Defence Science Journal, Vol. 59, No. 5, September 2009, pp. 485-493

Design of Packaging for Microballoon Actuators and Feasibility of their Integration within Aerodynamic Flight Vehicle

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ABSTRACT

The microballoon actuators are used for the active flow control in turbulent boundary layer for aerodynamic control of flight vehicles. The packaging, interfacing, and integration of the microballoon actuators within the flight vehicle play a key role for functioning of the microballoon actuators during the flight conditions. This paper addresses the design and analysis of packaging and integration aspects and associated issues. The use of microballoon actuators on the control surfaces and nose cone of flight vehicles has the positive influence of delaying the flow separation from the aerodynamic surface. This results in enhancing aerodynamic effectiveness and lift as well as reduction of drag. A typical control surface is configured with eight microballoon actuators symmetric wrt the hinge line of the control surface and embedded within the control surface. Provision of the Pneumatic feed line system for inflation and deflation of the microballoons within the control surface has been made. The nose cone has been designed to have 32 such actuators at the circular periphery. The design is found to be completely feasible for the incorporation of microballoon actuators, both in the nose cone and in the control surface.

Keywords: Microballoon actuator, control surface, nose cone, deployable flow effectors, solenoid valve, aerodynamic control

1. INTRODUCTION

Flow separation control over airfoil surfaces has been subject of continuous research for fluid dynamic scientists and researchers owing to its potential for drag reduction and the associated benefits important in aerospace systems. This paper focuses on design and analysis of packaging of MEMS-based microballoon actuators used for flow separation, control over control surface, and nose cones of a typical aerospace vehicle. The paper also addresses some of the important integration aspects and related issues. In addition to reduction of drag, the side force generation and eventually the hinge-less control are possible.

The MEMS-based microactuators [1-5] are readily suitable to be used within the boundary layer for flow separation control for providing unprecedented unconventional aerodynamic control systems with better efficiency and effectiveness. This type of microactuator-based active flow control is expected to greatly augment the conventional hinged type aerodynamic control systems for flight vehicles. The detailed design and analysis of MEMS-based microballoon actuator has been carried out by the author. The packaging and interfacing plays an important role in integration and functioning of the microballoon actuator. This paper presents the design and analysis of packaging of microballoon actuators and integration of the packaged microballoon actuators addressing the integration aspects and related issues.

2. DESIGN AND ANALYSIS OF PACKAGING AND INTERFACES

The packaging of MEMS devices will often be specific to the application being addressed. Three types of deployable configurations were designed keeping in view the requirements of aerodynamic control of projectiles for which the control elements are integrated at the nose cone for better aerodynamic effectiveness interms of generating side forces. For the micro air vehicles and UAVs, the micro actuators integrated on the control surface is one of the potential deployable configurations. The packaging solution will involve a design, as well as the selection of materials and processes suitable for that particular application. The degree of engineering involved for packaging will depend upon the particular application. A very important part of the MEMS design cycle is incorporating the device into an appropriate package, and which may require several design iterations. In the present research, different options of packaging the microballoon actuators have been studied, one of the practical and suitable options is combining the packaging of the microballoon actuator with mounting interface used for integration within the flight vehicle. Since the packaging and mounting interface are combined, the package design is mainly dictated by the mounting interfaces of the microballoon actuator and the type of deployment

Received 3 November 2008, Revised 2 July 2009

configuration used for the active aerodynamic control of flight vehicles. Even though the packaging and interfacing feature is combined, it is referred to as the packaging only. Selection of the material of the packaging is one of the important steps in the design of the packaging. After detailed study, three types of materials, such as polycarbon, polyamide and polypropylene were selected for the main housing of the microballoon actuators. The important properties of the materials are given in the Table 1.

Table 1. Important properties of polycarbon, polyamide and polypropylene as packaging material [7]

Material properties	Polycarbon	Polyamide	Polypropylene
Young's modulus (GPa)	2.37	1.0	1.78
Poison's ratio (µ)	0.35	0.35	0.35
Yield strength (MPa)	63.8	60	37.5
Density (g/cc)	1.20	1.47	0.931
Coefficient of thermal expansion (CTE) linear (µm/m °C)	65.2	32.4	115
Maximum service temperature (°C)	125	268	82.6

Depending upon the deployment configuration, the type of packaging has been emerged. The packagings designed for three deployment configuration are described in the following paragraphs.

2.1 Deployment Configuration of Microballoon Actuators Embedded in Control Surface

In the first deployment configuration, the microballoon actuators are required to be embedded within the control surface along with pneumatic pipes. The packaging is designed to meet these requirements. The pneumatic pressure is supplied to the microballoon actuators through this packaging. Since the control surface is tapered towards leading and trailing edges, two types of packages have been designed, one with smaller height and the other with bigger height as shown in Fig. 1.

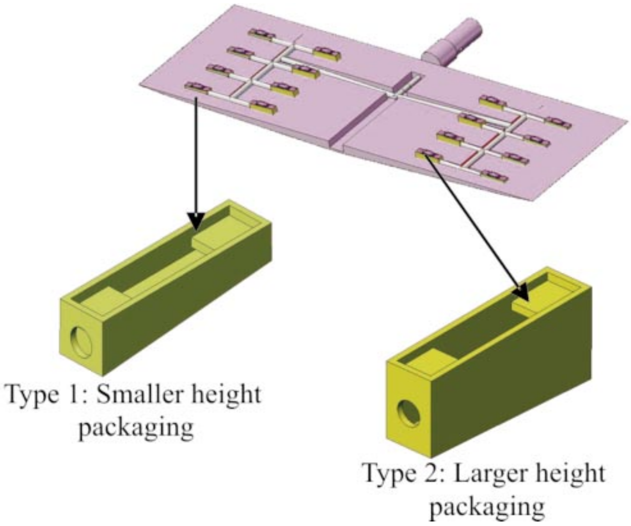


Figure 1. Details of packaging of the microballoon actuator within the control surface.

