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Static Shape Control of Spacecraft Structural Elements Using Piezoelectric Actuators

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Abstract— **This paper discusses piezoelectric actuators which are used in high precision structures in order to maintain static shape such as spacecraft antenna reflectors, sensor base structures, telescope etc. for its optimal performance, which is very challenging task. Surface errors are often introduced by pre-stress and thermal distortions due to temperature differences. In aerospace industry metals are replaced by composite materials for their improved structural properties, but when these materials subjected to large variation of temperature in space also yield small distortions because of Coefficient of Thermal expansion (CTE), which is different for constitutive materials present in its layer, even after using thermal insulations. So for these kinds of applications, smart structures involving attached piezoelectric actuators have been proposed earlier [1, 2].**

A representative model is taken to study the application of piezoelectric materials in static deformation control. Linear piezoceramic materials are considered in this study. The behavior of piezoelectric material alone or in combination with other materials was analyzed by using Finite Element Method (FEM) through MSC® Marc Mentat software. Based on these simulation results, it was possible to better understanding the behaviour of piezoelectric material and thus to predict its optimum location, voltage range to obtain a better performance. This paper includes analysis results from other papers in order to validate our procedure and capability of MSC® Marc Mentat software; it also includes the contribution of different piezoelectric strain coefficients on the displacement in piezoelectric analysis. The developed simulation methodology and modeling can be applied to other types of linear piezoelectric materials.

Index Terms—static shape control (SSC), piezoelectric material, finite element method, PZT, MSC® Marc Mentat.

I. INTRODUCTION

Static shape control (SSC) is the manipulation of the structure by means of actuation, to guide the structure to conform to a desired shape [1]. Static shape control is mainly applied in flexible beams and large space structures. In stealth technology, Shape Control may be implemented to reduce protuberance or to decrease radar cross-sections of aircraft. Other Shape Control applications in space structures include an inflatable deployable space antenna, a tendon control system for flexible structures and a space antenna reflector. Some of these space structure applications must consider thermal effects in their Shape Control procedures.The application of static shape control was investigated in this paper particularly for aluminium and composite plate and antenna reflectors configuration using piezoelectric actuators. In first section of this paper, in order to validate our results comparisons are made with some literature and theoretical results. In second section mainly focuses on the shape control of structures when subjected to thermal distortion using piezoelectric actuators. Also includes some results to give optimum location of actuators, best suitable material and voltage range for high actuation or shape control.

II. VALIDATION

A. Piezoelectric Single layer subjected to voltage

A Piezoelectric Single layer of size 76x26x1 mm is subjected to voltage change or potential difference at top and bottom surfaces and the FEA results obtained are compared with Analytical results. This FEA plate model consists of 76x26x1 numbers of Hex 8 elements (Element type 163 in MSC Marc Mentat). Material properties used for this analysis is PZT-5H is given in TABLE A. Boundary conditions used for this validation study are, 100V is applied at top face (Z=0.001m), 0V is applied at bottom face of element (Z=0 m) and mechanical constrains are on y-axis, u=w=0 and on x -axis, v=w=0.

Hand Calculations are made using below formulae

$$w = \frac{d_{33}\,V\,h}{h} = \frac{591x10^{-12}x100x0.001}{0.001} = 5.91x10^{-8}m$$

$$v = \frac{d_{33}V\,W}{h} = \frac{-274x10^{-12}x100x0.026}{0.001} = -0.699x10^{-6}m$$

$$u = \frac{d_{31}\,V\,L}{h} = \frac{-274x10^{-12}x100x0.076}{0.001} = -2.11x10^{-6}m$$

TABLE I COMPARISON BETWEEN THE FINITE ELEMENT RESULTS AND ANALYTICAL SOLUTION

Displacement(m)	Analytical	FE result (MSC Marc Mentat)	% Error
w (thickness direction)	5.91×10^{-8}	5.91×10^{-8}	0
v (width direction)	-6.99×10^{-7}	-7.124×10^{-7}	1.92
u (length direction)	-2.11×10^{-6}	-2.082×10^{-6}	1.33

It is observed from Table I that the perfect match between analytical and FE analysis results exist in the thickness direction or across poling direction, but slight variation of FE results in other two directions mainly due to boundary conditions

B. Validation of High Displacement Piezoelectric Actuator (THUNDER) Finite Elements Models

NASA's Langley Research Centre [2], have conducted both experiments and analyses on THUNDER piezoelectric actuator to predict doming during the manufacturing process and subsequent straining due to an applied input voltage. Analysis results are obtained by ANSYS and NASTRAN. This study is conducted in order to compare our results with Experimental and analysis results. Based upon thickness and length of base metal (steel), they divided into four groups, for these group both analyses and experiments are conducted separately. Tables below give material properties and geometric model configurations.

