SOME ISSUES IN THE DESIGN & DEVELOPMENT OF FUTURISTIC MECHANICALLY ACTIVE ANTENNA REFLECTORS USING PZT PATCHES

B. S. Munjal*  PVBAS Sarma#

*Head, Structural & Thermal Analysis Division (STAD)
Structural & Thermal Analysis Group (STAG)

#Scientist/Engineer G
Mechanical Engineering Systems Area(MESA)
Space Applications Centre, ISRO, Ahmedabad 380015
Email: *bsmamsd@sac.isro.gov.in, Phone: 079-2691 3948 / 3991 (O)

Abstract- This paper elaborates some typical potential issues faced during the entire process of design, analysis and fabrication of a mechanically active parabolic antenna reflector made up of metalized Polycarbonate material by using limited number of piezoceramic actuators (PZTs) on the skin of the reflector for micro level shape corrections. An innovative approach of piezo patches on the rear backup structure of the reflector is also proposed for possible solution & application in the futuristic Reconfigurable spacecraft reflectors for ISRO missions. Finite Element (FE) modeling to start with, has been carried out for a 450 mm diameter parabolic shell surface with piezoelectric actuators using ATILA, a FE software for modeling structures with smart materials and structural systems. Finally, a 700 mm diameter metalized Polycarbonate reflector with piezoceramic Unimorphs has been developed from the point of view of reflector shape deformation investigation under electric field. Attempt is also being made to investigate the Lower Zernike modes for achieving the right inward/outward displacements of the reflector skin at the periphery for few master points w.r.t the 2X2 or 3X3 grids presently. This bending of the reflector skin has potential applications in antenna beam shaping and beam steering in reconfigurable antenna reflectors required for India coverage (IC) to Extended Coverage (EC) for futuristic Indian space missions. This concept may also prove to be useful for shape correction of futuristic spacecraft antenna reflectors for thermal distortions etc.

Issues of not achieving the objective through piezo approach are also highlighted and an alternative approach is envisaged through Shape Memory Alloy (SMA) approach.

1.0 NOMENCLATURE
\{T\} = stress vector
\{D\} = electric flux density vector
\{S\} = strain vector
\{E\} = electric field vector (referred to as \{f\})
\{e\} = piezoelectric matrix
\{E\} = dielectric matrix
( evaluated at constant mechanical strain)
\[C\] = elasticity matrix
\[K\] = Structural stiffness matrix
\[K^e\] = Dielectric Conductivity matrix
\[K^\alpha\] = Piezoelectric coupling matrix
\text{F} = Focal length of the parabolic reflector
\text{D} = Diameter of the parabolic reflector

2.0 INTRODUCTION
Piezoelectric actuation has already been studied by various researchers on wide gamut of structural systems viz, beams plates and shells [1-15]. Recently, it has also been demonstrated by Fukashi Andoh[1] that the aperture antenna can have their performance enhanced by employing shape control on the antenna surface. Some researchers like Gregory Washington, et al[1-2], have studied the Polyvinylidene Fluoride (PVDF) material and observed the far field radiation pattern. They have also studied the radiation modes w.r.t the vibration modes. Gregory Washington, has highlighted the use of Piezo ceramic actuators (PZT) and found them to be more robust in the application domains of aperture
antennae[2]. Experiments have also been conducted in the domain of PZTs and have been highlighted that the, analytical model provides a reasonable prediction of actuator performance at low input voltage but does not account for the nonlinear behavior of piezoceramic. Ganguli et al. [3] has worked on cantilevers and Robert E Newnham has worked in the domain of Thunder actuators / Power Pack actuators in lieu of Unimorphs / Bimorphs, for studying beam shaping in the domain of reflector surfaces. B S Munjal et al [7-15] has worked in the domain of Piezo ceramic powders in the passive vibration domain and shape investigations of parabolic reflectors. This paper shows the FE modeling details and illustrates experimental work on a 450 mm diameter Aluminum parabolic shell surface (Prime Focal type antenna) & 700 mm Polycarbonate shell with piezoelectric actuators using ATILA, a Finite Element software for modeling structures with smart materials and structural systems.