The microballoon actuator is glue bonded with help of room temperature vulcanised (RTV) adhesive compounds (RTV 560/566/577) of aerospace grade. These compounds can be cured at room temperature on to the packagings (smaller height and bigger height) before embedding them in the control surfaces, as shown in Figs 2 and 3.

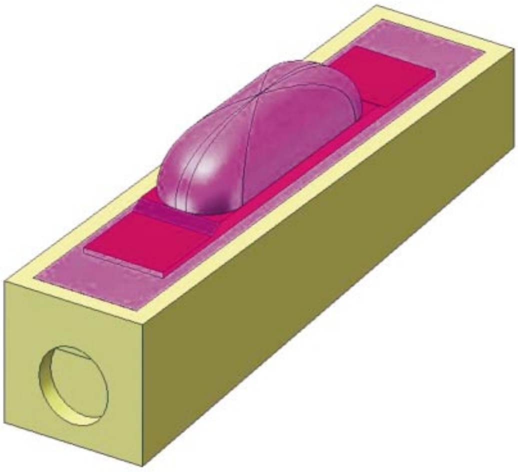


Figure 2. Microballoon actuator with smaller height packaging.

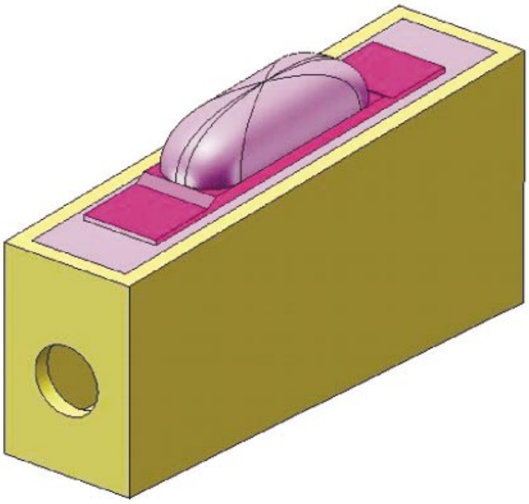


Figure 3. Microballoon actuator with bigger height packaging.

The finite element analysis of these packagings are carried out in ANSYS environment to determine the stresses induced and deflections taking place under the maximum operating pressure of 60,000 Pa.

Figure 4 shows stress plot and Figs 5 (a) to 5 (c) shows deformation plots of smaller height packaging respectively. Figure 6 shows stress plot and Figs 7 (a) to 7(c) shows deformation plots for bigger height package.

Following observations have been made from the above analysis.

- The stress induced was found to be about 2.29 MPa, and 1.16 MPa for smaller and bigger height packagings, respectively. The factor of safety was found to be greater than 10 for both the packagings.

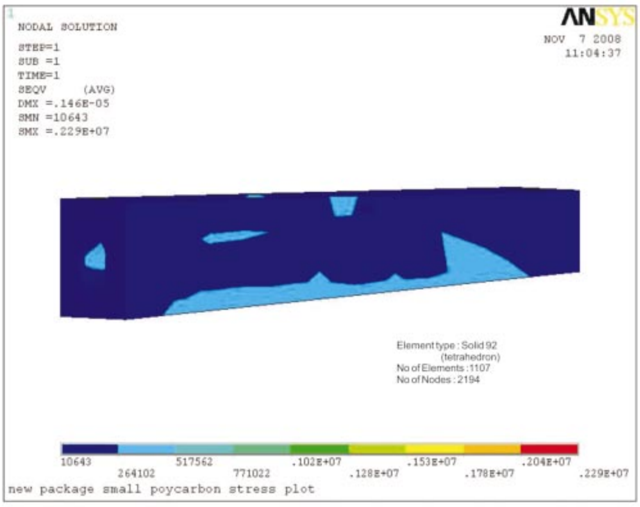


Figure 4. Stress plot of smaller height (polycarbon, polyamide and polypropylene).

- In the case of smaller height packagings, the maximum deformations of about 1.46 µm, 1.95 µm, and 3.46 µm were observed in polycarbon, polyamide, and polypropylene materials, respectively.
- In the case of bigger height packaging, the maximum deformations of about 1.38 µm, 1.84 µm and 3.27 µm were observed in polycarbon, polypropylene and polyamide materials, respectively.

