

Wirelessly controllable inflated electroactive polymer (EAP) reflectors

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ABSTRACT

Inflatable membrane reflectors are attractive for deployable, large aperture, lightweight optical and microwave systems in micro-gravity space environment. However, any fabrication flaw or temperature variation may result in significant aberration of the surface. Even for a perfectly fabricated inflatable membrane mirror with uniform thickness, theory shows it will form a Hencky curve surface but a desired parabolic or spherical surface. Precision control of the surface shape of extremely flexible membrane structures is a critical challenge for the success of this technology. Wirelessly controllable inflated reflectors made of electroactive polymers (EAP) are proposed in this paper. A finite element model was configured to predict the behavior of the inflatable EAP membranes under pre-strains, pressures and distributed electric charges on the surface. To explore the controllability of the inflatable EAP reflectors, an iteration algorithm was developed to find the required electric actuation for correcting the aberration of the Hencky curve to the desired parabolic curve. The correction capability of the reflectors with available EAP materials was explored numerically and is presented in this paper.

Keyword: Electroactive polymer, EAP, inflatable membrane mirror, thin film antenna, controllable reflector,

1. INTRODUCTION

Inflatable membrane reflectors i.e. visible or infrared optical mirrors, electromagnetic wave antennas, are attractive for large-apertures optical and microwave systems operating in micro-gravity space because the features of ultra-lightweight and deploy capability. Inflated membrane reflectors usually consist of two circular membranes that are sealed on their edges, attached to a tensioning ring and inflated to a pressure to produce the desired curved surface. Such inflated reflectors have been used for various applications wherein low imaging acuity is sufficient. The main problem to prevent the reflector applied to high quality imaging system is the difficulty to control their shape to the desired paraboloids or spherical. Even for a perfectly fabricated uniform membrane, inflation will generate a surface with a profile of so called Hencky curve [Marker et al 1998]. The aberration of the Hencky curve from the parabolic is termed "W-curve" following its shape. Although the aberration can be reduced by increase the pre-strain in the membrane, the effect is limited. An example of the aberration is shown in Fig. 11 and 12 where half of the W-curve, from center to the edge, is presented. The maximum value is ~6mm for a 2-m diameter, 1.25-m focal length, 1% pre-strained inflated reflector. Precision control of the surface shape of extremely flexible membrane structures is a critical challenge for the success of this technology [Jenkins et al 1998, Wangneret al 2000, Martin et al 2000, Dimkov et al 2000]. It requires matched soft actuation materials. Electroactive polymers (EAP) are one of potential candidates of the actuation materials [Bar-Cohen (ed.) 2001]. The material is soft and usually fabricated in form of thin film. Using the EAP to fabricate the membrane will provide needed controllability to the reflectors.

The EAP materials can be categorized to two main classes. One is the ionic EAP [Onishi et al 2000, Bao et al 2002]. The ionic EAP's contain electrolyte in a polymer frame. They show large bending deformation at low voltage excitation. However, the actuation mechanism of these materials involves transport of ions and molecules from one side to the other of the film. The component and properties of the electrolyte have to be maintained well to keep the performance stable. This type EAP may not be a good candidate for space application due to the volatility of the electrolyte. Another class is electric field EAP [Costen et al 2001, Cheng et al 2001, Zhang et al 2002, Bao et al 2004]. It includes piezoelectric, electrostrictive, ferroelectric or dielectric polymers. These materials behave like capacitors under excitation voltages and the strain is usually proportional to the square of the applied voltage. Although they require relative high voltage ($10 \sim 100\text{V}/\mu\text{m}$) to create maximum strain, these polymers are dry and have relatively

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stable performances. The study presented in this paper focuses on electric field EAP's. The strain of these EAP's can be as high as several to ten percents. An example is a P(VDF-TrFE)-based Co/Ter-polymer having a maximum transverse strain of ~4% [Cheng et al 2001].

In a previously published paper [Bao et al, 2003], we propose a reflector made of a single-layer EAP and electrically controlled by electron scanning beam. The concept reflector is illustrated in Fig. 1. The back surface could be electrode-less to allow a continuous voltage distribution for smooth control. Polymers can hold charge on their surface due to the high surface and bulk resistivity. This property is illustrated in the drum of laser printers where the charge is maintained to reproduce the image. However, it is still expected that the charge will decay slowly due to the limited resistivity of the polymer. An EAP with relatively large resistivity will be selected to reduce the discharge rate and the electron gun will re-scan the surface to compensate the charge loss.