TABLE II COMPOSITION OF TEST SPECIMENS

Thickness (m)	Dimension L x W	Dimension L x W
	$1\text{x}1\ \text{m}^2$	$2\text{x}1\ \text{m}^2$
7.62E-05 (3mil)	Group 1	Group 3
1.27E-04(5mil)	Group 2	Group 4

TABLE III PROPERTIES OF ALL SPECIMENS (ALL GROUPS)

Layers	Material	Thick 10^{-5} m	Modulus of Elasticity (E) GPa	Poisson's Ratio	Coefficients of Thermal Expansion (CTE) 10^{-6} /°C
1(Top Layer)	Aluminum	2.54	68.95	0.33	24
2	LaRC-SI	2.54	4	0.45	46
3	PZT-5A	17.272	Table	0.31	1.5
4	LaRC-SI	2.54	4	0.45	46
5(Bottom Layer)	Stainless Steel	TABLE II	262	0.33	17.3

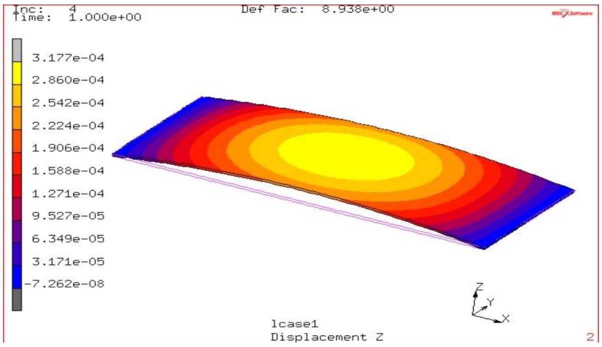

Figure 1. Displacement of Fourth Group specimen for 300Volt

The doming of THUNDER Piezoelectric actuator when subjected to different voltage change or potential differences across the thickness are obtained for all the four groups and is summarized into a table below.

TABLE IV SUMMARY OF RESULTS FOR ALL GROUPS

Voltage Applied (V)	Displacement in thickness(Z) direction in mm			
	Group 1	*Group 2*	*Group 3*	*Group 4*
100	0.03643	0.03506	0.1133	0.1059
150	0.05465	0.05258	0.1700	0.1589
200	0.07286	0.07011	0.2267	0.2118
250	0.09108	0.08764	0.2833	0.2648
300	0.10930	0.10520	0.3400	0.3177

From TABLE IV, it is concluded that higher actuation is possible for Group 3, where thickness of piezoelectric backing material is less and in plane dimensions are large (compared to other Groups) for same PZT-5A material and input voltage value.

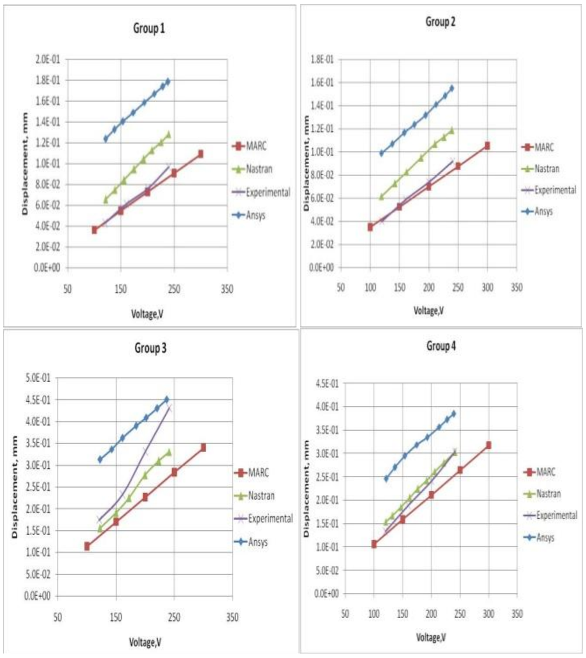

Figure 2. Comparison of Experimental and Different FEA results

Also From fig.2, graphs show the comparison for different groups and it is clear from these graphs that MSC Marc Mentat software package produces linear results and these results closely associated with experimental results when compared to ANSYS and NASTRAN.