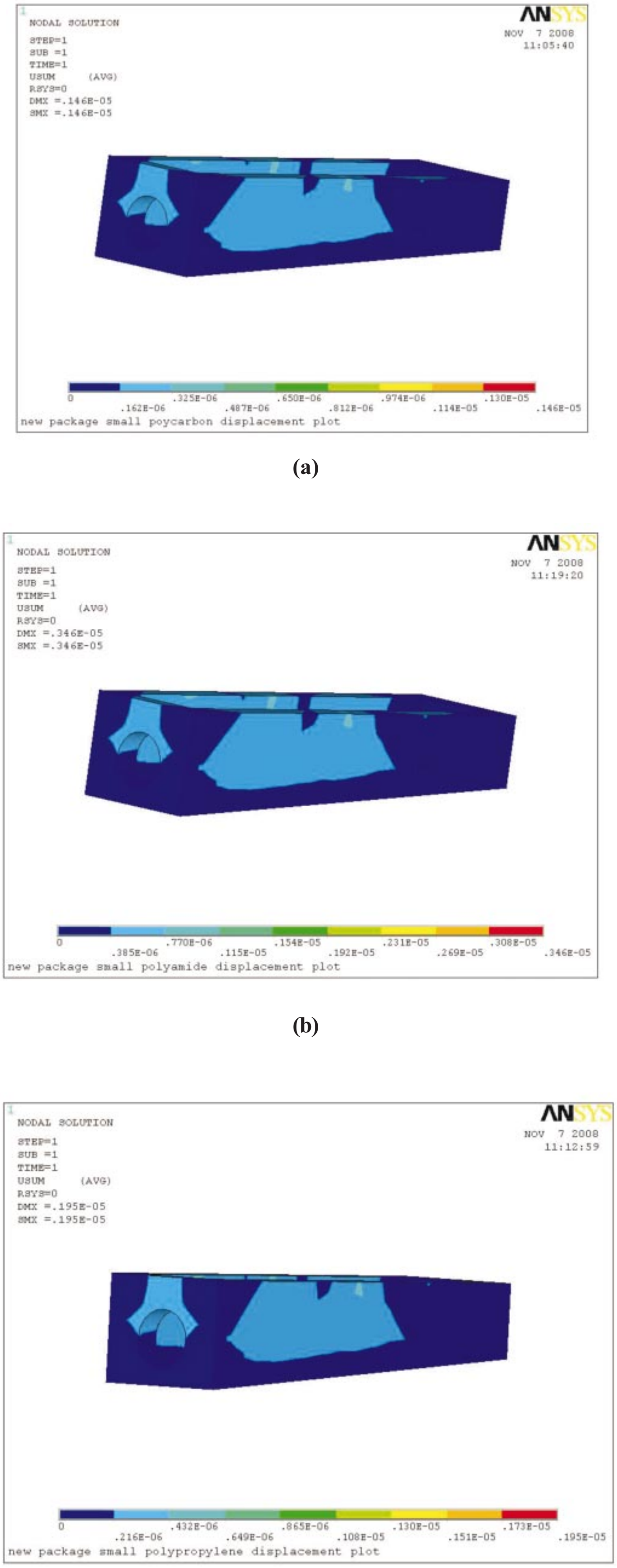
2.2 Deployment Configuration for Microballoon Actuator in the Nose Cone

In this deployment configuration, the microballoon actuators along with the packaging, on which it is glue bonded, are mounted inside the nose cone. In this case, the packagings are designed to facilitate the mounting of 32 numbers of microballoon actuators inside the nose cone, such that the top surface of the microballoon actuators just flushes with that of the nose cone (in the deflated condition) within the allowable mis-match value (not greater than 5 µm) from aerodynamic point of view. The microballoon actuators are glue bonded on to the packaging with RTV 560/566/577 adhesive compounds of aerospace grade bonding agents before integration in the nose cone. The details of the packaging with microballoon actuator and mounting features are shown in Fig. 8.

The finite element analysis of this packaging was carried out in ANSYS environment to determine the stresses induced and deflections taking place under the maximum operating pressure of 60,000 Pa. Figure 9 shows stress plot and Figs 10 (a) to 10 (c) show deformation plots of the packaging for the three selected materials.

The following observations have been made from the above analysis.

- The stress induced was found to be about 1.13 MPa and the factor of safety was found to be > 10.
- The maximum deformation of about 2.25 µm, 3.0 µm, and 5.34 µm were observed in polycarbon, polypropylene and polyamide, respectively.



(a)

(b)

(c)

Figure 5. Deformation plots of smaller height packaging: (a) polycarbon, (b) polyamide, and (c) polypropylene.

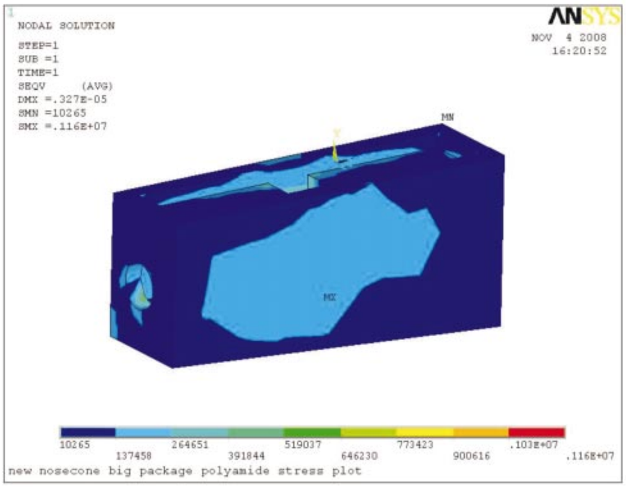


Figure 6. Stress plot of larger height (polycarbon, polyamide, and polypropylene).

2.3 Deployment Configuration of Deployable Flow Effectors in the Nose Cone

In the third configuration, rectangular type deployable flow effectors (DFEs) were used for active aerodynamic flow control of flight vehicles. In this configuration, the DFEs were in the air stream instead of microballoons, and these DFEs are driven by the microballoon actuators. The microballoon actuators along with the packaging on which these were glue bonded were mounted inside the nose cone. The DFEs rest on the microballoon actuator and were retained in the neutral position with the help of restraining springs during non-operation period, as shown in Fig. 11. In this configuration, total 32 numbers of DFEs are integrated in a circular array in the nose cone. In this case, the packaging is designed to facilitate the mounting of the microballoon actuators inside the nose cone, such that the top surface of the DFEs matches with that of the nose cone within the allowable mis-match value (not greater than 5 µm) from aerodynamic point of view. If higher is the mis-match higher will be the drag lesser will be the manoeuverability and vice-versa. In this configuration, the bottom faces of the DFEs rest on the microballoon actuators and top portion of DFEs enters into the rectangular slots made in the nose cone.

