Numerical Simulation of Inflatable Membrane Structures

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Abstract:

Inflatable structures are effective in space applications, as they are weight, volume and cost competitive. For certain space applications, higher gains are obtained for the antennas by increasing their size. Higher gains often result in increased data throughput. These and other advantages lead to inflatable structures being considered increasingly for building large space structures. However, large inflatable structures are prone to surface errors arising from environmental factors, among others. The degradation in the performance may be reduced by active and passive control of the shape of the antennas by using appropriate sensors. In this context, piezoelectric films are used for the active and passive control. In this paper, we discuss both experimental and numerical approaches exploring piezoelectric film. In order to explore the applications of piezoelectric films, a circular diaphragm is subjected to varying pressures and displacements are measured using laser instrumentation. The effects of applying voltage on the shape of the piezoelectric film subjected to pressurization are studied. The piezoelectric film is modeled as a large displacement/large rotation geometrically nonlinear membrane undergoing small strains. This paper presents experience gained in modeling the piezoelectric film subjected to both thermal and pressure loads. The numerical results are presented in the form of graphs. The response is studied for applied steady-state temperatures for various pressurization levels. Certain thermo-structural instabilities were encountered in the modeling and the paper presents procedures used in circumventing such instabilities for the piezoelectric type of thin inflatable membranes.

Introduction:

Inflatable structures are increasingly being considered for space applications as they are lightweight and cost competitive when compared with conventional metal structures. When used as antennas in communications satellites, the inflatable structures yield high gains and high data throughput. Typical

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applications include imaging remote galaxies, detecting life on extrasolar planets, monitoring the earth using high resolution, imaging extrasolar planets, imaging active galactic nuclei, monitoring earth's environment, investigating planet subsurface, communicating optically, providing solar power in deep space, taking short time travel trips, and developing infrared astronomy [1-7, 9-11]. However, the large inflatable structures are prone to surface errors arising from environmental factors. The degradation in performance may be reduced by active and passive shape control. Piezoelectric film [9] is known to be a candidate in sensing and controlling shape errors. We present in this paper some research work performed in exploring piezoelectric film for shape sensing and control. We review some relevant literature in this area and followed by modeling a circular piezoelectric film subjected to pressure loading. A thermal loading is applied in addition to pressure loads to simulate the voltage sensitivity analysis of the piezoelectric film. The membrane is modeled as a large displacement large rotation shell finite element. An incremental nonlinear formulation is used to study the deformation under both the pressure and thermal loading. The computational results show the adequacy of the numerical modeling of the piezoelectric membrane for these types of loading. Some thermo-mechanical instability that was encountered in the modeling is discussed and procedures to work-around the instabilities are also presented.

Experimental Model:

In Figure 1 the experimental set up for investigating the behavior of the piezoelectric membrane is shown. The Piezoelectric membrane is made of polyvinylidene fluoride (PVDF or Kynar, [5]) and is clamped on to a polyvinyl chloride (PVC) drum. Also visible in the figure is the displacement measurement laser system. A tank of pressurized nitrogen gas, a low pressure air regulator, a voltage source and computer interface used for taking measurements (d-Space), an amplifier, copper tape, a low current power source, and an oscilloscope constitute the rest of the experimental set up.

Finite Element Model:

In order to validate the tools available to model the PVDF membrane, MSC/NASTRAN software was selected. The software capabilities had to include modeling large displacements and large rotations of thin shells subjected to both thermal and pressure loading. The behavior of piezoelectric membrane to the application of electric field is to either enlarge or contract. In the experiment that was conducted and discussed as a separate paper elsewhere in this conference, the electric field was generated by the application of voltage to the surface of the PVDF membrane which is coated with a thin layer of Ni-Cu alloy on both sides.

In anticipation of the displacements to be of several orders of magnitude larger than the membrane thickness (t=0.002047 in.), the membrane is modeled as a thin shell with large displacement and large rotations included. The exposed diameter of the membrane is 8.5 in. after 24 bolts are used to clamp around the circumferential direction on to the lip of the drum. An incremental nonlinear finite element option is selected for the analysis. The effect of the electric field on the piezoelectric film is accomplished by the application of the voltages on either side of the membrane. Using the thermal analogy in analyzing the behavior of the membrane simulates this voltage effect. The thermal analogy converts the piezo strain constant into an equivalent thermal expansion coefficient as follows:

$$\alpha_{eq} = d / t_{piezo}$$

where, d is the piezo strain constant, and t is the thickness of the membrane.

Accordingly, the voltage effects are transformed by means of an equivalent thermal loading applied onto the PVDF membrane. By computing an equivalent thermal expansion coefficient and appropriate temperatures to be applied on to the PVDF membrane, the effects of applying an electric field on to the PVDF membrane is simulated in the numerical modeling of the behavior of the membrane.

It may be noted that applying a negative or a positive temperature field constitutes reversing the polarity of the applied voltage on to the PVDF membrane. The finite element model was generated using MSC/PATRAN software. Several mesh sizes were tried and final mesh selected for further analysis contained 216 nonlinear shell elements. Figure 2 shows the finite element model of the circular PVDF membrane.

