & 2.7778 & 0 & 0 & 0 \\
2.7778 & 2.7778 & 6.3889 & 0 & 0 & 0 \\
0 & 0 & 0 & 2.0 & 0 & 0 \\
0 & 0 & 0 & 0 & 2.0 & 0 \\
0 & 0 & 0 & 0 & 0 & 2.5 \\
\end{bmatrix} \cdot 10^{10} \frac{N}{m^2}
\]

*Equation 4.14*

\[
[e] = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 14.0 & 0 \\
0 & 0 & 0 & 14.0 & 0 & 0 & 0 \\
-13.8889 & -13.8889 & 22.0556 & 0 & 0 & 0 & 0 \\
\end{bmatrix} \frac{N}{m \cdot V}
\]

*Equation 4.15*

The elastic stiffness matrix, \([c]\), defines the mechanical material properties of the piezoceramic in ANSYS. The piezoelectric matrix, \([e]\), is the matrix needed by ANSYS to perform a piezoelectric, coupled-field analysis.

The permittivity matrix, \([\varepsilon]\), for PZT-5H is found directly from the permittivity values shown in Table 4.3.

\[
[e] = \begin{bmatrix}
279 & 0 & 0 \\
0 & 279 & 0 \\
0 & 0 & 279 \\
\end{bmatrix} \cdot 10^{-10} \frac{F}{m}
\]

*Equation 4.16*
4.4 Matrix Verification Model

To verify the matrices were input correctly, a model was generated that can be easily calculated by hand. The verification model chosen was a 10-cm long, 1-cm wide bimorph, with two layers of 1-mm thick PZT-5H. The poling orientation of the material was oriented in the same direction, but the field applied is opposite for each layer, creating the bimorph effect. A schematic of the bimorph can be seen in Figure 4.1.

![PZT-5H Bimorph](image)

**Figure 4.1: PZT-5H Bimorph.**

The deflection of the bimorph can be calculated using the following equation taken from the Measurement Specialties Inc. Technical Manual.

\[
u_3(x) = \frac{3}{4} d_{31} V \frac{x^2}{t^2}
\]

*Equation 4.17*

Inputting the bimorph geometry and the PZT-5H material properties yields the following.

\[
u_3(x) = \frac{3}{4} (-270 \times 10^{-12} \frac{m}{V}) \cdot (1000 V) \cdot \frac{x^2}{(0.001 m)^2} = -0.2025 x^2
\]

*Equation 4.18*

An ANSYS model was generated using the elastic stiffness matrix shown in Equation 4.14, the piezoelectric stress matrix shown in Equation 4.15, and the permittivity matrix shown in Equation 4.16. SOLID5 coupled-field brick elements were used. A displacement plot of the results is shown in Figure 4.2.
The z-displacement was recorded every 2-cm along the length of the beam (at $y=0.005\text{-m}$ and $z=0$) and compared to the theoretical result.

Table 4.4: Verification Model vs. Theory.

<table>
<thead>
<tr>
<th>Location (m)</th>
<th>0.02</th>
<th>0.04</th>
<th>0.06</th>
<th>0.08</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (m)</td>
<td>-0.000081</td>
<td>-0.000324</td>
<td>-0.000729</td>
<td>-0.001296</td>
<td>-0.002025</td>
</tr>
<tr>
<td>FEM (m)</td>
<td>-0.000080</td>
<td>-0.000327</td>
<td>-0.000735</td>
<td>-0.001305</td>
<td>-0.002037</td>
</tr>
<tr>
<td>% Error</td>
<td>0.70</td>
<td>0.84</td>
<td>0.82</td>
<td>0.72</td>
<td>0.59</td>
</tr>
</tbody>
</table>

The verification model was within 1% of the theoretical results for all of the locations considered, verifying that the piezoelectric stress matrix and elastic stiffness matrix were calculated and input correctly.
CHAPTER 5
Finite Element Model Generation for Composite Reflector

5.1 Reflector Description
The ANSYS finite element model generated in this thesis is a model of a prototype composite mirror developed at NASA Langley Research Center. The mirror substrate is a laminated six-layer carbon-fiber, T300 fiber/5208 epoxy lay-up. The T300 fibers are oriented unidirectionally within the 5208 epoxy resin. The composite mirror substrate can be seen in Figure 5.1.

Figure 5.1: Composite Mirror Substrate.