C. Thermal Distortion Analysis

In this type of analysis, irrespective of structures material properties, when it is subjected to change in temperature, it will deform depending on the Coefficient of Thermal Expansion and distance from fixed end. This validation is to show and calculate the thermal distortions due to change in temperature for simple space antenna reflectors of different materials, which are needs to be very precise for optimal performance.

1) Space antenna reflector of 0.6m diameter and F/D=0.4

Space antenna reflector of diameter 0.6m and F/D (F- Focal Length and D- diameter of reflector) ratio 0.4 is subjected to 10°C change in temperature and various displacements are calculated and tabulated below for different materials like Aluminium, Kapton, and Composite etc.

Hand Calculations

a) *For Aluminium*

Coefficient of Expansion of Aluminium $\alpha = 23\text{x}10^{-6}\ /^{o}\text{C}$

Displacement X = $\alpha \text{ x } \Delta T \text{ x } L$

$=23\text{x}10^{-6}\text{x}10\text{x}0.3=6.9\text{x}10^{-5}$ m

Displacement Y = $\alpha \text{ x } \Delta T \text{ x } L$

$= 23\text{x}10^{-6}\text{ x}10\text{x}0.06 = 1.38\text{x}10^{-5}$ m

Displacement Z = $\alpha \text{ x } \Delta T \text{ x } L$

$= 23\text{x}10^{-6}\text{ x}10\text{x}0.3 = 6.9\text{x}10^{-5}$ m

b) *For KAPTON*

Coefficient of Expansion of KAPTON $\alpha = 20\text{x}10^{-6}\ /^{o}\text{C}$

Displacement X = $\alpha \text{ x } \Delta T \text{ x } L$

$= 20\text{x}10^{-6}\text{ x}10\text{x}0.3 = 6.0\text{x}10^{-5}$ m

Displacement Y = $\alpha \text{ x } \Delta T \text{ x } L$

$= 20\text{x}10^{-6}\text{ x}10\text{x}0.06 = 1.20\text{x}10^{-5}$ m

Displacement Z = $\alpha \text{ x } \Delta T \text{ x } L$

$= 20\text{x}10^{-6}\text{ x}10\text{x}0.3 = 6.0\text{x}10^{-5}$ m

c) *For Composite Material*

TABLE V COMPOSITE MATERIAL PROPERTIES

CTE /°C	Elastic Moduli(GPa)	Shear Moduli(GPa)	Poisson's ratio
α_{11}=5.2	E_{11}=17.2	G_{12}=1.7	γ_{12} =0.14
α_{22}=5.2	E_{22}=17.2	G_{23}=2.76	γ_{23} =0.4
α_{33}=21.6	E_{33}=6.9	G_{13}=2.76	γ_{31}= 0.4

Density = 1717kg/m^3

Displacement X = $\alpha_{11}\text{x}\Delta T\text{x}L$

$= 5.2\text{x}10^{-6}\text{ x}10\text{x}0.3 = 1.56\text{x}10^{-5}$ m

Displacement Y = $\alpha_{33}\text{x}\Delta T\text{x}L$

$= 21.6\text{x}10^{-6}\text{ x}10\text{x}0.06 = 1.29\text{x}10^{-5}$ m

Displacement Z = $\alpha_{22}\text{x}\Delta T\text{x}L$

$= 5.2\text{x}10^{-6}\text{ x}10\text{x}0.3 = 1.56\text{x}10^{-5}$ m

TABLE VI SUMMARIES OF THEORETICAL RESULTS

Materials	CTE /°C	Length (m)	Height (m)	Temp Change °C	Disp x (m)	Disp y (m)	Disp z (m)
Aluminium	$23e^{-6}$	0.3	0.06	10	$6.90e^{-5}$	$1.38e^{-5}$	$6.90e^{-5}$
KAPTON	$20e^{-6}$	0.3	0.06	10	$6.00e^{-5}$	$1.20e^{-5}$	$6.00e^{-5}$
Composite	TABLE V	0.3	0.06	10	$1.56e^{-5}$	$1.296e^{-5}$	$1.56e^{-5}$