The material and other geometric data are as follows:

Average Young's Modulus of Elasticity, E = 537,500 psi (This value as supplied by the manufacturer, Measurements Specialities, Inc, ranges from 290,000 psi to 570,000 psi for a membrane thickness of 0.002047 in., [5])

Thermal Expansion Coefficient, α_{eq} = 2.498E-7 ^{0}F in/in

The voltages applied to the membrane were converted into equivalent temperatures. These temperatures were applied to the membrane in a sequential manner. The program allows an arbitrary number of steps to be prescribed for each of the temperature increments. In the present analysis, 20 incremental steps were used for each temperature increment. In other words, 20 incremental steps are used to reach each temperature increment and nonlinear finite element matrices are computed and stored for these steps. This step size seems to adequately work well in terms of achieving convergence in the equilibrium equations.

It may be noted that a singularity was encountered in the stiffness generation of the analysis when thermal loading was applied. Later it was observed that the thermal loading introduced local instabilities of the membranes and hence analysis could not proceed further. However, this was overcome by applying a small pressure loading prior to the application of the thermal loads. This process eliminated the thermal instability and reasonable results were obtained for subsequent computations.

The PVDF membrane was subjected to a pressure loading varying from 0.1 psi to 1.0 psi in increments of 0.1 psi. For each of this pressure loading, a thermal loading corresponding to a voltage range of 0 – 850 Volts was applied and the deformation behavior computed.

Figure 3 depicts the experimental maximum transverse displacement response of the piezo membrane. The membrane was first subjected to a pressure loading of 0.1 psi and then the voltage was gradually varied. Figure 4 shows the response obtained at a pressure setting of 0.7 psi.

The maximum transverse displacements of the PVDF membrane is shown in are shown in the Figures 5 –10. In Figure 5, the displacement is plotted as a function of the transverse pressure loading. Present results are compared with Ref [8] and experimental readings. All the three values agree for a pressure loading of 0.1 psi. As the pressure in increased, the present model seems to be closer to the experimental values than the Ref [8] results. However, the experimental resolution for the present setup has some severe limitations as reported in Ref [12]. To that extent, the numerical model seems to reasonably represent the PVDF membrane.

In order to study the effect of the shape control aspects of the PVDF membrane, a systematic application of the thermal loading at each of the pressure setting is carried out. The response of the membrane under different voltage settings at 0.1 psi loading is given in Figure 6. In Figure 7, the results are presented with same parameters but with negative voltage applied on the surface facing the measuring device. This comparison is given to bring out the importance of applying the right polarity of voltage to the piezoelectric film to control the shape of the surface. In Figures 8, 9, and 10 the results of the maximum displacements of the membrane are given at pressure settings of 0.3 psi, 0.5psi., and 0.7 psi respectively.

Conclusions:

In this paper we report some numerical simulation of piezoelectric membranes. The response of polyvinylidene fluoride (PVDF) piezoelectric membranes subjected to pressure and thermal loading is presented. The inflated membranes are modeled as large displacement and large rotation shell elements and a nonlinear incremental finite element analysis using MSC/NASTRAN is performed. Thermal instabilities are encountered when only temperature loading is present and is overcome by applying a small mechanical loading. The results agree with the experimental values obtained for the configuration considered. Simulation results are presented for a combination of pressure and thermal loading (voltage variation), thereby validating the usefulness of the analysis tools.

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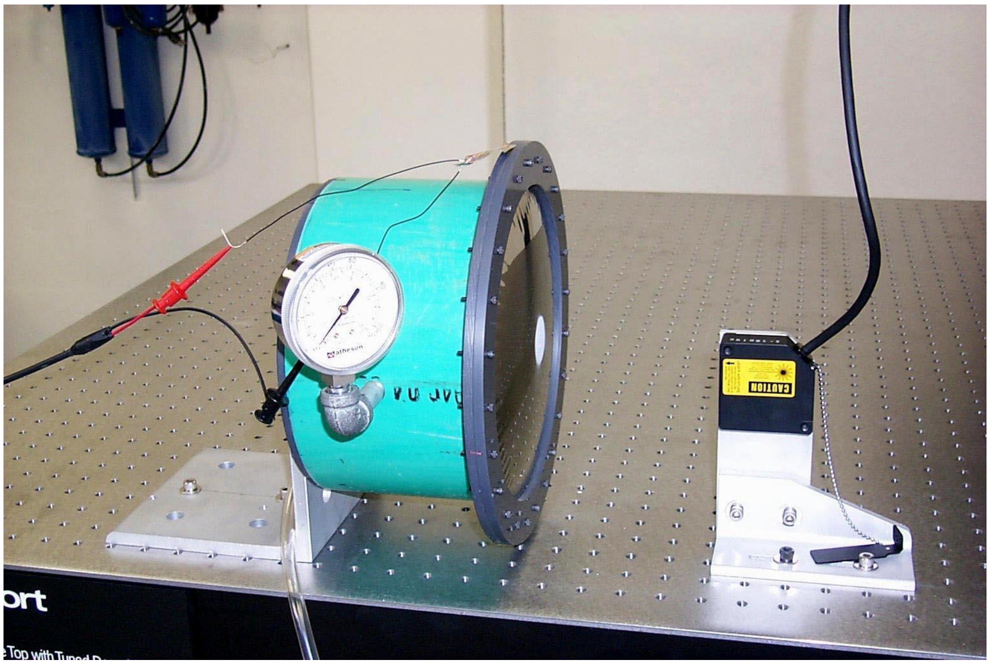