A layer of 3M DP-100 clear epoxy is used to adhere a piezoceramic actuator (PZT-5H) to the back surface of the composite mirror. The adhering epoxy was assumed to the uniform and free of imperfections. In practice, the composite surface would have a coating of aluminum, gold, or silver vacuum deposited on the surface to act as the reflecting surface. However, this coating is so thin that it can be neglected in the model. Figure 5.2 details the material lay-up and the geometry of the structure.
The profile of the mirror in the undeformed state can be calculated using the following equation for a paraboloid mirror, with the focal length equal to 1.524-m.

\[ z = \frac{1}{4f} r^2 \]

\[ z = 0.164r^2 \]

Equation 5.1

The high strength-to-weight ratio of the T300/5208 carbon fiber/epoxy composite mirror makes it an ideal choice for the construction of lightweight, rigid structures. The areal density of the mirror is approximately 2-kg/m², in comparison to Hubble’s areal density of 180-kg/m². However, due to manufacturing irregularities inherent with laminated composite materials, correction is necessary to achieve the accuracy needed for optical applications. The PZT-5H piezoceramic layer acts as the control actuator to maintain surface quality.

The ANSYS model generated applies circular spot loads of electric potential to simulate the actuation due to an electron gun. Cases of uniform loading are examined as well. The spot loads can be placed anywhere on the mirror due to the meshing scheme used. The ability to deform small areas anywhere on the mirror surface allows for a high spatial resolution, making the lightweight design concepts feasible.

The entire ANSYS code is included in Appendix A.
5.2 Material Property Definitions

5.2.1 PZT-5H Material Property Input Data
The elastic stiffness matrix and the piezoelectric stress constant matrix calculated in Chapter 3 are the matrices input in the ANSYS program to describe the mechanical and piezoelectric properties of the material. Those matrices are repeated here for reference:

\[
[c] = \begin{bmatrix}
7.8456 & 3.2655 & 2.7778 & 0 & 0 & 0 \\
3.2655 & 7.8456 & 2.7778 & 0 & 0 & 0 \\
2.7778 & 2.7778 & 6.3889 & 0 & 0 & 0 \\
0 & 0 & 0 & 2.0 & 0 & 0 \\
0 & 0 & 0 & 0 & 2.0 & 0 \\
0 & 0 & 0 & 0 & 0 & 2.5 \\
\end{bmatrix} \cdot 10^{10} \frac{N}{m^2}
\]

Equation 5.1

\[
[e] = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 14.0 \\
0 & 0 & 0 & 0 & 0 & 14.0 \\
-13.8889 & -13.8889 & 22.0556 & 0 & 0 & 0 \\
\end{bmatrix} \frac{N}{m \cdot V}
\]

Equation 5.2

The material property data was input using the TB command in ANSYS. The elastic stiffness constant matrix was input using the ANEL data table, while the piezo stress constant matrix was input using the PIEZ data table.

5.2.2 Composite and Epoxy Material Property Definitions
The material properties of the T300/9208 carbon fiber matrix/epoxy resin composite material are summarized in Table 5.1.
Table 5.1: T300/5208 Carbon Fiber/ Epoxy Material Properties.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y₁</td>
<td>Young’s Modulus</td>
<td>181</td>
<td>$10^9$ N/m²</td>
</tr>
<tr>
<td>Y₂, Y₃</td>
<td>Young’s Modulus</td>
<td>10.3</td>
<td>$10^9$ N/m²</td>
</tr>
<tr>
<td>G₁₂, G₁₃</td>
<td>Shear Modulus</td>
<td>7.17</td>
<td>$10^9$ N/m²</td>
</tr>
<tr>
<td>G₂₃</td>
<td>Shear Modulus</td>
<td>2.87</td>
<td>$10^9$ N/m²</td>
</tr>
<tr>
<td>ν₁₂</td>
<td>Poisson’s Ratio</td>
<td>0.28</td>
<td>-</td>
</tr>
<tr>
<td>v.f.</td>
<td>Fiber Volume Fraction</td>
<td>0.7</td>
<td>-</td>
</tr>
</tbody>
</table>

The epoxy chosen for this application was 3M DP-100 clear epoxy. The thickness applied was 100-µm.

Table 5.2: 3M DP-100 Clear Epoxy Material Properties (3M Product Literature).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Young’s Modulus</td>
<td>0.385</td>
<td>$10^9$ N/m²</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson’s Ratio</td>
<td>0.3</td>
<td>-</td>
</tr>
</tbody>
</table>

5.3 Model Generation

5.3.1 Element Types

The PZT-5H actuator was modeled with SOLID5 elements. SOLID5 elements are a 3-D coupled-field brick element with magnetic, thermal, electric, piezoelectric and structural field capability. The element has eight corner nodes with up to six degrees of freedom at each node. KEYOPT(1)=3 was chosen so that UX, UY, UZ, and VOLT degree of freedoms were activated.

The composite mirror substrate and the epoxy layer were modeled using SHELL99 element type. SHELL99 is an 8-noded, multi-layered shell element for modeling linear materials with up to 250 layers. The element has six degrees of freedom at each node: UX, UY, UZ, ROTX, ROTY and ROTZ. The element type is ideal for modeling laminated composite fiber materials since each layer can be given its unique orientation with respect to the active coordinate system. Inclusion of the 3M DP-
100 epoxy layer entailed adding a seventh layer to the laminate with the epoxy’s isotropic material properties shown in Table 5.2.