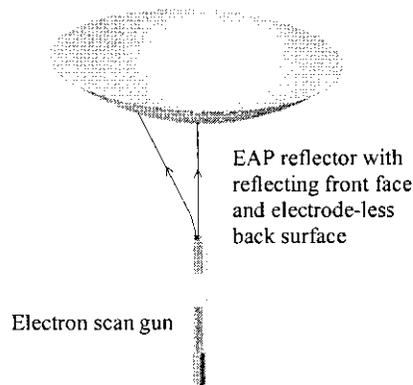


Fig. 1 The concept of a wirelessly controllable EAP mirror

We also suggested a shape control method based on the effect of electrically introducing un-uniform extension in the EAP and numerically proved that a distributed voltage can form a parabolic mirror of $f/0.625$ from an initially planar EAP membrane.

In order to control the reflector to the required precision, a close-loop control system including a sensor to detect the shape of the reflector, an adaptive controller and the controllable reflector outlined above is required. The adaptive controller can tolerate the performance variation of the elements in the loop. The control precision of such a system will, for the most degree, depend on the precision of the sensor. A controllable secondary reflector or lens may be added to the observation system to compensate remaining errors of the main reflector.

In this paper, the controllability of the EAP in inflatable reflectors is investigated. A numerical iteration algorithm was developed to find the control voltage distribution for desired shape. The effort is focused on the correction of the aberration of the Hencky curve to the parabolic curve.

2. CONTROL THE ABERRATION OF INFLATED REFLECTORS BY EAP ACTUATION

A numerical iteration algorithm was developed to find the needed electrical actuation to correct the aberration. When the inflatable reflectors made of EAP, voltage applied to a certain area will intend to expand the area and help the pressure to move the area and the surrounding area near further in the pressure direction. The iteration algorithm is based on this physical understanding. We calculate the aberration of the membrane from the desired surface first and,

then, add a small electrical voltage with a distribution proportional to the aberration to the EAP membrane in each step. Then, we recalculate the aberration and iterate the procedure. A flowchart of the iteration is shown in Fig. 2.

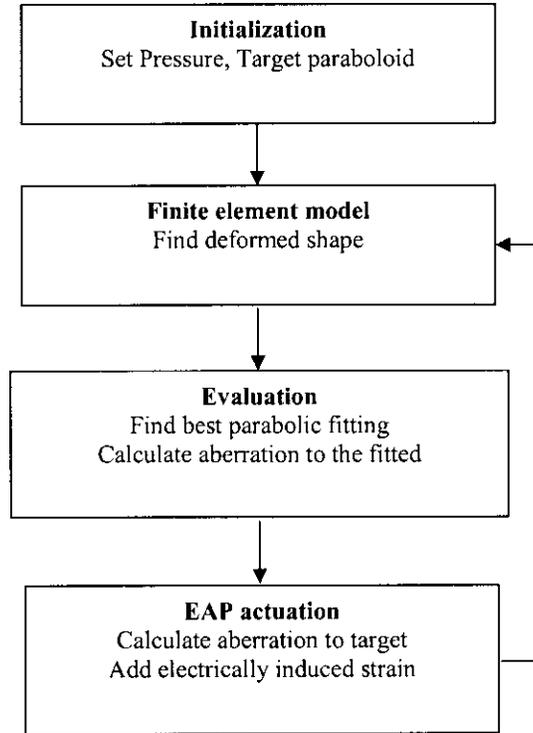


Fig. 2 Flowchart of the numerical iteration algorithm

A finite element software package ANSYS was used to calculate the shape of the membranes under the pressure, applied electrical voltage on EAP and possible pre-strain. The geometry and material properties of the membrane used in the computation are listed in Table 1. The planar films were expressed by 100 shell elements (Shell-151, ANSYS). The element describes the shell and a surface. Therefore the deformation of the surface of the membrane due to the thickness change is not taken in account. The deformation is in the range of a few micrometers for the 10 μm thick membrane. This error can be compensated if high accuracy is required. The extension strain/stress created by the electric voltage on the EAP membrane was simulated by thermal expansion by set proper material thermal coefficient and corresponding temperature change. "Large Deflection" function of the ANSYS was activated to take the geometry nonlinear effect into account.