Figure 1. Experimental setup: Piezoelectric Membrane clamped on a PVC drum pressurized with Nitrogen. A Laser system measures transverse displacement

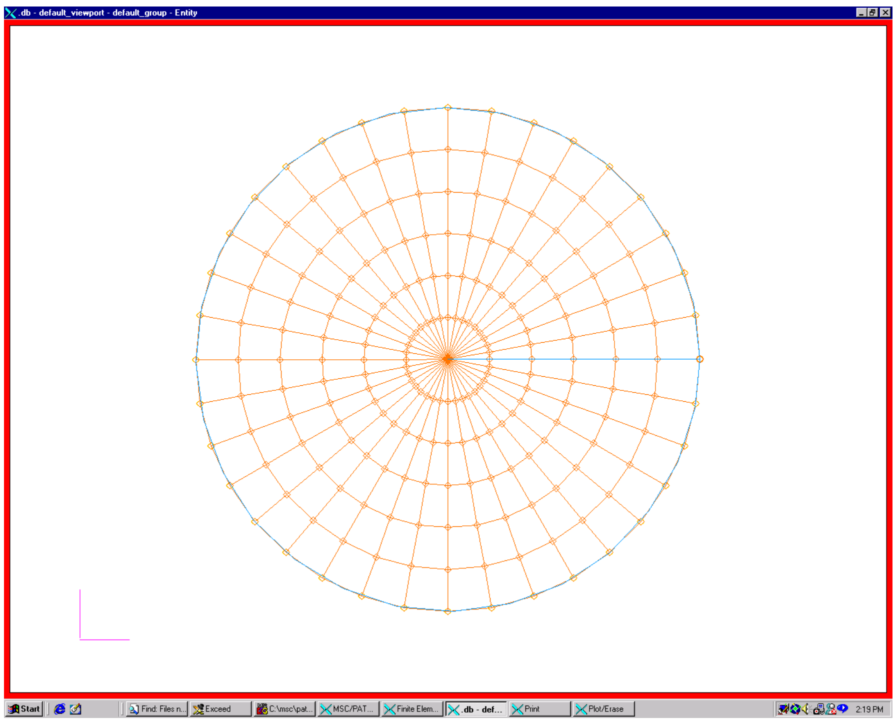

Figure 2. Finite Element Model of the Piezoelectric Film- 8.5 in diameter Clamped Circular Membrane; 216 Shell Elements; t=0.002047 in.; E=537,500.0 psi;$\alpha = 2.498E\text{-}7$

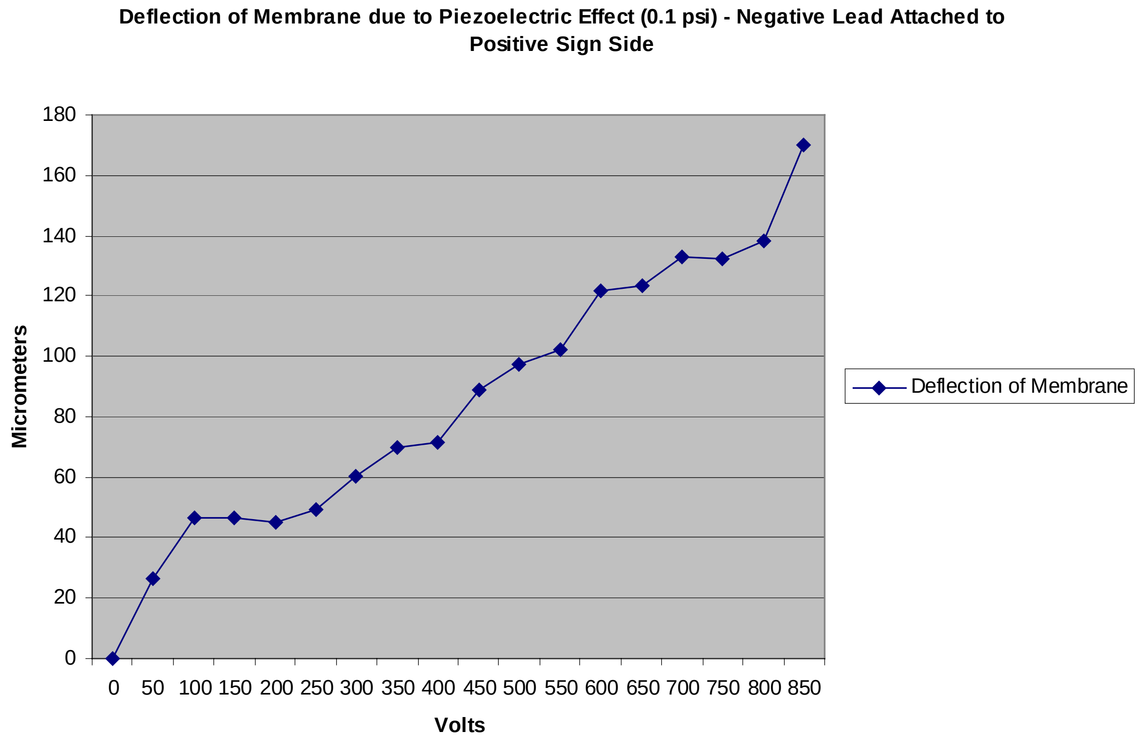

Figure 3. Response of the piezoelectric membrane to 0.1-psi pressure to applied voltage