A guiding feature has been provided in the packaging to guide the DFEs. Finite element analysis of the packaging was carried out in ANSYS environment. Figure 12 shows stress plot and Figs 13 (a) to 13 (e) deformation and Stress plots for the selected materials for packaging and DFE.

Following observations have been made from the above analysis.

- The stress induced was found to be about 1.56 MPa and the factor of safety was found to be > 10.
- The maximum deformations of about 4.76 µm, 11.3 µm and 6.34 µm were observed in polycarbon, polyamide and polypropylene, respectively.
- In the case of DFEs, the stress induced is found to be about 0.14 MPa and deformation of < 1 µm is observed for the selected materials.

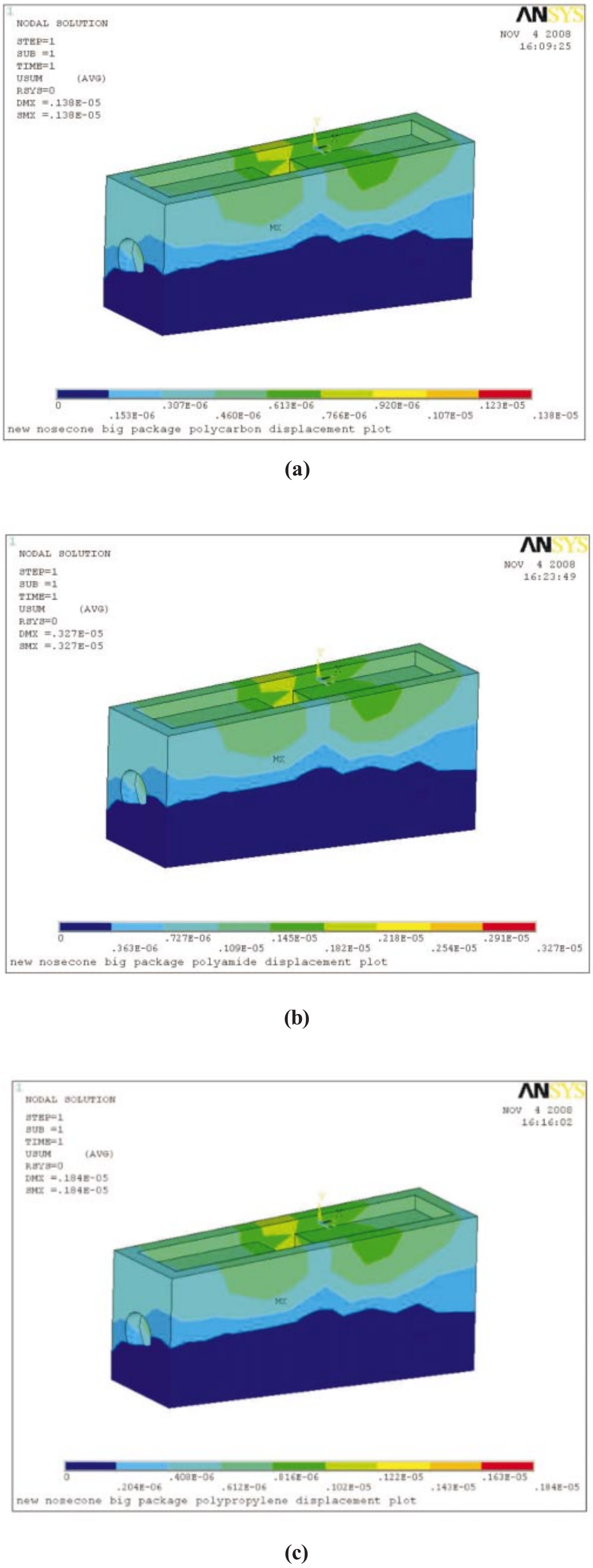


Figure 7. Deformation plots of bigger height packaging: (a) polycarbon, (b) polyamide, (c) polypropylene.

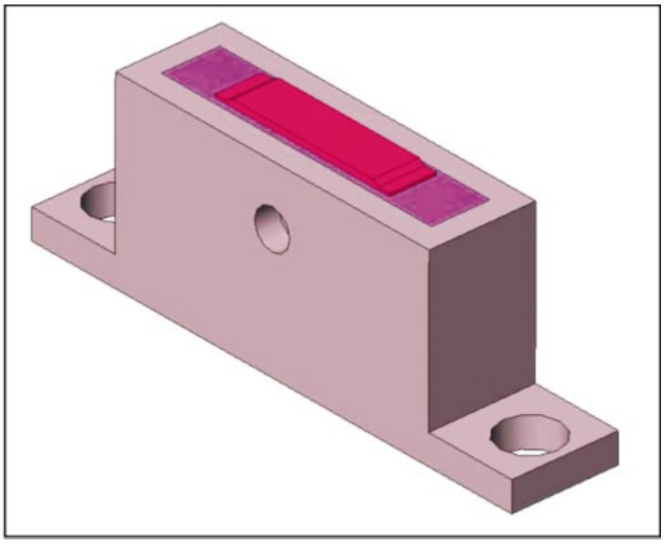


Figure 8. Microballoon actuator glue bonded on to the packaging with mounting features.