### 3.0 CONSTITUTIVE EQUATIONS

In this investigation, an attempt has been made to simplify & study the complex static shape displacement problems of parabolic antenna reflectors by using limited number of discrete piezoceramic actuators by assuming a linear material behavior.

The electromechanical constitutive equations (1) to (8) for linear material behavior are as follows:

\[
\{T\} = \{C\} \{S\} - \{e\} \{E\} \quad (1)
\]

\[
\{D\} = \{e\}^T \{S\} + \{E\} \{E\} \quad (2)
\]

or equivalently,

\[
\begin{bmatrix}
\{T\} \\
\{D\}
\end{bmatrix} =
\begin{bmatrix}
\{C\} & \{e\} \\
\{e\}^T & -\{E\}
\end{bmatrix}
\begin{bmatrix}
\{S\} \\
\{E\}
\end{bmatrix}
\]

The following equations provide constitutive equations for structural and electrical fields, respectively:

**Structural Elastic matrix in displacement domain:**

\[
[K] = \int_\text{vol} \{B_u\}^T \{C\} \{B_u\} \ d(\text{vol})
\]

**Dielectric Conductivity:**

\[
[K_d] = -\int_\text{vol} \{B_v\}^T \{E\} \{B_v\} \ d(\text{vol})
\]

**Piezoelectric coupling matrix:**

\[
[K'] = \int_\text{vol} \{B_u\}^T \{e\} \{B_v\} \ d(\text{vol})
\]

**Structural load vector:**

\[
\{F\} = \text{vector of nodal forces, surface forces, and body forces}
\]

**Electrical load vector:**

\[
\{L\} = \{L^{\text{nd}}\} = \text{applied nodal charge vector}
\]

**Elastic energy**, where \(u\) is displacement vector:

\[
U_E = \frac{1}{2} \{u\}^T \{K\} \{u\}
\]

**Dielectric energy**, where \(V\) is Voltage vector:

\[
U_D = \frac{1}{2} \{V\}^T \{K_d\} \{V\}
\]

**Electromechanical coupling energy:**

\[
U_M = \frac{1}{4} \left( \{u\}^T \{K'\} \{V\} + \{V\}^T \{K'\}^T \{u\} \right)
\]

### 4.0 ADHESION IMPROVEMENT OF REFLECTOR SURFACE

A reflector has been developed using vacuum forming technique in a Polymer material (Polycarbonate) for carrying out initial experiments. To improve the strain transfer properties between the reflector surface and the piezo materials it was necessary to improve the surface by way of metallization. The reflector surface was treated with RF plasma to modify its properties such that they incorporate in the adhesion enhancement between plasma treated polymer surface and the piezo ceramic material coating.

Deposition of copper was first tried on the flat samples of polycarbonate and then on parabolic shaped reflector of 300mm diameter.

### 4.1 OBJECTIVE OF STUDY

The objective of the investigation is to attempt to achieve the following displacements for the four master points as explained further in detail in Fig. 16 for 700 mm dia. IC-EC Antenna:

- Maximum limits for C-band for +40 mm
- Maximum limits for Ku-band -5 mm +12 mm
5.0 EXPERIMENTS WITH PARABOLIC SHAPE REFLECTOR SHELLS

Work related to the piezo patches on the doubly curved shells made of metal and non-metals is described as follows :-

5.1 Experimental investigations on metallic reflector

To start with, a 450 mm diameter (F/D=0.4) parabolic reflector of Aluminum was developed for with 1mm thickness. Patches (Unimorphs with wrap around electrodes with lead wires soldered) were fixed in two different configurations, i.e Case-I, radial direction case, with piezo patches along one axis only and Case – II, with piezo patches along both the axes and at periphery forming a T-arrangement (Figure 4.0).