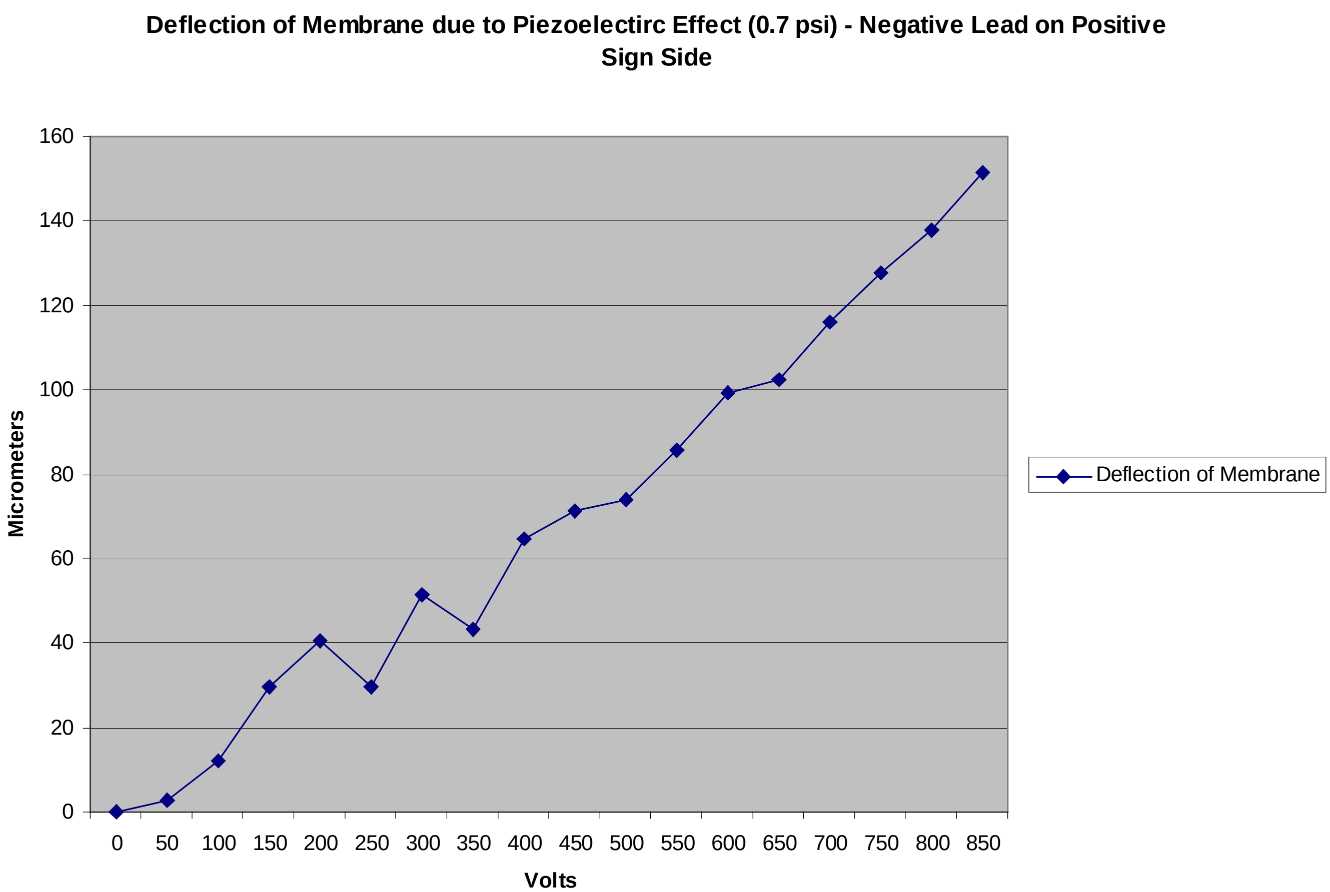

Figure 4. Response of the piezoelectric membrane to 0.7-psi pressure to applied voltage