Table 1. Parameters used in computation

| Diameter (m) | Thickness (μm) | E (Gpa) | Poisson's ratio σ |
|--------------|-----------------------------|---------|--------------------------|
| 2 | 10 | 1 | 0.3 |

The algorithm was first verified by the case for which analytical solution is available [Bao et al 2003]. It is to form a parabolic reflector from a planar EAP membrane purely by electric actuation with no pressure. The results are shown in Fig. 3-6. Figure 3 shows the analytical solution of the needed electrical strain to curve the membrane and the Fig. 4 is the aberration of the computed shape from the best fitted parabolic curve. The parabolic curve was in the form of

$$z = ar^2 + b.$$

and the coefficients a and b were found by a least square curve fitting method. This aberration in the level of several micrometers is caused by the limitation of the accuracy of the finite element modal, i.e. limited element number, converging error in large deflection calculation etc. Fig. 5 and 6 present the corresponding results found by the iteration algorithm. The number of iterations was 50. The aberration obtained by the iteration algorithm is in the same range as the finite element result based on the analytical solution. It was concluded that the iteration algorithm worked well for this case.

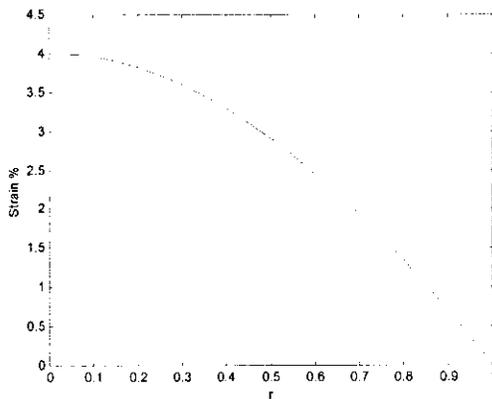


Fig. 3 Analytical solution of required strain distribution for $z = 0.2r^2$ membrane reflector

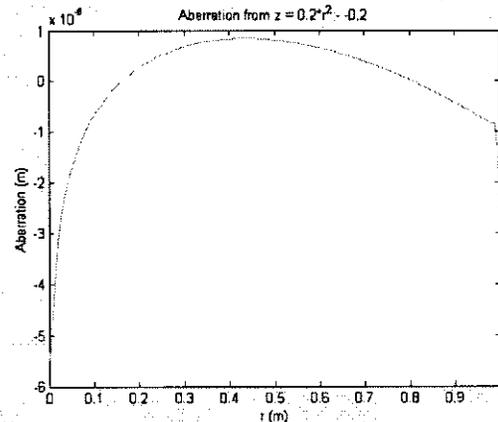


Fig. 4 Aberration of the membrane shape computed by FE using analytical solution to the best fitted parabolic curve.

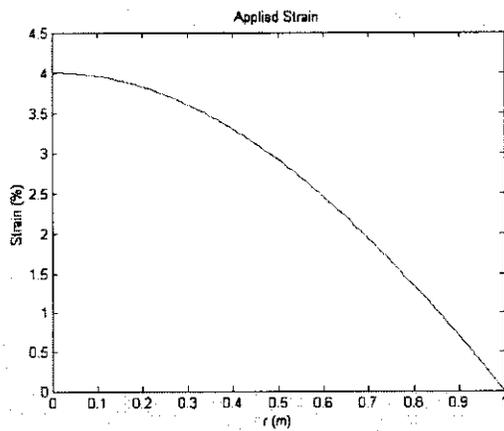


Fig. 5 Numerical solution of required strain distribution for $z = 0.2r^2$ membrane reflector by iteration algorithm.

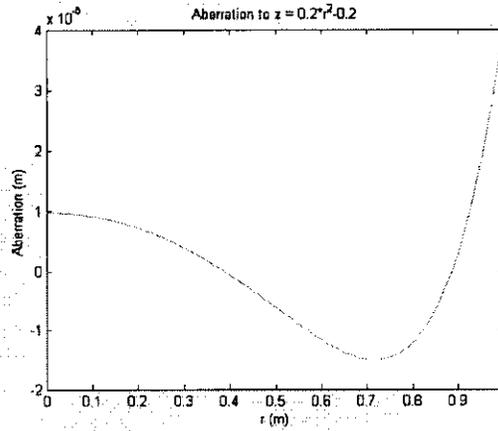


Fig. 6 Aberration of the membrane shape computed by FE using the numerical solution of the iteration algorithm to the best fitted parabolic.