Fig. 3.0 Aluminum Parabolic Reflector 0.45m diameter

Total twelve nos. of piezo patches, PZTs–SP-5H (50.0X50.0X0.5mm) have been used in T-arrangement form in a group of three each. Araldite AV138 M with Hardener has been used for sticking the patches on the convex side of shell as shown in Figure 4.0. 400 V/mm DC (Forward) case for the piezo patches has been tried in order to study the inward / outward displacement patterns for the parabolic shell. Patches have not been fixed on the concave side because of the electrical test that has been planned for the reflector. Patches on the concave side would cause Radio Frequency signal obstruction and reduce the efficiency of the reflector.

Figures 3.0 & 4.0 represent the pictorial representation of the radial vs. T-shaped configurations of the patches investigated on 450 mm dia. parabolic Aluminium reflector.

In order to understand the physics of the inward / outward displacements, series of experimentation has been carried out in the static displacement domain. Later, these aspects are covered in the Feed Control Loop related paragraphs. (Inward displacements means towards concave side of the reflector).

5.2 FEM Solution

ATILA FE software has been used for the Finite element modelling of the parabolic shells. The substrate and the patches have been modelled as solid tetrahedrons. The details of the Real constants are given in article 7.0 and Piezo properties used are furnished in Table 1.0.

The numerical displacement at the reflector periphery due to group of three piezo patches (PZTs–SP-5H (50.0X50.0X0.5mm)) has been obtained to the tune of -2.037E-06 m as per the post processed plot from Post-ATI.

Figure 4.0 shows Pictorial representation of piezo patches on a typical Aluminum Parabolic Reflector. Figure 5.0 shows FE model in post processed domain. This investigation was the starting point.
and later on after obtaining the encouraging results, the patches were added in the orthogonal direction also.

Properties of the piezo electric actuators are as follows in Table-1:

<table>
<thead>
<tr>
<th>Property Table</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP-5H#</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezoelectric Charge Constants</td>
<td></td>
</tr>
<tr>
<td>$d_{33}$, $(x \times 10^{-12} \text{C/N})$</td>
<td>550</td>
</tr>
<tr>
<td>$d_{31}$, $(x \times 10^{-12} \text{C/N})$</td>
<td>-247</td>
</tr>
<tr>
<td>Piezoelectric Voltage Constants</td>
<td></td>
</tr>
<tr>
<td>$g_{33}$, $(x \times 10^{-3} \text{Vm/N})$</td>
<td>20</td>
</tr>
<tr>
<td>$g_{31}$, $(x \times 10^{-3} \text{Vm/N})$</td>
<td>-9</td>
</tr>
<tr>
<td>Elastic Constants, short circuit</td>
<td></td>
</tr>
<tr>
<td>$S^{E}_{11}$ $(X \times 10^{-12} \text{m}^2/\text{N})$</td>
<td>15</td>
</tr>
<tr>
<td>$S^{E}_{33}$ $(X \times 10^{-12} \text{m}^2/\text{N})$</td>
<td>21</td>
</tr>
<tr>
<td>Density, $\rho$ $(\text{g/cm}^3)$</td>
<td>7.5</td>
</tr>
</tbody>
</table>

# Data available online at http://www.sparklerceramics.com

Table -2 Reflector results

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Reflector periphery displacement in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial type</td>
<td>(FE -numerical ) -2.037E-06, (Experimental ) 3.001E-06</td>
</tr>
</tbody>
</table>

6.0 EXPERIMENTAL INVESTIGATION
ON POLYCARBONATE REFLECTOR

The lessons learnt from the Aluminum reflector have been used for more suitable contemporary material for spacecraft reflectors that is Polycarbonate.

First time a successful attempt has been made from RF reflectivity point of view to metalize these hydrophobic materials using Magnetron Sputtering approach.

6.1 0.3m dia. Polycarbonate reflector

A 300mm diameter reflector with (F/D=0.4) made of Polycarbonate has been metalized with 8 microns thick Copper for RF reflectivity purpose.