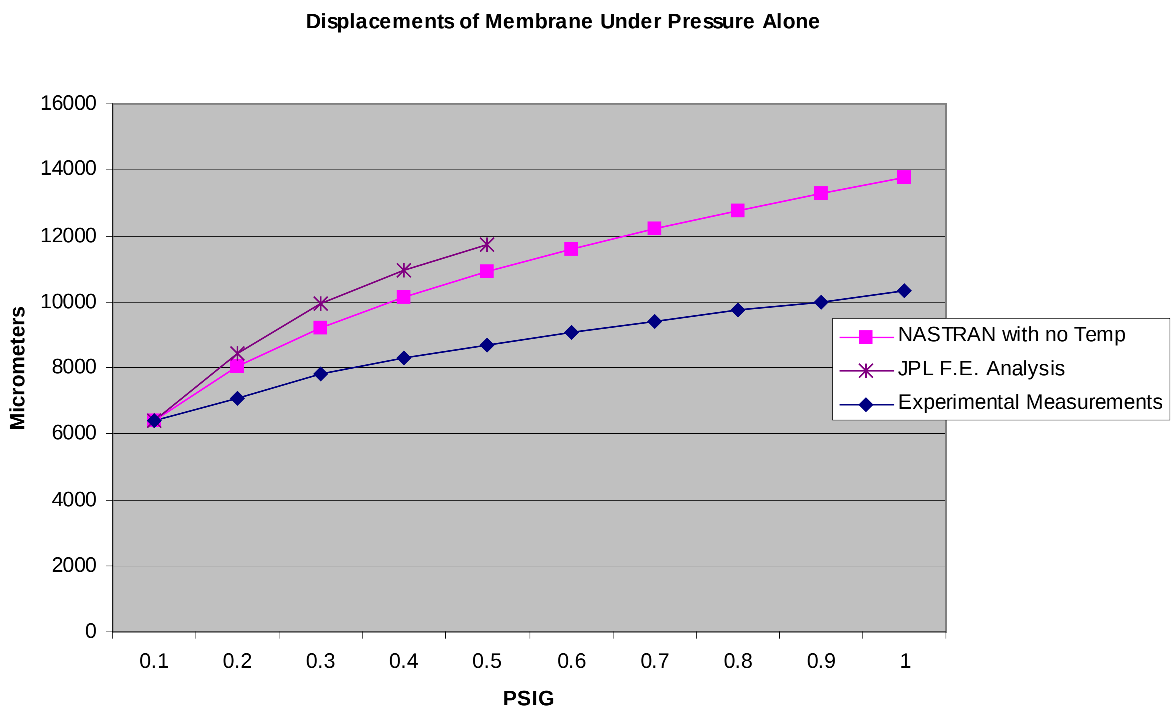

Figure 5. Load Displacement Behavior of the Circular Membrane under Transverse Pressure Loadings

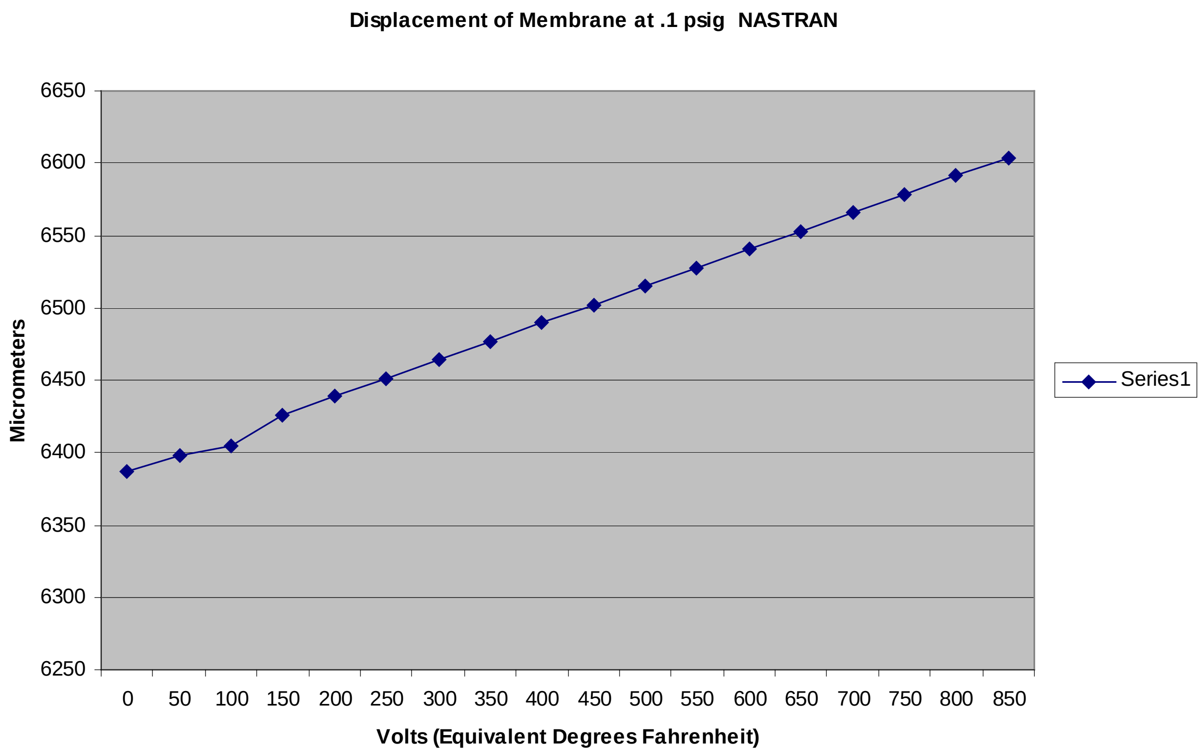

Figure 6.Response of the Piezoelectric Film as a Function of Positive Voltage (Thermal Loading) under 0.1 psi Transverse Pressure Loading