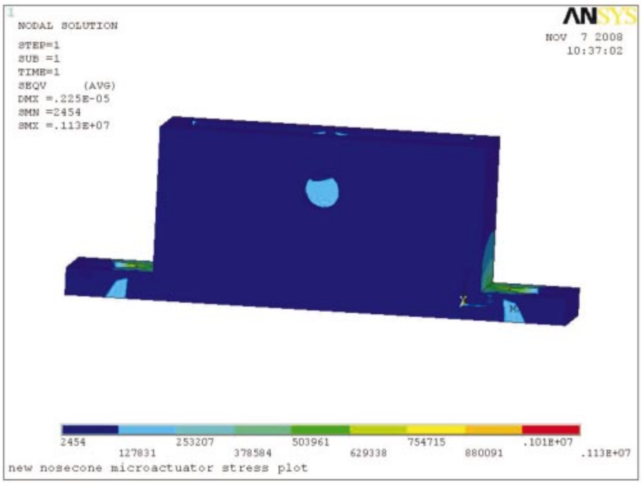
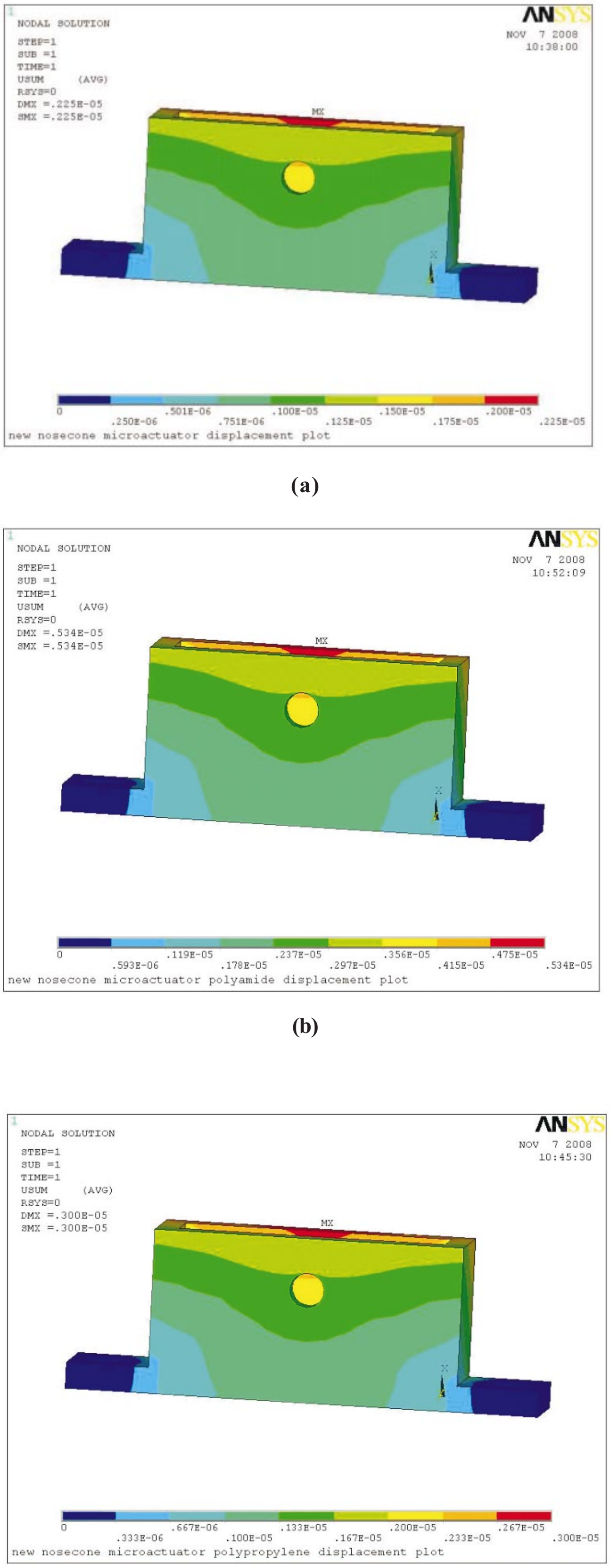


Figure 9. Stress plot of packaging.

2.4 Spring Design for DFEs Deployment Configuration

The maximum pressure applied is equal to 60 KPa. The stress induced in the springs is equal to(60 Sec θ/2), where θ is the angle made by the axis of the spring with the direction of the pressure. The stress induced in the springs for $\theta = 60^0$ is 60 KPa. The maximum deflection is 3 mm (3000 μm). The force acting $F = p \times A$; where A (= 6 x 2 mm^2) is the pressure effective area. F = 0.72 N (or 720 mN) for typical configuration. Spring index (generally between 3-12) is used in the design, the spring index is chosen to be about 4 for this typical design case. The stress induced will be usually greater than 40 per cent of the tensile strength. Stress in spring is found to be very less, the metallic springs are not suitable and hence plastic springs have been explored. The plastic springs made of polycarbonate have been designed to



(a)

(b)

(c)

Figure 10. Deformation plots of packing for three materials: (a) polycarbon, (b) polyamide, (c) polypropylene.

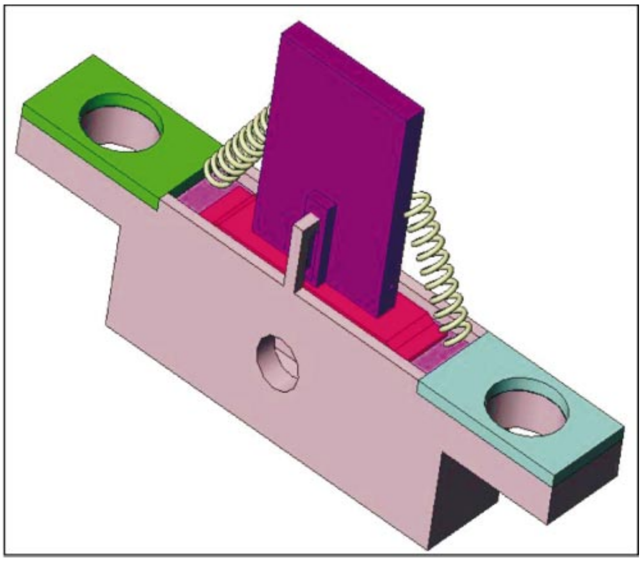


Figure 11. DFE resting on microballoon actuator at neutral position.