5.3.2 Preprocessing
The node data and element connectivity information was calculated using a Matlab program that prompts the user for information regarding the geometry of the mirror. Dr. William T. Smith, Associate Professor of Electrical Engineering at the University of Kentucky, wrote the original code used to calculate the electric field around a current carrying conductor. Dr. Suzanne Smith, Associate Professor of Mechanical Engineering at the University of Kentucky, made extensive modifications to fit the current application. Jacqueline Ackman, Mechanical Engineering Graduate Student at the University of Kentucky, and I made additional significant modifications to finalize the program. The input data can be seen below for a case where keyboard input was used to determine the mirror geometry. An input file could also be created to read in the geometric parameters. The following example is a 10-in diameter mirror with a 0.4-in (1-cm) spot load, 2-in (5-cm) off center on the x-axis. The mesh has 16 concentric layers of elements, with 3 of those layers being within the electron spot, the mesh is also broken in 24 radial segments.

Do you want to use an input file or input from keyboard? (F/K) k
What is the outer diameter of the e-gun spot? (0.4 inches) 0.4
What is the x-offset for the e-gun spot? (0 inches) 0
What is the y-offset for the e-gun spot? (0 inches) 0
What is the outer diameter of the reflector? (10 inches) 10
What is the total number of concentric layers for the mesh? (16) 16
What is the total number of concentric layers for the spot? (3) 3
What is the total number of elements around a layer? (16 or 24) 24

The Matlab meshing program takes this information and generates the nodes used to model the PZT-5H actuator layer, as well as the composite mirror layer. The program then generates the element connectivity data for each element type. Three output files are created that are read into ANSYS to generate the finite element model. Two of those files contain the node locations and the element connectivity for the PZT-
5H layer and the composite layer, ‘PZT.out’ and ‘composite.out,’ respectively. The third file, ‘nodenum.out,’ contains node data necessary for applying the loads and boundary conditions.

The SOLID5 brick elements are collapsed into a wedge element by combining the corner nodes of one corner. The PZT-5H layer consists of two layer of nodes since the piezoelectric elements are solid elements with a thickness. The output data format for one element and a schematic describing the wedge node location and element connectivity is shown in Figure 5.3.

```
!**********************************************************************
!*****************  PZT Mesh Node Data   *************************
!**********************************************************************
n,  1,  0.05080000,  0.00000000,  0.00042333
n,  2,  0.05334000,  0.00000000,  0.00046672
n,  3,  0.05259605,  0.00179605,  0.00045432
n,3001,  0.05080000,  0.00000000, -0.00059267
n,3002,  0.05334000,  0.00000000, -0.00054928
n,3003,  0.05259605,  0.00179605, -0.00056168
!**********************************************************************
!*****************  PZT Element Connectivity Data   **************
!**********************************************************************
e,  1,   2,   3,   3,3001,3002,3003,3003
```

Figure 5.3: SOLID5 Wedge Element Example.

The SHELL99 elements were collapsed into a triangle by combining the nodes on one side of the quadrilateral element into a single node. The corner nodes of the composite elements (nodes 6001 through 8999) are set to be exactly coincident with the
corner nodes of the top layer of the SOLID5 piezoelectric elements (nodes 1 through 2999). The midside nodes (nodes 9001 through 11999) are then calculated as the midpoint between each corner node. It was necessary to define duplicate nodes for the composite layer since the piezoelectric elements require a volt degree of freedom, while the SHELL99 element is not able to supply that degree of freedom. The coincident corner nodes are joined together using the CPINTF command in ANSYS. This command was used to couple the displacements of the coincident nodes, serving as the “glue” holding the two element layers together. Figure 5.4 details a SHELL99 triangle element.

Figure 5.4: SHELL99 Triangular Element Example.

The last file that the Matlab program outputs, ‘nodenum.out,’ is used in the ANSYS program to define the nodes to which the loading is applied. Three variables

```
!**********************************************************************
!************  Composite Mesh Node Data  **************
!**********************************************************************
n,6001, 0.05080000, 0.00000000, 0.00042333
n,6002, 0.05334000, 0.00000000, 0.00046672
n,6003, 0.05259605, 0.00179605, 0.00045432
n,9001, 0.05207000, 0.00000000, 0.00044502
n,9002, 0.05169803, 0.00089803, 0.00043883
n,9003, 0.05080000, 0.00127000, 0.00042386

!**********************************************************************
!********  Composite Element Connectivity Data  *********
!**********************************************************************
e,6001,6002,6003,6003,9001,9002,6003,9003
```
are defined and read into the ANSYS program. The variable ‘hispot’ denotes the highest node number within the spot. This determines nodes to which the actuation voltage applied for the spot loading case or the nodes to which the displacements and rotations are set to zero for the center constrained case. The variables ‘edge1’ and ‘edge2’ are the lowest and highest node numbers on the edge of the reflector. These variables determine the nodes to which the cantilever boundary conditions are applied for the edge-constrained case.