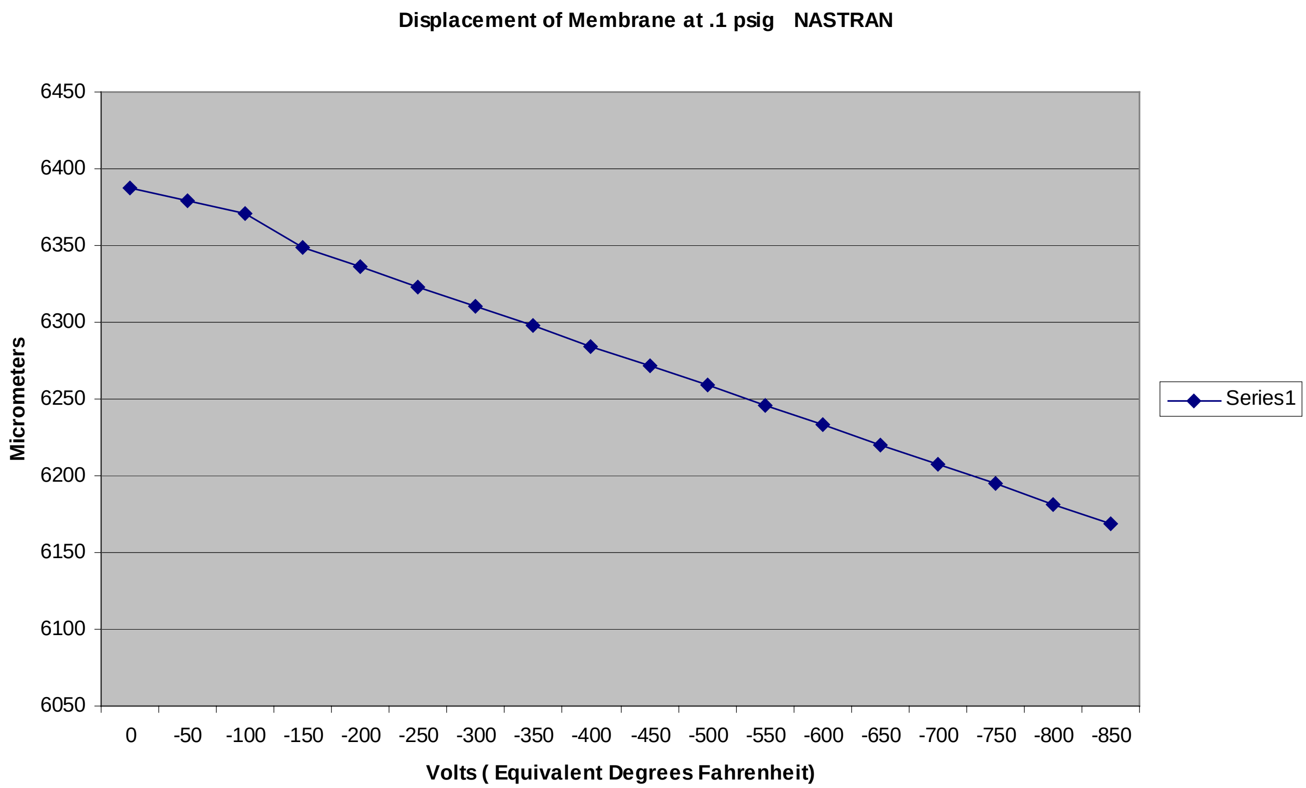

Figure 7.Response of the Piezoelectric Film as a Function of NegativeVoltage (Thermal Loading) under 0.1 psi Transverse Pressure Loading