FE Analysis results are same as above table

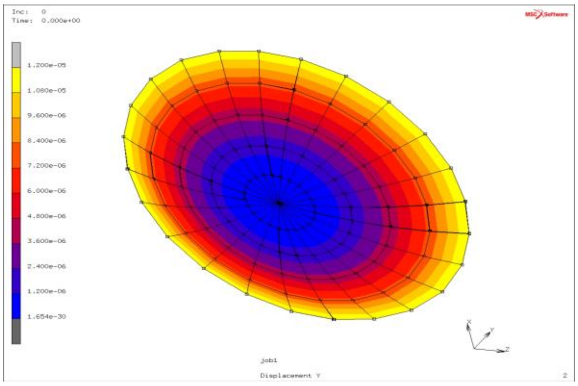

Figure 3. Displacement in Y (thickness) direction for Space KAPTON antenna reflector

III. ANALYSIS

This section consists of shape control of cantilever beam and Space antenna reflector, using piezoelectric actuators when they are subjected to thermal distortion. two types of analyses are carried out, thermal distortion analysis due to temperature change and piezoelectric analysis due to application of voltage or potential difference to piezoelectric actuators. For cantilever beam or plate these analysis are carried out, in order to find out best location, permissible thickness of actuators, voltage or potential difference for piezoelectric actuators for better actuation or shape control. First section is to find out best location and thickness and in second section, all those concepts are applied in shape control of space antenna reflector subjected to thermal distortion due to change in temperature.

A. Cantilever beam

The analyses are carried out on cantilever beam to find best location, permissible thickness of actuators, and voltage or potential difference for piezoelectric actuators. These parameters for best actuations are found out on simple cantilever beam made up aluminium and composite materials, when it is subjected to a unit degree change in temperature across it thickness.

Six different cases are made and analyzed by changing position of actuators, and thickness piezoelectric patch. Even though the depoling voltage is depends on thickness, type of piezoelectric material used, but in these analyses up to 400V is applied across the electrode which need not to be applicable in experiments because high electric field (generally depoling will starts over 1000V/mm electric field).

a) Aluminium Cantilever Beam attached with piezopatch subjected to temperature change

The aluminium cantilever beam of length 100mm, width 10mm and thickness 1mm is subjected to 1^{0}C change in temperature across its thickness. Because of temperature difference the cantilever beam will deflect. To regain the original shape of cantilever beam, piezoelectric actuators are used. Piezoelectric patch of dimension 20mm (length), 10mm (width) and by varying thickness with constant voltage value percent regain in tip deflection is measured.

Placing Unimorph and bimorph of PZT patches of 1mm,or 0.75mm, or 0.5mm or 0.25mm thick at a position from fixed end are either x=0, 10, and 20 mm. PZT -5H material properties used in this analysis.

TABLE VII VOLTAGE REQUIRED TO REGAIN 100% TIP DEFLECTION

Aluminium Cantilever Beam		**Unimorph**			**Bimorph**		
		Position From fixed end (mm)			***Position From fixed end (mm)***		
Voltage required for 100% tip deflection	***PZT thickness***	X =0	X=10	X=20	X=0	X=10	X=20
	1mm	1523*	1383*	1321*	367	493*	606*
	0.75mm	1145*	1058*	1017*	251	333	406*
	0.5mm	756*	709*	683*	152	202	243
	0.25mm	423	339	326	82	105	126

**** Theoretical values and these values may not be applicable in experiments.***

From above summary, the maximum actuation is possible when the piezoelectric patch is placed near the root i.e. where the maximum strain density present and thickness of piezoelectric patch should be very less. Bimorph require very less voltage value compared to Unimorph, because bimorph itself add more stiffness to structure compared to Unimorph and there are two oppositely polarized Piezopatches mounted on either side surface of the cantilever beam.

b) Composite beam attached with piezopatch subjected to temperature

The composite cantilever beam of length 100mm, width 10mm and thickness 1mm is subjected to 1^0C change in temperature across its thickness. Because of temperature difference the cantilever beam will deflect. To regain the original shape of cantilever beam, piezoelectric actuators are used. Piezoelectric patch of dimension 20mm (length), 10mm (width) and by varying thickness with constant voltage value percent regain in tip deflection is measured. Placing Unimorph and bimorph of PZT patches of 1mm,or 0.75mm, or 0.5mm or 0.25mm thick at location from fixed end are either x=0, 10, and 20 mm.