The mesh generation scheme described produces a mesh generated around the spot. The mesh density inside and outside the spot can be varied, depending on the mesh necessary for the application. Generally, for spot-load cases, the higher strains will occur near the spot, so a higher mesh density is used there. However, the mesh density should be uniform throughout for uniform-load cases. The mesh corresponding the input data presented above is shown in Figure 5.5.

![Example Mesh](image)

**Figure 5.5: Example Mesh Corresponding to Input Data Presented (0.4-in spot, 2-in off center).**

This meshing method provides a very convenient means of applying off-center circular loading. The ability to easily change the density of the mesh inside and outside of the spot separately makes mesh convergence problems easy to solve. Additionally,
the ability to move the spot virtually anywhere on the reflector and generate a model quickly allows for numerous models to be generated in a short period of time.

5.3.3 Boundary Conditions and Loading
The boundary conditions of the reflector can be fixed around the perimeter or constrained in the center. This is changed by setting 'BC' equal to zero for center boundary conditions or one for edge boundary conditions in the program file.

All displacements and rotations of the nodes around the perimeter are set to zero for the edge-constrained case. The voltage loading is set so that the top nodes (nodes 1-2999) of the piezoceramic is set to ground, or voltage equal to zero. Note that there were 3000 nodes available for each layer, which does not mean that each layer contains that many nodes. The number of nodes varies for each mesh generated. The user must choose whether to apply a uniform voltage load or a spot load on the other side of the piezoceramic. This is done by setting the variable 'spot' equal to 0 for a uniform load or 1 for a spot load in the ANSYS program file. For the uniform voltage load case, nodes 3001 to 5999 are set to the variable 'zvolt,' which is also set by the user within the program file. Nearly all cases within this thesis used 'zvolt'=1000-V.

Two uniform loading cases, one with edge-constraint boundary conditions and the other with center-constraint boundary conditions, were run for 'zvolt'=-1000-V. The linear behavior of the piezoelectric property eliminated the need for numerous load magnitudes. For the spot voltage load case, nodes 3001 to 'hispot'+3000 are set to 'zvolt.'

The center-constrained case can only be solved for the uniform load condition. The nodes within the spot (1 through 'hispot') are set to zero displacements and zero rotations in the x, y and z directions. The voltage loading is applied in the same manner as the loading in the uniform-load, edge-constrained case.
5.3.4 Output of Results

After the solving the model, the program outputs the necessary results to files. The displacement results along the x-axis are output to ‘z1.xls,’ where the results are compiled for each test case. In addition, all of the displacement results for one layer of nodes (1-2999) are output to 'allnode.xls.’ A color contour plot of the z-displacement of the entire model is also generated within ANSYS and output as ‘disp.jpg.’
CHAPTER 6
Composite Reflector Finite Element Model Results

The test cases chosen were intended to show the versatility of the modeling method. In addition, the data is organized to help define design parameters in similar systems. Uniform loading and spot loading cases were considered and the results are broken into those two sections. Most test cases were performed at 1000-V, except two uniform test cases for with −1000-V applied.

6.1 Uniform Load
Four test cases were considered with uniform load. Two cases were run with edge-fixed boundary conditions, with 1000-V and −1000-V applied to the bottom nodes (nodes 3001-5999) of the piezoelectric layer. Another two cases were examined with center-fixed boundary conditions and a 1000-V and −1000-V applied to the bottom layer. The results are summarized in the following figures. The maximum displacement is seen as red and minimum displacement as blue. The color chart on each plot defines the intermediate colors. The mesh for the uniform load cases consisted of 20 layers of mesh in the radial direction with 4 of those being in the 2-cm diameter spot area. There were also 24 divisions radial lines completing the mesh.
Figure 6.1: Z-Displacement, 1000-V Uniformly Applied, Edge Constrained (meters).

Figure 6.2: Z-Displacement, -1000-V Uniformly Applied, Edge Constrained (meters).
Figure 6.3: Z-Displacement, 1000-V Uniformly Applied, Center Constrained (meters).

Figure 6.4: Z-Displacement, -1000-V Uniformly Applied, Center Constrained (meters).
Figure 6.5: Edge vs. Center Boundary Constraints, 1000-V Uniform Loading.