The algorithm was applied to inflatable EAP membranes. We set a paraboloid surface as a target to be approached. The computation started with a pressure P under which the deformation of the membrane is less than the target parabolic curve. We looked for the needed electrical actuation using the algorithm. However, in the iteration the added electrically induced strains at the edge are always zero because that both the target surface and the calculated membrane are fixed at

the edge. For the previous verification case, the zero is just the right solution at the edge occasionally as the analytical solution showed. However, it may not be correct when the pressure is applied. To overcome the problem, modifications of the algorithm are needed. Trial computation showed that the required strain was jumped at the edge because the algorithm constrains the application of the electrically induced strain at the edge. A reasonable guess is the strain should be extended to the edge. We found the required strains are always going down in the area near the edge. A modification was made as to set the strain in the zone outside of the minimum strain ring to be the minimum value.

The iteration may lead to negative required strains in some area. Negative strains mean to shrink the membrane but the EAP actuation is always to extend the area. To overcome the difficulty, a pre-strain in the membrane by stretching the membrane is needed. The pre-strain can be set to equal to the minimum of the required strain found by the iterations. After adding the pre-strain, the required electrically induced strains become all positive or zero.

Several different cases were computed. Results of an example are shown in the Fig. 7-10. The target profile of the parabolic surface was set as $z = 0.2r^2 - 0.2$ and the diameter was 2 m. The pressure applied was 1000 Pa. In the iteration, we monitored the maximum aberrations of the whole surface and that of the area within 0.9 of the diameter. After 950 iterations, the aberration was converged to a few micrometers as shown in Fig. 7. The remaining aberration is within the range of computation errors. An improvement of the computing accuracy may improve the results. As is shown in Fig. 9 and the enlarged curve in Fig. 10, the large aberration is located in the narrow rings near the edge and the center. The aberration in most area is much smaller, less than 0.1 μm . Shadowing the ring areas or coating them with absorbing layers should greatly improve the quality of the reflector. This result proves that, in principle, the Henkey-curve aberration of the inflatable reflectors can be corrected electrically when the reflectors are made of EAP membranes.

The required electrically induced strain is -1.06% at the edge as is shown in Fig. 8. It means a 1.06% pre-strain is needed to shift the required electrically induced strain to all positive. With the pre-strain, the maximum of the required electrically induced strain is 4.4%. It is actually a little higher than the required 4% for form the same paraboloid surface without inflation pressure (see Fig. 3-6). The benefit of the inflated reflectors is the applied pressure will make the reflectors more rigid and stable.

For comparison, the aberration of a reflector with the same parameters but without EAP actuation control was computed. The reflector has the same geometry and pre-strain. The pressure was adjusted to 3900 Pa and resulted in a curved profile having a best fitting of $z = 0.1961r^2 - 0.2026$, which is close to the target profile. The result is presented in Fig. 11 and 12. The maximum aberration is more than 6 mm, which is much larger than the controlled EAP membrane and not acceptable for most imaging system.

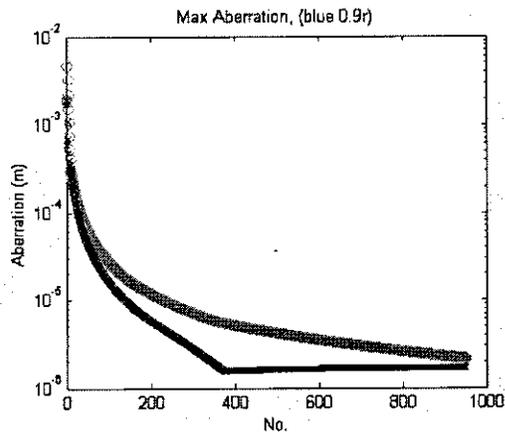


Fig. 7 The maximum aberration of the computed membrane shape vs. iteration number. Up line is that on whole surface, the low line is that within $r = 0.9$ m.