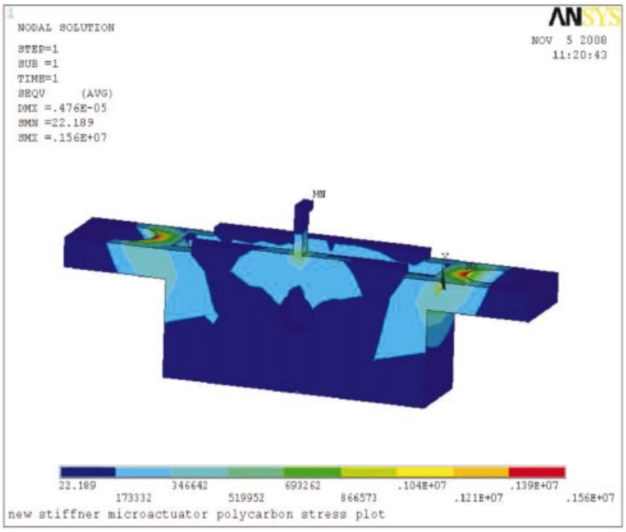


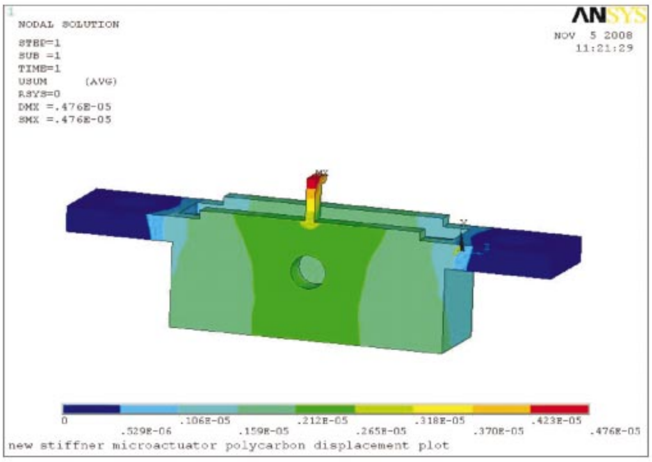
Figure 12. Stress plot of packaging for DFEs.

meet the deflection and load requirements. The details of the polycarbonate spring designed for a typical configuration are:

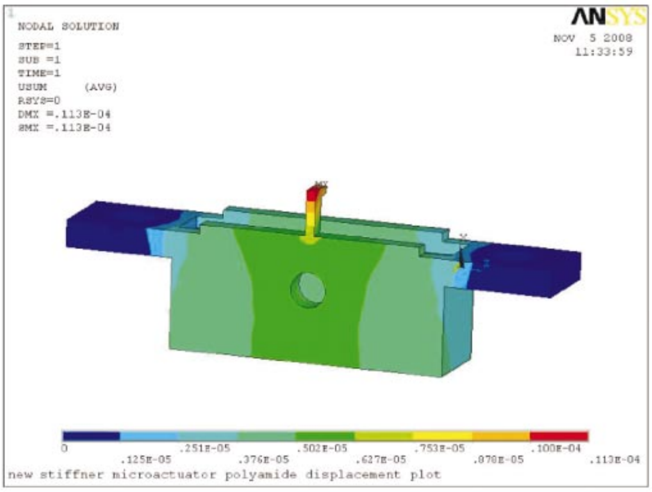
- Wire diameter is 430 µm,
- Coil diameter is 1.72 mm, and
- Number of turns is 8.

3. INTEGRATION STUDIES

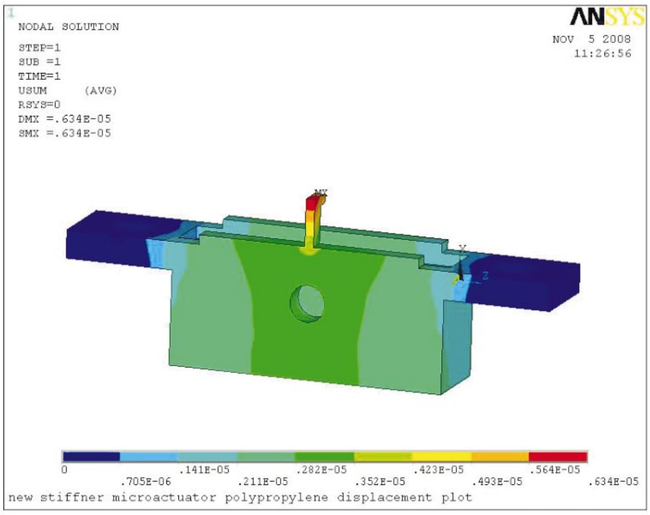
Integration studies of the microballoon actuator and the pneumatic system for three deployment configurations such as microballoon actuators embedded in control surfaces, integration of microballoon actuators within nose cone, and DFEs in the nose cone. In the first deployment configuration, the integration of microballoon actuators within the control surface and



(a) Deformation plot (polycarbon)

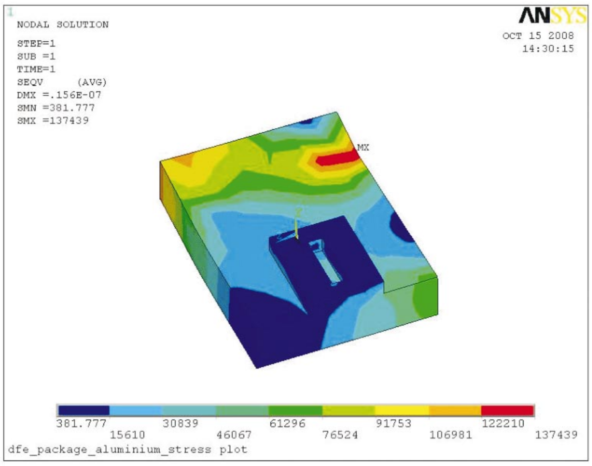


(b) Deformation plot (polyamide)