On this reflector, PZTs–SP-5H (25.0X25.0X0.5mm) piezo patches have been used on the convex side with 60 % area coverage. Araldite AV138 M with Hardener has been used for sticking the patches. Investigation has shown that Polycarbonate Parabolic reflector of 0.3m diameter with Unimorphs give 1 mm reflector peripheral deflection in outward direction (towards convex side) under electrical field.

With the preliminary study on Polycarbonate material, the results w.r.t the reflector peripheral displacement are found to be encouraging.
Experimentally, 2mm tip deflection (inward i.e towards the patch side) has been measured with central fixity condition in the centre of the beams.

This phenomenon of inward displacement of the beam tips has potential applications for Planar antennas also. The investigations w.r.t the tip displacements on beams pinned in the center and with piezo patches on one side, pave the way for adaptive Planar antennas as well.

In this part of the investigation with Bimorphs, in the experiment initially an Aluminum beam held in the center has been taken which is of 450 mm length, 30mm width & 0.8mm thickness with piezo patches (Bimorphs) with Wrap around electrodes with lead wires soldered. PZT–SP-.5H (25.4 X 25.4X0.7mm) twelve numbers on one side of the beam have been used with approx. 50.96 % area coverage. Araldite AV138 M with Hardener has been used for sticking the patches on the beam on one side as shown in Figure 7.0. 400 V DC (Forward) has been used per mm thickness of patch. (Araldite AV138 M with Hardener has been used for sticking the patches on the beam on one side with a provision for pre-loading the patches during curing stage.)

After Experimental results, now the analysis work done on a 700 mm diameter parabolic shell surface is furnished.

The details of the numerical investigation have been furnished for 700 m diameter parabolic shell surface a follows:

7.0 FEASIBILITY STUDY

FE modeling has been carried for a 700 mm diameter parabolic shell surface made up of Polycarbonate material with a beam as backup structure (Fig 8.0) using NISA. Hysteresis and nonlinearities of smart materials have not been modeled presently.

This novel attempt has been made to simplify & study the complex static shape displacement problems of parabolic antenna reflectors by using limited number of discreet piezoceramic Bimorph actuators of series and parallel type by introducing the concept of piezo actuated backup beams as mentioned above for parabolic reflectors.
At present only preliminary investigation in the linear static deflection domain has been done. Following Finite elements of NISA have been used in the FE modeling of the Polycarbonate reflector by simulating the equivalent piezo related forces as calculated using equation (9). The details of these elements are as follows:

NKTP12, First order 3D Beam element
NKTP20, First Order Plate / Shell element 8 noded, General Plate / Thin Shell

ACTIVE Degrees of Freedom, Ux, Uy, Uz, θx, θy and θz (#3 translations # 3 rotations)

Design Specifications are as follows for the Optical Design for simplified 4 master points:

Objective, Requirements as per TICRA software:

C-band: (2x2 grid) +40 mm for reflector tip displacement
Ku-band (2x2 grid) -5 to +12 for reflector tip displacement -ve sign is for inward and +ve for outward displacement of reflector.

Fig. 9 Electrical connectivity for the reflector with active backup concept
Structural properties of the Polycarbonate material used in FE model are as follows:

- Material = Polycarbonate, 144R
- Modulus of Elasticity $E = 2350$ Mpa
- Density $\rho = 1.2$ gm/cc
- Flexural strength at yield = 90 MPa
- Coefficient of Thermal Exp. = $7.0E-05 / ^{0}C$

In this case, fourteen numbers (twelve numbers have been used on the flat sides and one each on the bent portion) of Bimorph piezo patches PZT–SP-5H (25.4 X 25.4X0.7mm), on one side of the Aluminum backup beam have been used with approx. 59.45 % area coverage. Figure 9 shows the experimental setup for testing the 700mm dia. (2mm thick) Polycarbonate reflector with 400 V/mm DC in two orthogonal directions. In the FE model for this case also, all three linear translational and one rotational DOF normal to the aperture plane of the reflector have been restrained in the center of the reflector at four appropriate near by nodes. Fig 10 shows a typical Bimorph used for the investigation.