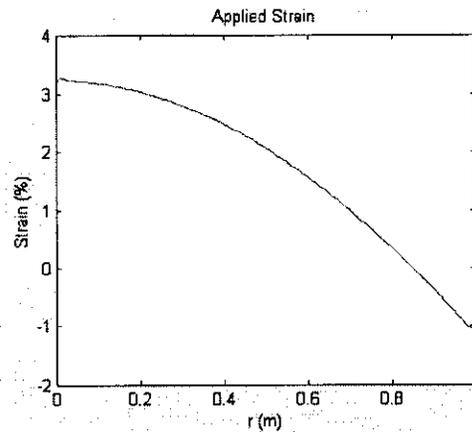


Fig. 8 The required electrically-induced strain computed by numerical iteration for aberration correction.

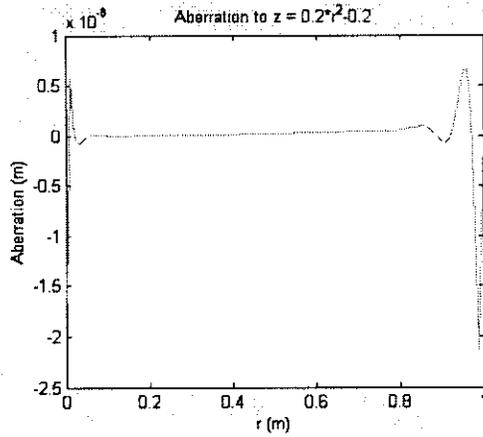


Fig. 9 The computed remaining aberration of the membrane after applying control actuation

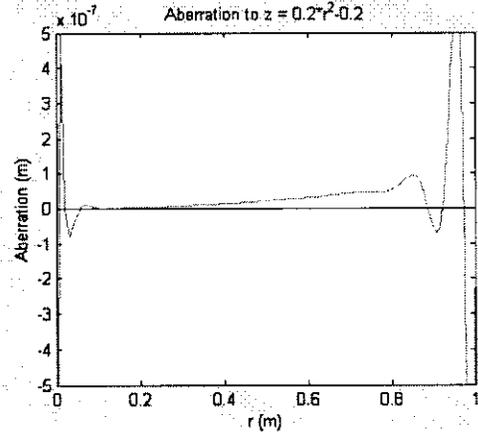


Fig. 10 Enlarged remaining aberration of the membrane after applying control actuation

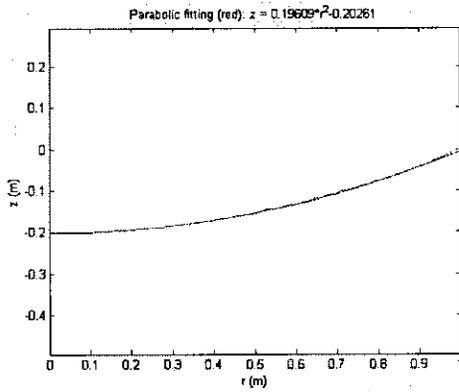


Fig. 11 The computed membrane (gray) with 1.06% pre-strain under applied pressure of 3900 Pa and the best fitted parabolic curve (black).

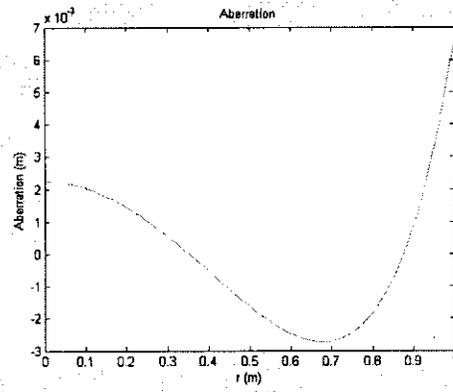


Fig. 12 The aberration of the membrane with 1.06% pre-strain under applied pressure of 3900 Pa to the best fitted parabolic curve.

3. CONCLUSIONS

Controllable inflatable reflectors made of single-layer EAP membrane were proposed. Applying a distributed voltage to the backside of the EAP reflector can control the shape of the reflector. The voltage may be applied wirelessly by using electron beam.

An iteration algorithm was developed to find the required electric actuation required for obtaining desired surface shape. The algorithm was applied to aberration correction of inflatable reflectors. Computed results show that the proposed EAP membrane reflector is able to change the profile of the inflated membranes to the desired parabolic curve electrically.

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