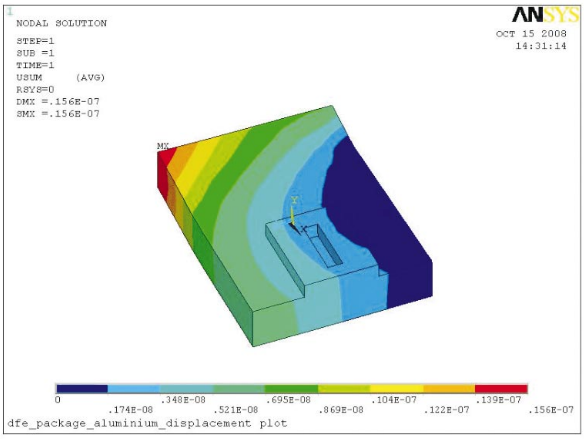


(c) Deformation plot (polypropylene)

Figure 13. Deformation and stress plots of packaging for DFE deployment configuration in nose cone. Deformation plot: (a) polycarbon, (b) polyamide, and (c) polypropylene.



(d) Stress plot of DFE (aluminum)



(e) Deformation of DFE plot (aluminum).

Figure 13. Deformation and stress plots of packaging for DFE deployment configuration in nose cone. (d) Stress plot of DFE (aluminum), and (e) Deformation of DFE plot (aluminum).

the pneumatic system within the flight vehicle close to the control surface is carried out. The second deployment configuration houses the microballoon actuators and the associated pneumatic system in the nose cone and in the third deployment configuration the microballoon actuators drive the rectangular type deployable flow effectors (DFEs) integrated in circular array of the nose cone and the pneumatic system is housed in the nose cone of the flight vehicle. Under these integration studies, various options such as, using individual pneumatic components, modular pneumatic systems, etc, were studied. The modular system (all the pneumatic system components are assembled in the common housing along with interconnecting pneumatic passages) is selected from the minimum space and volume considerations and this meets the performance requirements of the flight vehicle. However, the utility and performance of the designs of the packagings of all the three deployment configurations have to be evaluated in wind tunnel tests.

3.1 Embedding of Microballoon Actuators within the Control Surface

The integration of the microballoon actuator within the control surface is very critical as compared to the integration in the nose cone. On each control surface, 16 numbers of microballoon actuators are used. The configuration is arrived at based on CFD studies. The packaged microballoon actuator is embedded in the control surface along with pneumatic tubes/pipes, as shown in Fig. 14. The pneumatic passage (flow port) is made in the control surface shaft connecting the pneumatic system of the microballoon actuators and the manifold, as shown in Fig. 15.

The integration studies carried out indicate that it was feasible to embed the microballoon actuators within the control surface, however it is a practical challenge to integrate the pneumatic pipes/tubes on the movable control surface and it has been addressed in the present research, from the consideration of scalability and flight dynamics.

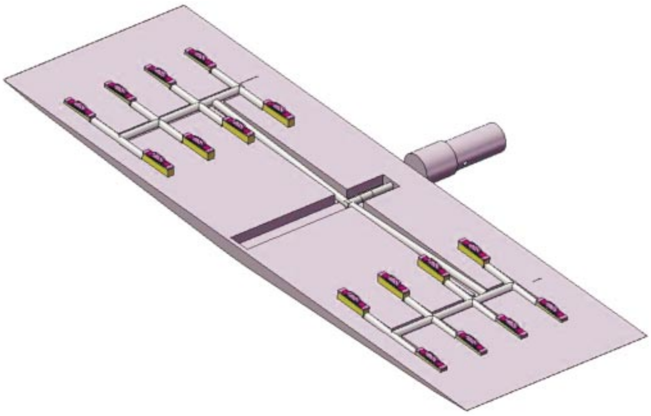


Figure 14. Embedded microballoon actuators with pneumatic tubes/pipes.

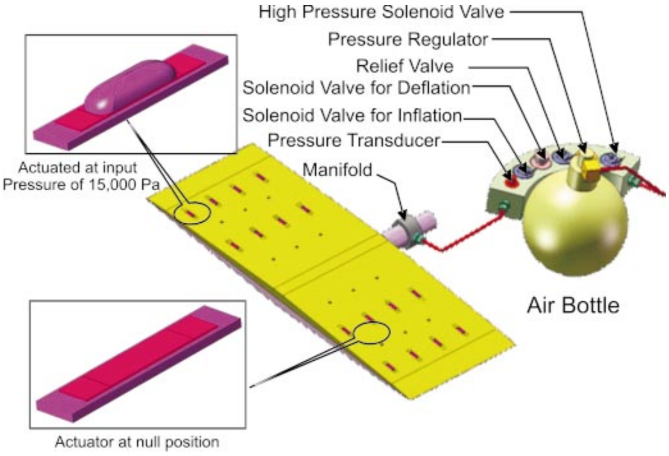


Figure 15. Details of pneumatic system and manifold.

3.2 Integration of Microballoon Actuators within the Nose Cone

In this configuration, 32 microballoon actuators were integrated on rear portion of the nose cone and 16 actuators could be controlled at a time. The criticality in the integration within a nose cone is to match the geometric profile of the nose cone with that of the microballoon actuator; however certain amount of mis-match (< 5 µm) always exists between them which may not be affecting the performance significantly. The integration and interconnecting of actuators and sensors is designed such that the entire pneumatic system can be fitted inside the nose cone. This would be a typical design challenge in practical situations. The configuration of the microballoon actuators along with the pneumatic system integrated within the nose cone is shown in Fig. 16.