Figure 6.6: Edge vs. Center Boundary Constraints, -1000-V Uniform Loading.
The curves in Figures 6.5 and 6.6 are not the actual profile of the mirror, but the plot of the displacement of the structure from the undeformed state. Figure 6.7 shows the deformed and undeformed mirror profile for the uniformly loaded, edge constrained test cases.

Piezoelectric actuation can change the profile of the mirror significantly. The original mirror profile equation is seen in Equation 5.1.

\[ z = 0.154r^2 \]
\[ z = 0.173r^2 \]

*Equation 6.1*

This slight change in curvature corresponds to a significant change in focal length. Table 6.1 summarizes this change.

<table>
<thead>
<tr>
<th>Electric Field (V/mm)</th>
<th>Focal Length (cm)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>152.4</td>
<td>-</td>
</tr>
<tr>
<td>1000</td>
<td>162.3</td>
<td>6.5</td>
</tr>
<tr>
<td>-1000</td>
<td>144.5</td>
<td>5.2</td>
</tr>
</tbody>
</table>
6.2 Spot Loading

The spot load set of test cases was performed at 1-, 3-, 5- and 10-cm spot diameters as well as numerous offset values to demonstrate the flexibility of the modeling method. All of the spot load cases were examined with edge-constrained boundary conditions. Table 6.2 overviews the cases to be considered.

Table 6.2: Spot Load Test Cases.

<table>
<thead>
<tr>
<th>Spot Diameter (cm)</th>
<th>x-Offset (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10</td>
</tr>
<tr>
<td>3</td>
<td>0, 1.5, 3, 4.5, 5, 6, 7.5, 9</td>
</tr>
<tr>
<td>5</td>
<td>0, 2.5, 5, 7.5</td>
</tr>
<tr>
<td>10</td>
<td>0, 5</td>
</tr>
</tbody>
</table>

All of the offset cases were considered at a x-offset. This is sufficient due to the symmetry of the problem. Only the ANSYS displacement plots of the 0- and 5-cm offset cases will be presented for the sake of comparison and brevity. The remaining ANSYS displacement plots can be found in Appendix B. Comparison plots of all the cases were done by considering only the displacements of the nodes along the x-axis.

One of the problems with spot loading was getting the mesh to converge. Numerous models had to be run for each spot load diameter before the converged solution mesh was found. In addition, as the spot approached the edge of the reflector, the mesh had to be refined to eliminate aspect ratio problems. The spot load test cases are presented in the following figures.
Figure 6.8: Z-Displacement Plot for 1000-V, 1-cm Spot Load, Centered (meters).

Figure 6.9: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 5-cm Offset (meters).
Figure 6.10: Profile Summary, 1-cm Diameter Spot Loads.

Figure 6.11: Z-Displacement Plot for 1000-V, 3-cm Spot Load, Centered (meters).
Figure 6.12: Z-Displacement Plot for 1000-V, 3-cm Spot Load, 5-cm Offset (meters).

Figure 6.13: Profile Summary, 3-cm Diameter Spot Loads.
Figure 6.14: Z-Displacement Plot for 1000-V, 5-cm Spot Load, Centered (meters).

Figure 6.15: Z-Displacement Plot for 1000-V, 5-cm Spot Load, 5-cm Offset (meters).
Figure 6.16: Profile Summary, 5-cm Diameter Spot Load.

Figure 6.17: Z-Displacement Plot for 1000-V, 10-cm Spot Load, Centered (meters).
Figure 6.18: Z-Displacement Plot for 1000-V, 10-cm Spot Load, 5-cm Offset (meters).

Figure 6.19: Profile Summary, 10-cm Diameter Spot Load.
Figures 6.10, 6.13, 6.16 and 6.19 demonstrate the effect of spot location on displacement for a given spot diameter. The 21.8% change in the magnitude of the displacement from centered to 5-cm offset demonstrates the effects of the boundary conditions for this diameter loading. A 4.2% change is seen for the 1-cm diameter case at the same offset. The difference between the global effects of the 10-cm diameter and the local effects of the 1-cm diameter is evident.

This effect is described by Saint-Venant’s principle. Saint-Venant’s principle states that the difference between stresses caused by statically equivalent load systems is insignificant at distances greater than the largest dimension of the area over which the loads are acting. This principle applies to the current application because for distributed loads sufficiently small in area compared to the distance from the fixed boundary condition, the boundary conditions do not affect the results. Therefore, the 1-cm spot-load cases are not greatly affected by the boundary conditions until approximately 6-cm offset. However, the displacement due to the 10-cm diameter spot-load is effected greatly at the 5-cm offset.