Araldite AV138 M with HV998 has been used for sticking the patches on the beam on one side with a provision for pre-loading the patches during curing stage. Figure 9 shows the experimental setup for testing the 0.7m dia. (2mm thick) Polycarbonate reflector with 0.45 m long backup beam (1mm thick & 30 mm wide) under the 400 V/mm DC.

The modus operandi involved in calculating the normal force at the four master point locations.

As the bimorph patches require minimum 100 V DC to polarize, then the actual in-plane Force, F in Newton(N) exerted by the patch on the backup beam can be estimated using this value of voltage for the chosen piezo patch, its $g_{33}$ value in Vm per N (as per Table 1), thickness of the patch in meter(m) and area of patch in m$^2$ as follows in equation 9:

$$\text{Voltage} = \frac{Fx g_{33} \times \text{thickness}}{\text{Area of the patch}} \quad (9)$$

Fourteen numbers of Bimorph piezo patches, PZT–SP-5H (25.4 X 25.4X0.7mm), pasted on both the reflector backup L-beams generate linear strain which causes inward movement of the backup due to generated moment and this moment exerts normal force at each master locations. The NISA post processed results are shown in Figure 13.0.

Aluminum beam used is of 450 mm length, 30mm width & 0.8mm thickness and was held in the center as shown in Figure 9, where Piezo patches were with wrap around electrodes with lead wires soldered. Figure 10 shows the pictorial representation of the backup beam with 14 bimorphs.

![Figure 16](image.png)

Figure 16 shows the four master points (MP-1 to MP-4) of observation due to backup beams on the proposed layout of reconfigurable reflector. Figure 12 also shows pictorially the details of the Polycarbonate reflector with two backup beams as a prototype.

![Figure 11](image.png)

Fig 11 Polycarbonate reflector with backup
The maximum Polycarbonate reflector tip displacement obtained normal to the aperture plane (inwards) experimentally was to the tune of 3 mm each at load transfer master points. As shown in Figure 11, these master points are identified on the periphery of the reflector, on the convex side with active backup concept of two Aluminum beams placed in the orthogonal directions mounted with 14 Bimorphs as explained in Figure 9. Figure 15.0 shows the details of control loop.

Table 3 Results for Reflector with backup

<table>
<thead>
<tr>
<th>1. Theoretical deflection using FEA – through NISA</th>
<th>3.66 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Experimental deflection</td>
<td>3.00 mm</td>
</tr>
</tbody>
</table>

Fig 12.0: Front end for the software

Fig 13.0: Post processed plot of the reflector

Fig 14.0: Displacement contours of the reflector

When a piezoelectric Bimorph actuator is attached to the beam surface, the converse effect develops a bending moment in the backup structure making the reflector surface displacements inward & outward under an electrical field.

Maximum tip displacement obtained was to the tune of 3.66 mm on the 700 mm dia. reflector. Results are shown in Table -3.
The particulars of back up used in study are as follows:

- 4 orthogonal ribs
- 4 Master Points (MP1, MP2, MP3, MP4)
- 12 PZT and 12 displacement sensors

For Active feedback control loop system for Mechanically active antenna, the data will be acquired from various sensors mounted on 4 ribs of active antenna (Figure 12.0 show the details of the Feed back Loop Front View).

12 Piezo Patches (PZT) are to be excited and displacement transducer feedback is to be taken into a Computer.

Windows based Interactive software application acts as master for data logging and control.

Driver software for all data acquisition and control hardware will be integrated with the software.

Master point approach synthesis:

There are 4 radial ribs to be controlled by software. Each radial rib consists of 3 PZT actuators along with displacement sensors to make it mechanically active and to measure the displacement respectively. Fig 17.0 shows the layout plan of the control system.