The above integration studies indicate that the feasibility of integration of microballoon actuator within the nose cone exists. The feature of combining mounting and packaging of microballoon actuators eases the integration process.

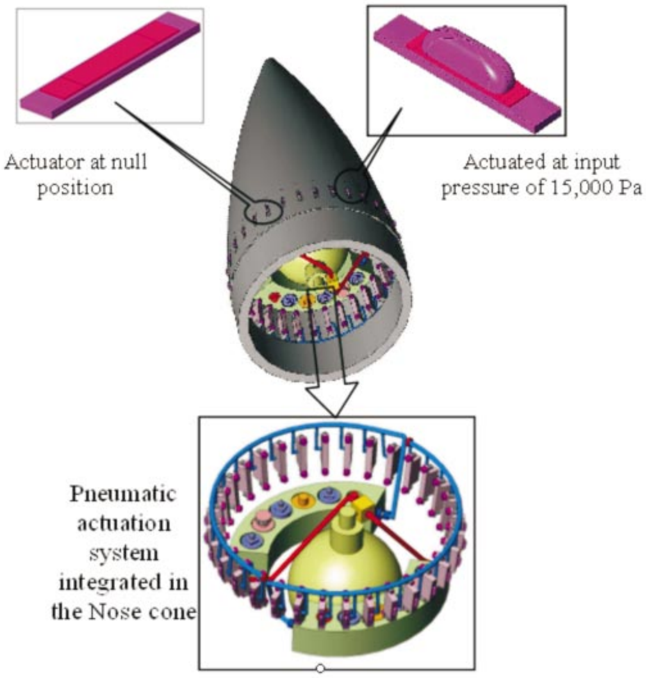


Figure 16. Microballoon actuator along with pneumatic system integrated in the nose cone.

3.3 Integration of Microballoon Actuators alongwith DFEs in Nose Cone

This section is focused on describing the details of the integration of microballoon actuators along with DFEs in the nose cone of the flight vehicle or a projectile. Rectangular slots were made in the nose cone in the plane of actuators to facilitate and move DFEs in these slots beyond the outer surface of the nose cone in the air stream for aerodynamic flow control.

There were 32 DFEs in a circular plane on the nose cone; each DFE was driven by the microballoon actuator mounted inside the nose cone. When the microballoon actuator is at rest, the top surfaces of the DFEs match with outer surface of the nose cone and bottom surface is resting on the diaphragm of the microballoon actuator. As soon as the microballoon actuator was actuated, the silicon rubber diaphragm of the actuator deflected which drive the DFEs which projects into the air stream, thereby creating asymmetry on the aerodynamic body, resulting in control of flow separation. One of the important design challenges would be to retract the DFEs to their normal position. For this purpose, two small springs were used. The challenges of integration and interconnecting the actuators and the pneumatic systems components were met by designing the entire pneumatic system, such that it could be fitted inside the nose cone. The microballoon actuation system with DFEs integrated within the nose cone is shown in Fig. 17.

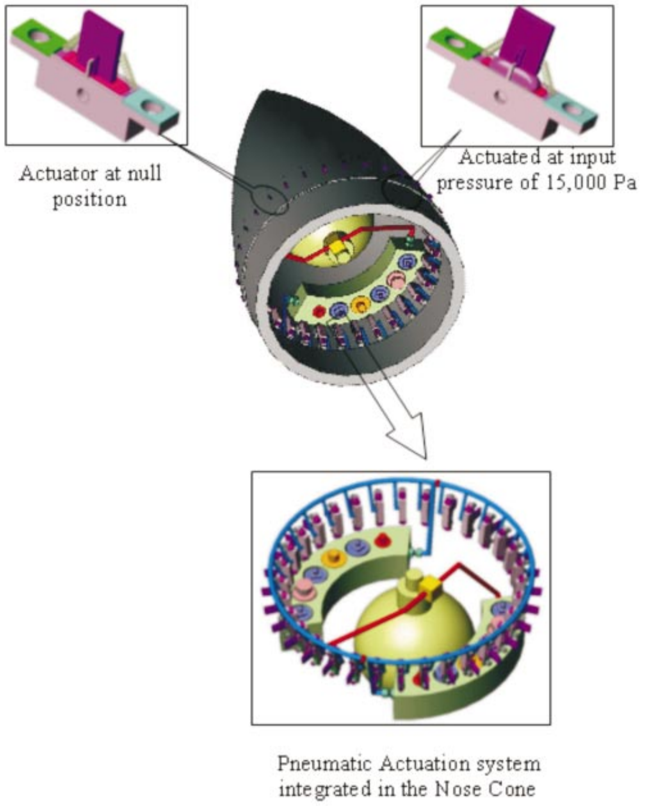


Figure 17. Microballoon actuation system with DFEs integrated in the nose cone.

The above integration studies indicate that the feasibility of integration of DFEs and microballoon actuators in the nose cone exists and one of the important challenges to overcome is design of small plastic springs to keep the DFEs in neutral position during non-operational periods.

4. CONCLUSIONS

The important conclusions drawn are:

(a) The design is found to be completely feasible for integration of microballoon actuators, both within the nose cone and in the control surface of the flight vehicle.

(b) Integration studies indicated the feasibility of realisation of all the three configurations of microballoon actuation system.

(c) The maximum stress induced was about 2.30 MPa and maximum deflection of the packaging was found to be about 6.6 µm at an input pressure of 60,000 Pa.

(d) The deflections of the packagings made of polycarbon were found to be minimum and stiffness of the packagings is maximum and meets the requirements of the flight vehicles.

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