Another interesting design parameter is the effect of spot diameter on displacement at a given location. Figures 6.20 and 6.21 plot this relationship for the 0- and 5-cm offset cases.
Figures 6.20 and 6.21 demonstrate the significant effect that spot size has on displacement for identical loading magnitude (1000-V). A maximum displacement of 6.13-µm is seen for the 1-cm centered spot-load case, whereas the 10-cm centered spot-load produces a maximum displacement of 37.2-µm. Similarly, the 1-cm spot-load with a 5-cm offset produces a maximum displacement of 5.87-µm, whereas the 10-cm spot-load with a 5-cm offset produces a maximum displacement of 29.1-µm.
6.3 Superposition of Test Cases
The linear nature of the displacements allows for cases to be superimposed on one another, allowing for compound problems to be solved. For example, in adaptive optics, the wavefront of the light is distorted as it passes through the atmosphere. In order for adaptive optics to correct the distortion, the mirror is distorted to match the wavefront profile. One example case is shown here to briefly demonstrate the ability to solve problems that require multiple loads. The test case data for four test cases are superimposed and compared to the profile of each case. The cases superimposed are as follows: 3-cm offset with 1-cm spot, 9-cm offset with 3-cm spot, -4.5-cm offset with 3-cm spot and -7.5-cm offset with 5-cm spot. All loads considered are 1000-V.

Figure 6.22: Superposition Example.
6.4 Discussion

The test cases shown demonstrate the flexibility of this modeling method. The uniform load cases prove that the mirror can be deformed significantly. This type of loading would be ideal for the design variable focal length mirrors or counteracting a uniform deformation such as strains induced due to temperature change. To apply this type of load, the electron gun would be scanned rapidly over the actuator side of the mirror.

The spot loading cases demonstrate the ability of the program to model a wide range of spot diameters and locations. These test cases range from a very localized deformation induced by a 1-cm spot load to a global deformation induced by a 10-cm spot load. The effects of the boundary conditions on the displacements are consistent with Saint-Venant's principle. Additionally, the profile summaries presented give the designer of a mirror system the tools to predict the amount of deformation for a given load and the effects of the boundary conditions for a spot diameter/location combination.

Due to the linear behavior of the results, superposition of individual cases allows for much more complex systems to be modeled. This application could be particularly useful for adaptive optics systems where the wavefront of incoming light is compensated for using deformable mirror.
CHAPTER 7
Conclusions and Future Work

7.1 Conclusions

7.1.1 Manufacture of Doubly Curved PVDF Bimorph Mirror
A dome of ordinary unpoled PVDF was poled using simple laboratory equipment. The piezoelectric constant ($d_{31}$) was measured to be $20 \times 10^{-14}$-m/V. The poled PVDF dome was then adhered to an aluminized Mylar dome of matching dimensions, creating a doubly curved mirror. A backpressure voltage lead was attached to the aluminized surface and actuation was attempted using the electron gun actuation method in a vacuum chamber. However, the piezoelectric constant was not sufficient to achieve measurable deflections with the available equipment.

Next, a PVDF bimorph mirror was formed using material poled at the manufacturer. Two pieces of mono-oriented PVDF were laminated with the 1-direction of each layer rotated 90° to one another. This lay-up allows for equal actuation in both directions. The laminate was stretched in a special machine designed to slowly form the material into a doubly curved surface.

Initially, the bimorph held its shape but would gradually lose its curvature. A possible reason for the failure is the orthotropic mechanical properties of mono-oriented PVDF. The yield stress of mono-oriented PVDF in the 1-direction is over 10 times the magnitude of the yield stress in the 2-direction. Therefore, as the 2-direction of the material failed, the 1-direction had not approached its yield point.

7.1.2 Piezoelectric Matrix Formulation and Verification
The piezoelectric stress matrix and the elastic stiffness matrix were formulated using the linear theory of piezoelectricity and the material properties of PZT-5H. A verification model was generated that showed that the transverse displacement of a PZT-5H bimorph beam was within 1% of the theoretical value, verifying the matrix calculation.
7.1.3 Finite Element Model of Composite Reflector

A unique mesh scheme was used to model a carbon fiber composite reflector with a layer of PZT-5H adhered to the back surface. The modeling method was proved to be versatile in applying centered and offset loading virtually anywhere on the reflector surface. This type of loading is intended to mimic that of an electron gun.

Uniform loading cases were also considered to show the significant deformation achieved by piezoelectric actuation. A loading of 1000-V/mm produces approximately 138-µm of displacement at the center of the mirror. This corresponds to a change in focal length useful for counteracting uniform strains such as thermal strains or for the design of variable focal length mirrors.

Spot loading cases were considered at a variety of spot diameters and offsets to demonstrate the versatility of the model and outline design parameters. The localized effects of the 1-cm spot diameter contrast the global effects of the 10-cm diameter spot. The centered 1-cm spot-load produced a 6.13-µm maximum displacement, whereas the centered 10-cm spot-load produced a 37.2-µm maximum displacement.