Material Properties used in this analysis are
Elastic moduli (GPa): $E_{11}=E_{22}=17.2$ $E_{33}=6.9$
Shear moduli (GPa): $G_{12}=1.7$ $G_{13}=G_{23}=2.76$
Poisson's ratio: $\gamma_{12}=0.14$ $\gamma_{13}=\gamma_{23}=0.4$
Density $\rho=1717$ kg/m^3
Thermal expansion coefficient (μm m^{-1} °C^{-1}): $\alpha_{11}=\alpha_{22}=5.2$ $\alpha_{33}=21.6$

TABLE VIII VOLTAGE REQUIRED TO REGAIN 100% TIP DEFLECTION

Composite Plate		**Unimorph**			**Bimorph**		
		Position From fixed end (mm)			**Position From fixed end (mm)**		
Voltage Required for 100% tip deflection	PZT thickness	X =0	X=10	X=20	X=0	X=10	X=20
	1mm	254	169	126	206	252	296
	0.75mm	222	148	117	135	176	210
	0.5mm	135	100	81	82	68	130
	0.25mm	56	42	33	40	52	62

It shows from table that, composite beam requires very less DC voltage to regain its tip deflection compared to aluminium cantilever beam, because thermal distortion is less in composite when compared to isotropic aluminium material. These above concepts and conclusions are applied to reflector in next section.

B. FEA for reflector surfaces

In this section two types of analysis are done on structural elements used in space industry i.e. Space antenna reflector. Thermal load is considered as a main reason for distortion of space structures and this distortion may be of very less in magnitude. In order to regain shape of precise structures piezoelectric actuators are used. So in this section, both thermal distortion analysis first and piezoelectric analysis second are carried out in sequence for same model.

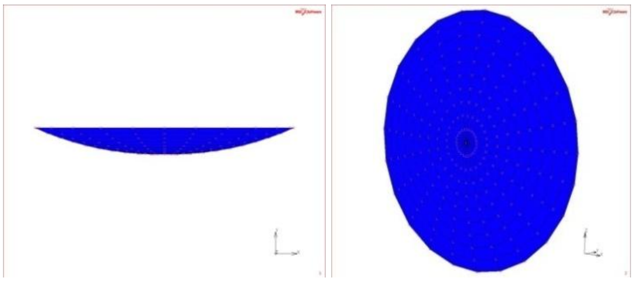

Figure 4. FE models of Reflector surfaces

1) Aluminium reflector surface

Following Finite elements of MSC Marc Mentat have been used in the FE modeling. The details of these elements are given below:

ELASTIC

8 noded, HEX, Element type 7, ACTIVE Degrees of Freedom, Ux, Uy and Uz (#3 translations)

PIEZOELECTRIC

8 noded, HEX, Element type 163, ACTIVE Degrees of Freedom, Ux, Uy and Uz and v (#3 translations, 1 electric potential)

a) Analysis of 0.6m dia., aluminium reflector with 12 numbers of PZT-5H patches

FE investigation has been carried out for 0.6m dia. (F/D=0.4) Aluminium (0.5mm thick) parabolic shell with 12 numbers of piezo patches, PZT-5H using MSC Marc Mentat software, to predict the deflection pattern of reflector.

All three linear translational DOFs of the reflector have been restrained in the center of the reflector. The patches are affixed on the convex side of the surface along the main X-Z axis, 90 degree apart with 3 patches on each side of the centrally held point for the reflector. Both thermal distortion analysis for 10°C and piezoelectric analysis for 200V are carried out and results are plotted

TABLE IX DISPLACEMENT IN THICKNESS DIRECTION FOR ALUMINIUM REFLECTOR

Analysis type	Displacement
Thermal Distortion	50.3 microns
Piezoelectric actuation	0.56 microns

Max. Reflector tip displacement FEA is 5.596x10^{-07}m (0.56 microns). Less displacement is attributed to higher stiffness of the small size of the reflector.

For this case not much actuation is possible because thermal distortion is in the order of 10’s microns and piezoelectric actuation is in 0.1’s microns.

b) Analysis of 0.6m dia. Aluminium reflector with 4 numbers of PZT-5H patches

FE investigation has been carried out for 0.6m dia. (F/D=0.4) Aluminium (0.5mm thick) parabolic shell with 4 numbers of piezopatches, PZT-5H using MSC Marc Mentat software, to predict the deflection pattern of reflector.

All three linear translational DOFs of the reflector have been restrained in the center of the reflector. The patches are affixed on the convex side of the surface along the main X-Z axis, 90 degree apart with 1 patch on each side of the centrally held point for the reflector. Both thermal distortion analysis for 10°C and piezoelectric analysis for 200V are carried out and results are plotted.