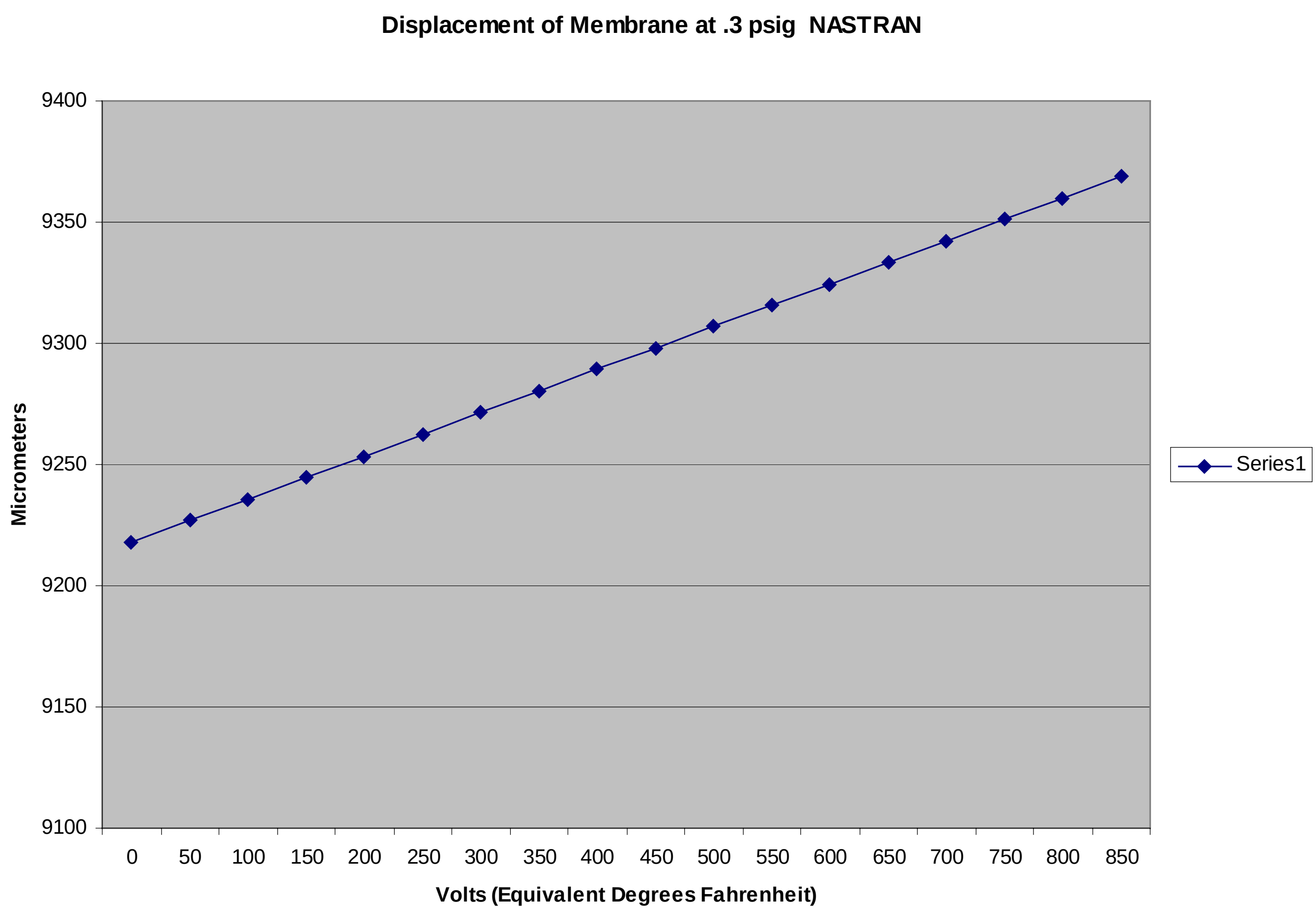

Figure 8.Response of the Piezoelectric Film as a Function of Voltage (Thermal Loading) under 0.3 psi Transverse Pressure Loading