The effects of the boundary conditions on the various spot diameters are also examined. The magnitude of the displacements reduces greatly as the spot load is moved off-center for larger diameter spots. In contrast, displacement magnitudes of the 1-cm diameter spot were not significantly affected until approximately 6-cm offset. This effect is consistent with Saint-Venant’s principle.

Plots were generated to outline critical design parameters in similar systems. The effects of spot location and spot diameter on displacement were examined.

Additionally, it was demonstrated that due to the linear behavior of the displacements considered, superposition could be used to solve for more complex systems. This type of compound problem solving could be used for wavefront compensation in the deformable mirrors used in adaptive optics systems.
7.2 Future Work

7.2.1 Manufacture of Doubly Curved PVDF Bimorph Mirror
Future work in examining the ability to fabricate a mirror of this type is to consider copolymer PVDF. The 1-2 plane of copolymer PVDF has mechanical and electrical isotropy. These more uniform properties could lead to a successfully fabricated, very lightweight deformable mirror.

7.2.2 Finite Element Model of Composite Reflector
The next step to creating a lightweight, deformable composite reflector is to experimentally attempt actuation in a vacuum chamber with an electron gun. However, more experimental work needs to be done to understand the physics that occur when a discrete electron spot is applied to a piezoelectric material.
APPENDIX A

ANSYS Finite Element Code

! Composite/Piezo Mirror
/filename, comppiez
/prep7
/title, Composite/Piezo Mirror

! Define Loading and Boundary Conditions
zvolt=1000 ! Volts
ground=0
/input,nodenum,out, d:\home\roche\comppiezo

! Uniform loading or spot loading?
! spot=0 for uniform, spot=1 for spot loading
spot=0

! If spot=0, Center or Edge Constraints?
! BC=0 for center, BC=1 for edge
BC=0

! Composite Material Properties
theta1=60 ! 1st ply orientation (deg)
theta2=-60 ! 2nd ply orientation (deg)
theta3=0 ! 3rd ply orientation (deg)
tply=1.067e-4 ! ply thickness (m)
Y11c=181e9 ! Young's Modulus, x (Pa)
Y22c=10.3e9 ! Young's Modulus, y=z (Pa)
Y33c=Y22c
G12c=7.17e9 ! Shear Modulus, xy=xz (Pa)
G23c=5.62e8 ! Shear Modulus, yz (Pa)
G13c=G23c
pr12c=.2                                     ! Poisson's ratio
pr13c=0.016
pr23c=pr13c

! Epoxy Material Properties
tg=100e-6
Eg=3.85e8
pr12g=.3

! PZT Material Properties
e13=-13.6081  ! Piezo Constants (N/V*m)
e23=e13
e33=21.9692
e51=14.0
e42=e51
c11=7.952e10   ! Stiffness Constants (N/m^2)
c12=3.3721e10
c13=2.9254e10
c33=6.5115e10
c44=2.0049e10
c66=2.5e10
K=3150  ! Relative dielectric constant
epsilon=K*8.85e-12 ! Permittivity of PZT (F/m)

! Composite element type and material property defitions
et,1,shell99
r,1,7
rmore
rmore,1,theta1,ply, 1,theta2,ply
rmore,1,theta3,ply, 1,theta3,ply
rmore, 1, theta2, tply, 1, theta1, tply
rmore, 2, , tg
mp, ex, 1, Y11c
mp, ey, 1, Y22c
mp, ez, 1, Y22c
mp, gxy, 1, G12c
mp, gyz, 1, G23c
mp, gxz, 1, G12c
mp, prxy, 1, pr12c
mp, pry, 1, pr23c
mp, prxz, 1, pr13c

! Epoxy Material Property Definitions
mp, ex, 2, Eg
mp, prxy, 2, pr12g

shpp, modify, 1, 100

! Read in Composite Geometry
/input, composite, out, d:\home\roche\comppiezo

! PZT element type and material property definitions
et, 2, solid5
keyopt, 2, 1, 3
mp, perx, 3, epsilon
mp, pery, 3, epsilon
mp, perz, 3, epsilon

tb, piez, 3
tbmodif, 1, 3, e13
tbmodif, 2, 3, e23
tbmodif, 3, 3, e33
tbmodif, 5, 1, e51
tbmodif, 4, 2, e42

tb, anel, 3
tbdata, 1, c11, c12, c13
tbdata, 7, c11, c13
tbdata, 12, c33
tbdata, 16, c44
tbdata, 19, c44
tbdata, 21, c66

type, 2
mat, 3

! Read in PZT geometry
/input, pzt, out, d:\home\roche\comppiezo

! Boundary Conditions
*if, BC, eq, 0, then
    nsel, s,,, 1, hispot
    nsel, a,,, 3001, hispot+3000
d, all, ux, 0
d, all, uy, 0
d, all, uz, 0
allsel

    nsel, s,,, 6001, hispot+6000
d, all, ux, 0
d, all, uy, 0
d, all, uz, 0
d,all,rotx,0
d,all,roty,0
allsel