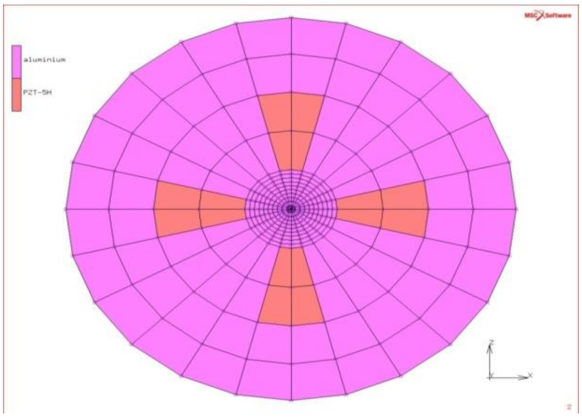

Figure 5. FE model on MSC Marc Mentat for 0.6m dia. Aluminium reflector with 4 Unimorph

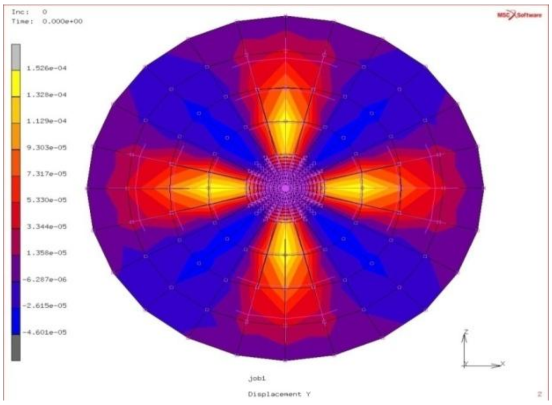

Figure 6. Thermal distortion of 0.6 m dia. Al. Reflector with 4 piezo patches subjected 200V

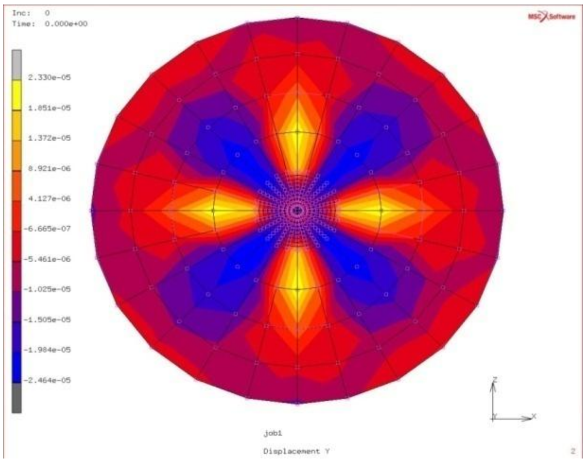

Figure 7. Compensated Thermal distortion of 0.6 m diameter Aluminium Reflector by 4 piezo patches subjected 200V

Thermal distortion is compensated by one order with only 4 Piezopatches attached near fixed end. So this concept is applied to regain shape of composite material reflector in the next section.

2) Composite reflector surface

FE investigation has been carried out for 0.6m dia. (F/D=0.4) composite (0.08mm thick) parabolic shell with 4 numbers of piezo patches, PZT-5H using MSC Marc Mentat software, to predict the deflection pattern of reflector.

All three linear translational DOFs of the reflector have been restrained in the center of the reflector. The patches are affixed on the convex side of the surface along the main X-Z axis, 90 degree apart with 1 patch on each side of the centrally held point for the reflector. Both thermal distortion analysis for 10°C and piezoelectric analysis for 200V are carried out and results are plotted.

Four piezoelectric layers each is having thickness of 0.2 mm are considered in this analysis.

Material Properties used in this analysis are
Elastic moduli (GPa): $E_{11}=E_{22}=17.2$ $E_{33}=6.9$
Shear moduli (GPa): $G_{12}=1.7$ $G_{13}=G_{23}=2.76$
Poisson’s ratio: $\gamma_{12}=0.14$ $\gamma_{13}=\gamma_{23}=0.4$
Density $\rho=1717$ kg/m^3
Thermal expansion coefficient (µm m^{-1} °C^{-1}): $\alpha_{11}=\alpha_{22}=5.2$ $\alpha_{33}=21.6$

The details of these elements are given below:

ELASTIC

8 noded, HEX composite, Element type 149, ACTIVE Degrees of Freedom, Ux, Uy and Uz (#3 translations)

PIEZOELECTRIC

8 noded, HEX, Element type 163, ACTIVE Degrees of Freedom, Ux, Uy and Uz and v (#3 translations, 1 electric potential)

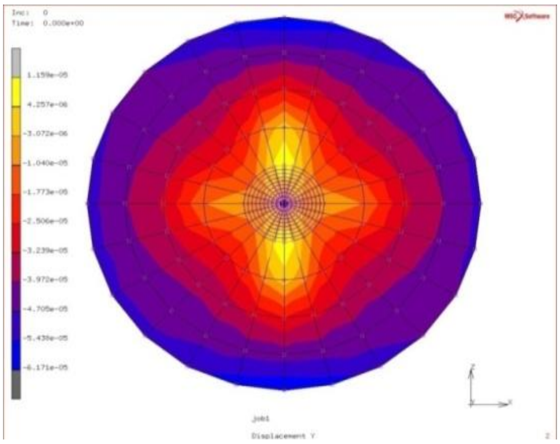

Figure 8. Thermal distortion of 0.6 m dia. composite Reflector with 4 piezo patches

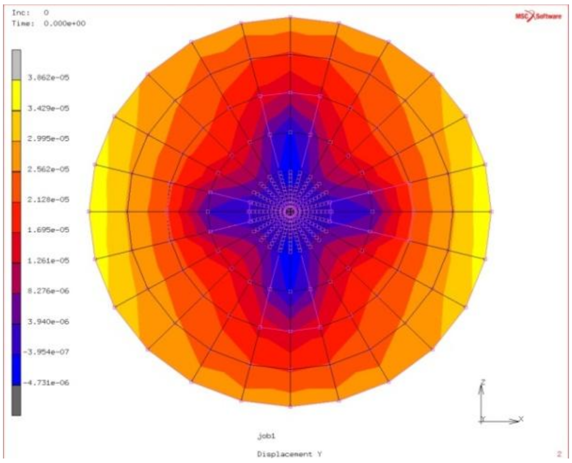

Figure 9. Piezoelectric actuation of 0.6 m dia. Composite Reflector with 4 piezo patches subjected 200V

TABLE X DISPLACEMENT IN THICKNESS DIRECTION FOR COMPOSITE REFLECTOR

Analysis type	**Displacement**
thermal Distortion	11.59 microns
piezoelectric actuation	38.62 microns

Max. Reflector tip displacement by thermal distortion is 1.159E-05m (11.59 microns) and by piezoelectric actuation is 3.862E-5 m (38.62 microns)

From this case, the shape of reflector surface can be regained by only 4 Piezopatches with less than 200V DC.

IV. CONCLUSIONS

Studied the Electromechanical behavior of Piezoelectric (PZT) material in the actuation, Validation study is carried out to establish a procedure to analyze structural models attached with piezoelectric actuators and compared results with theoretical and experimental results. It is found that the result shows close correlation with the test results compared to the other software.

Thermal deformation analysis using Finite element analysis of different structural elements is carried out. Cantilever beam with different configurations are studied for tip displacement control. It is demonstrated through Finite element analysis that the small displacement can be controlled by using piezoelectric materials.

An attempt is made to use piezoelectric material for reflector. Reflector of diameter 0.6m is considered, with Aluminium as well as composite. Different PZT locations are studied. Since the thermal deformation in composite reflector is very less compared to the aluminium reflector, deformation compensation shows better results in composite reflector.

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TABLE A PZT -5H PIEZOELECTRIC MATERIAL PROPERTIES

Material: PZT-5H (Anisotropic)
Density=7500kg/m^3
Elastic coefficient matrix(C):6x6 N/m^2
C_{11}=C_{22}=1.26x$10^{11;}$ C_{12}=C_{21}=7.95 x $10^{10;}$
C_{13}=C_{31}=8.41x10^{10}; C_{33}=1.17x10^{11}
C_{44}=C_{55}=C_{66}=2.3x10^{10}
Dielectric or permittivity matrix (k):3x3 Farad/meter
ε_{11}=ε_{22}=1.505x10^{-8}; ε_{33}=1.301x10^{-8}
Piezoelectric Strain coefficient properties (d):3x6 C/N
d_{31}=d_{32}=274x10^{-12}
d_{15}=d_{24}=741x10^{-12}
d_{33}=591x10^{-12}