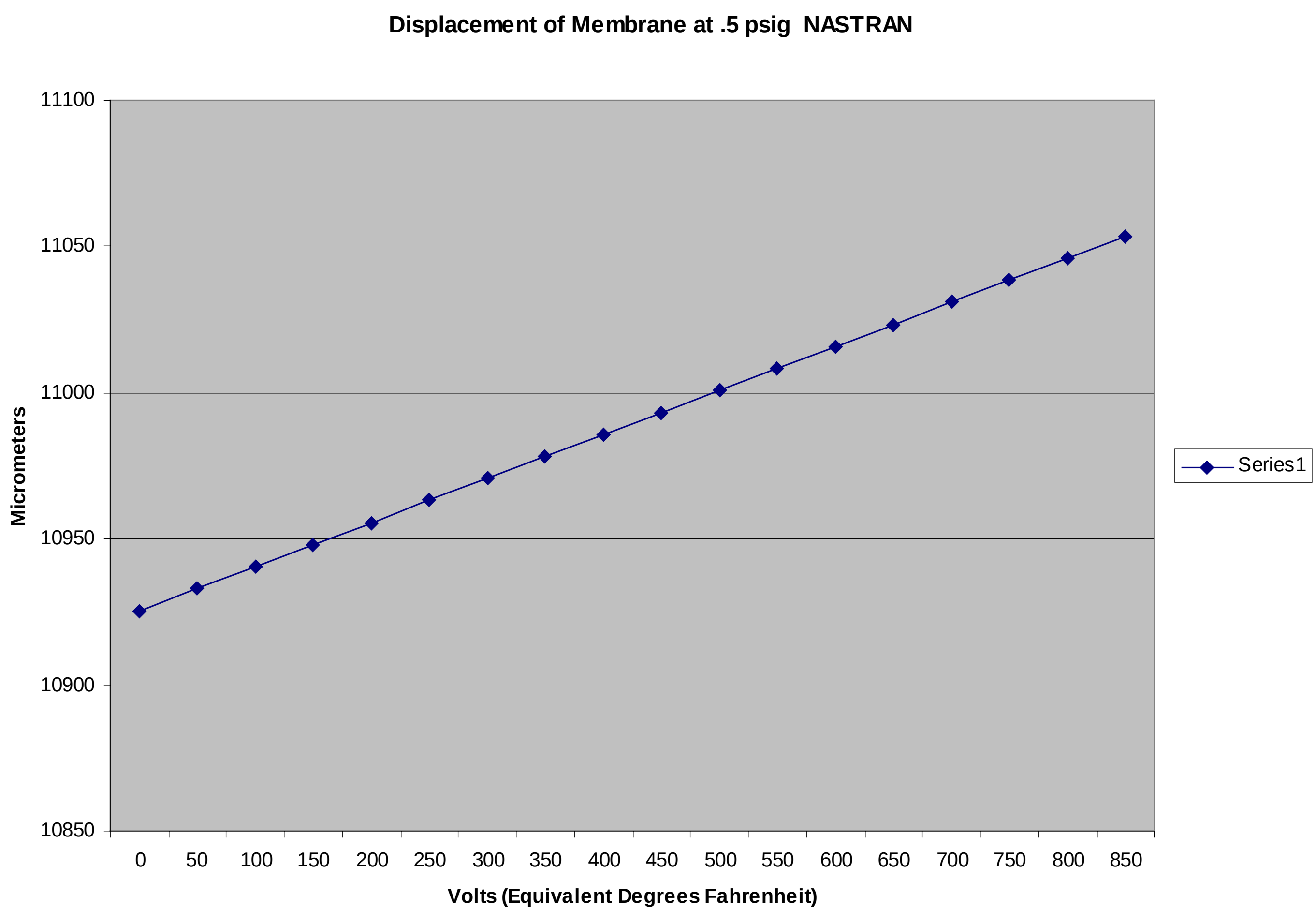

Figure 9.Response of the Piezoelectric Film as a Function of Voltage (Thermal Loading) under 0.5 psi Transverse Pressure Loading

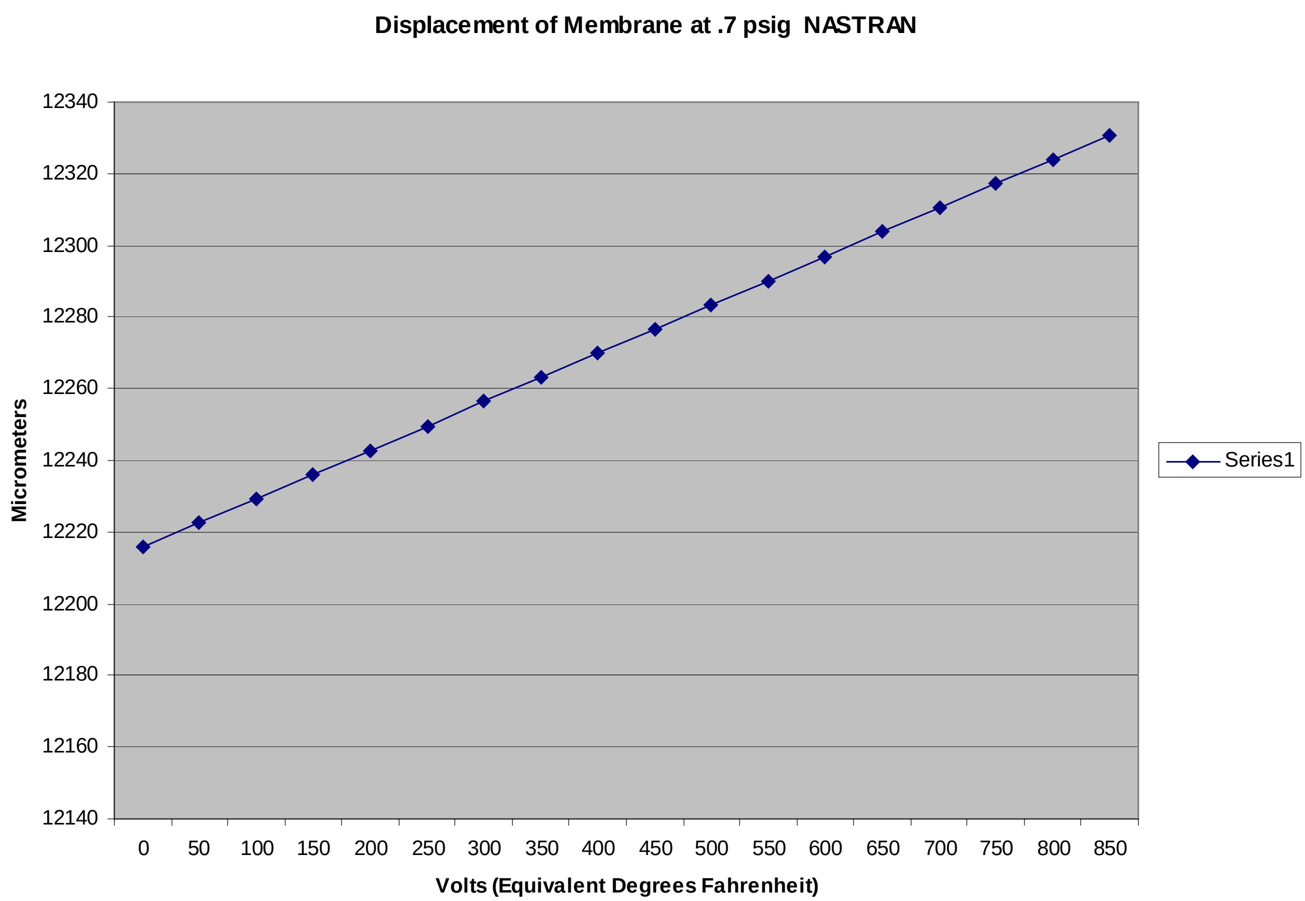

Figure 10.Response of the Piezoelectric Film as a Function of Voltage (Thermal Loading) under 0.7 psi Transverse Pressure Loading