*elseif,BC,eq,1
  nsel,s,,,edge1, edge2
  nsel,a,,,edge1+3000, edge2+3000
d,all,ux,0
d,all,uy,0
d,all,uz,0
allsel

  nsel,s,,,edge1+6000, edge2+6000
d,all,roty,0
d,all,rotx,0
allsel
*endif

! Couple epoxy to the PZT
cpintf,ux,1e-8
cpintf,uy,1e-8
cpintf,uz,1e-8

! Apply Voltage loading
nsel,s,,,1,2999
d,all,volt,ground
allsel
*if, spot, eq, 0, then
    nsel, s,,, 3001, 5999
    d, all, volt, zvol
    allsel
*elseif, spot, eq, 1
    nsel, s,,, 3001, hispot+3000
    d, all, volt, zvol
    allsel
*endif

! Solve
/solu
solve

! Output nodal displacements of interest
/post1

! Output x=0 UZ to Excel File
nsel, s,,, 1, 2999
nsel, r, loc, y, 0
cm, cross1, node
/output, z1, xls, d:\home\roche\comppiezo
cmsel, s, cross1
prnsol, u, z
nlist, all,,, coord, node, node, node
/output
allsel

! Output y=0 UZ to Excel File
nsel, s,,, 1, 2999
nsel, r, loc, x, 0

cm, cross2, node
/output, z2, xls, d:\home\roche\comppiezo

! Output all nodal UZ to Excel File
nsel,s,,1,2999
cm, allnode, node
/output, disp, xls, d:\home\roche\comppiezo
cmsel, s, allnode
prnsol, uz, z
nlist, all,,, coord, node, node, node
/output
allsel
APPENDIX B
Spot Load Displacement Plots

Figure B.1: Z-Displacement Plot for 1000-V, 1-cm Spot Load, Centered (meters).

Figure B.2: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 1-cm Offset (meters).
Figure B.3: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 2-cm Offset (meters)

Figure B.4: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 3-cm Offset (meters)
Figure B.5: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 4-cm Offset (meters).

Figure B.6: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 5-cm Offset (meters).
Figure B.7: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 6-cm Offset (meters).

Figure B.8: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 7-cm Offset (meters).
Figure B.9: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 8-cm Offset (meters).

Figure B.10: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 9-cm Offset (meters).
Figure B.11: Z-Displacement Plot for 1000-V, 1-cm Spot Load, 10-cm Offset (meters).

Figure B.12: Z-Displacement Plot for 1000-V, 3-cm Spot Load, Centered (meters).
Figure B.13: Z-Displacement Plot for 1000-V, 3-cm Spot Load, 1.5-cm Offset (meters).

Figure B.14: Z-Displacement Plot for 1000-V, 3-cm Spot Load, 3-cm Offset (meters).
Figure B.15: Z-Displacement Plot for 1000-V, 3-cm Spot Load, 4.5-cm Offset (meters).

Figure B.16: Z-Displacement Plot for 1000-V, 3-cm Spot Load, 6-cm Offset (meters).
Figure B.17: Z-Displacement Plot for 1000-V, 3-cm Spot Load, 7.5-cm Offset (meters).

Figure B.18: Z-Displacement Plot for 1000-V, 3-cm Spot Load, 9-cm Offset (meters).
Figure B.19: Z-Displacement Plot for 1000-V, 5-cm Spot Load, Centered (meters).

Figure B.20: Z-Displacement Plot for 1000-V, 5-cm Spot Load, 2.5-cm Offset (meters).
Figure B.21: Z-Displacement Plot for 1000-V, 5-cm Spot Load, 5-cm Offset (meters).

Figure B.22: Z-Displacement Plot for 1000-V, 5-cm Spot Load, 7.5-cm Offset (meters).
Figure B.23: Z-Displacement Plot for 1000-V, 10-cm Spot Load, Centered (meters).

Figure B.24: Z-Displacement Plot for 1000-V, 10-cm Spot Load, 5-cm Offset (meters).
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He began his college career at the University of Kentucky in Fall of 1994, entering the Mechanical Engineering program. Michael began his participation in the Engineering Cooperative Education Program in the summer of 1996, working for two full semesters and two summer semesters at Central Manufacturing Company/Central Light Alloy. In May 1999, Michael received his Bachelor of Science in Mechanical Engineering, graduating Summa Cum Laude.

Michael worked in the Advanced Structures Lab at the University of Kentucky during the summer of 1999. He was awarded a NASA Graduate Student Researcher’s Program fellowship through Langley Research Center in July 1999 and began his graduate career in August 1999.