There will be total 12 PZT and 12 displacement sensors in whole antenna system.

The input voltage range of PZT actuator is from -200V to +200V.

In initial phase, system is of 2X2 grid and it should be capable of measuring 4 master points (MP), one MP per radial rib.

8.0 FUNCTIONAL FEATURES OF THE INTERFACE SOFTWARE

8.1 Graphical User Interface (GUI)
Developed GUI using LabView based front panel has the following features:

- Voltage Control for all Analog Voltages
- Numerical Display of Output Analog Voltage
- Numerical Display of Input Analog Voltage
- Graphical Display of all Input channels
- Over range and below range indications
- Change of view from Voltage to Length and/or Force
- Synchronization of inputs and outputs by a suitable algorithm.

Appropriate PCI card with following details are installed in the industrial computer, which is interfaced with the active feedback control loop system:

- Two 16 bit analog outputs (833 ks/s), 24 digital I/O, 32 bit counters
- NIST-traceable calibration.
• More than 70 signal conditioning options.
• Correlated duo (8 clocked lines, 1 MHz).
• Select high-speed m series for 5x faster sampling rates or higher accuracy m series for 4x resolution.

• Ni-DAQMX driver software and NI labview signal express interactive data-logging software.

**Active Feedback Control Loop System for Mechanically Active Antennas**

**9.0 OBSERVATIONS**

When a piezoelectric actuator is attached to the reflector surface, the converse effects develop a bending moment in the antenna skin making the reflector show displacements inward or outward under an electrical field.

With the preliminary experimental study on Polycarbonate material, the results w.r.t the reflector tip displacement are found to be encouraging in both reflector form & discrete beam form for IC-EC coverage applications in future, though it needs to increased by displacement amplifiers.

Finite element and experimental results show reasonable correlation (less than 15% deviation) for the cases investigated both ways. Deviation between the Finite element model results and the experimental investigations can be attributed to unmodeled effects like adhesive bonding layer, hysteresis and variation of properties/piezo constants at temperature rise due to high voltages.

It has also been observed that placement of patches along the two orthogonal axes in a straight line configuration is more effective for peripheral displacements of the reflector, vis-a-vis, the T-configuration of placement of piezo-patches near the periphery of the reflector.

Experimental models provide a reasonable prediction of actuator performance at low input voltage but does not account for the nonlinear behavior of the material.

**10.0 ISSUES & CONCLUSIONS**

Polycarbonate beams pinned in the center and with piezo patches on one side, pave the way for futuristic reconfigurable spacecraft antennas for IC-EC coverage.

This displacement obtained at the periphery of the reflector is to the tune of 3 mm only which is
presently inadequate and is a potential issue for C-band 0.7 m dia. reflector. Present displacement of 3 mm is also observed to be inadequate for a Ku band type high frequency spacecraft parabolic reflectors.

For the time being, present 0.7m diameter polycarbonate reflector, efforts have been made to control the Lower Zernike modes for achieving the right inward / outward displacements of the reflector skin as obtained by the Antenna Optics Design software TICRA for few master points w.r.t the 2X2 grids presently. This bending of the reflector skin has potential applications in antenna beam shaping and beam steering in reconfigurable antenna reflectors required for India coverage (IC) to Extended Coverage (EC) for futuristic Indian GEOSAT missions. This concept may also prove to be useful for in-orbit shape correction of futuristic spacecraft antenna reflectors for thermal distortions etc.

Therefore, keeping the above lessons learnt during investigation in mind, a feed back control loop using LABVIEW software is also under development for 1.2m C-band full fledged reconfigurable reflector under Technology Development Programme mode at SAC & through Respond mode at IIT-Kanpur using SMA sensors and actuators pasted on a mechanically active backup structure of the reflector for proper Micro-Macro control options for Reconfigurable Reflectors. This approach is envisaged to overcome some of the potential issues mentioned above.

11.0 ACKNOWLEDGEMENTS

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