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Design and Structural Analysis of Propulsion Module for Sample Return Mission to 2010TK7

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***Abstract*:- The Earth based Trojan asteroid, later named as 2010TK7, was discovered by the WISE (Wide field Infrared Survey Explorer) space telescope in the year 2010. The objective of the mission is to perform a soft landing on the object, collecting some sample material and safely return it back to Earth for further scientific studies. This paper highlights the design and structural analysis of propulsion module which is attached to Re-entry module. The major load coming on the propulsion module is the inertia loads due to acceleration. FE analyses are to be carried with a longitudinal acceleration of 15g and lateral acceleration of 5g. Maximum expected operating pressure (MEOP) of the propellant tank is 1.7 MPa, Proof pressure 1.87 MPa (with 10 % proof factor). Maximum expected operating pressure (MEOP) of Helium gas bottle is 1.7 MPa. Burst pressure of Helium gas bottle is 69 MPa on the main conical support structure which is designed with a skin shell thickness 2 mm, stringer with 4 mm thick hat section, skin buckling stress 220 N/mm^2, and with maximum column buckling stress of stringer 230 N/mm^2 will be considered based on design load calculations.**

Keywords:- Asteroid, Design, Loads, Re-entry, Structural

1. INTRODUCTION

The earth based Trojan asteroid, later named as 2010TK7 [1], was discovered by the WISE (Widefield Infrared Survey Explorer) space telescope in the year 2010. The detailed orbit analysis carried out later identified it as an object sharing the earth's orbit and revolving around the sun at the L4 Lagrangian point of earth. Though many Trojans were identified for the outer planets, 2010TK7 became the first earth based Trojan to be identified and studied. Most Trojans are expected to be in the L4 or L5 [2] points of earth. Hence they are most likely to appear in the daytime sky and hence are extremely difficult to be identified and observed from earth's surface. The study of this object can not only through light into the origin of earth and the solar system, but also can be of huge socio-economical significance. Though the object is comparatively nearer to earth, it is hard to do any study using earth based or space telescopes due to its small size and rather odd orbital parameters. Detailed analysis of the orbital parameters of the target object revealed that the mission would be characterized by the very large delta-V requirement. The mission intends to perform a soft landing on the object, collecting some sample material and safely return it back to earth for further scientific studies. This paper concerns with the design and structural analysis of Propulsion module. The propulsion module is attached to the re entry module and gives sufficient thrust for onward journey to the Trojan 2010TK7 after the injection of the space craft from the launch vehicle. The propulsion module after separated from the reentry module will hit the Trojan surface for creating a particle cloud and thereby helping the sample collection. In this process, the propulsion module gets self destroyed. The propulsion module and reentry module are kept inside the heat shield, and hence it is protected from all aerodynamic loads in atmospheric flight regime of the launch vehicle. The major load coming on the propulsion module is the inertia loads due to acceleration. The propulsion module consists of the support structure, propellant tanks, gas bottles, feed lines, engine, navigation and guidance, electronic systems etc. Design [3] concerns with main conical support structure, propellant tanks and gas bottle in the propulsion module. Even though the propulsion module is intended to hit the Trojan surface after separation, the structural health after the impact is not estimated since the propulsion module is left at that location and not intended for recovery.

2. SPECIFICATIONS

Configuration of the stage- Conical with propellant tanks attached outside and Helium gas bottles inside

TABLE I Configuration of the stage.

S No	Dimension	Value	Units
1	Total height	1300	mm
2	Bottom side diameter	2000	mm
3	Top side diameter	1200	mm
4	Propellant mass of propulsion module	1350	kg
5	Mass of Helium (He) required	4.3	kg
6	Mass of MMH	500	kg
7	Mass of MON3	850	kg

The main conical support structure has a conical shape with an axial height of 1300 mm, bottom side diameter of 2000 mm and a top side diameter of 1200 mm. The main conical support structure is having interfaces with reentry module at top side and pay load adapter at bottom side. Different configurations are analyzed for the main conical support structure; they include stringer stiffened shell and isogrid construction.

Loads coming on propulsion module are:

1) Inertia loads due to acceleration.
2) The maximum longitudinal (axial) acceleration expected is 13 g.

3) Maximum lateral acceleration is 5 g.
4) Maximum expected operating pressure (MEOP) of the propellant tank - 1.7 MPa.
5) Proof pressure - 1.87 MPa (with 10 % proof factor).
6) MEOP of He gas bottle - 34.5 MPa
7) Burst pressure of He gas bottle - 69 MPa

In order to accommodate the high thermal loads in space environment, adequate thermal protection systems will be provided. Hence thermal loads are not considered for structural design. Design of main conical support structure and propellant tanks are given by:

TABLE II Main conical support structure

S. No	Type of section	Value	Units
1	Skin shell thickness	2	mm
2	Stringer with thick hat section	4	mm
3	Skin buckling stress	220	$\frac{N}{mm^2}$
4	Column buckling stress of stringer	230	$\frac{N}{mm^2}$
5	Axial stress noticed in the skin	89	$\frac{N}{mm^2}$
6	Axial stress noticed in the stringer	69	$\frac{N}{mm^2}$
7	Margin on skin buckling	1.47	
8	Margin on column buckling	2	

TABLE III Propellant tanks

S. No	Specification	Value	Units
1	Volume of MON3 tank (with 3 % ullage)	608	Liters
2	Volume of MMH tank (with 3 % ullage)	585	Liters
3	Yield strength of Ti6Al 4V ELI grade	880	$\frac{N}{mm^2}$
4	Estimated ID of MON3 tank	861	mm
5	Estimated ID of MMH tank	850	mm
6	Thickness of MON3 tank	1	mm
7	Thickness of MMH tank	1	mm

Volume of Helium gas bottle – 39 Liters (2 gas bottles considered). Estimated ID of Helium gas bottle is 318 mm (Fibre wound helium gas bottles with Ti6Al4V Inner liner is suitable. However, if it is decided to go ahead with the uni-thick shell construction for gas bottles also, the required thickness at this pressure is 6.5 mm, for Ti6Al4V ELI grade material).

3. RESULTS AND DISCUSSION

Different configurations are analyzed for the main conical support structure; they include Stringer stiffened shell and isogrid construction. After detailed analyses it is decided to configure the main conical support structure as a conical stiffened shell structure stiffened by stringers. The Conical shell is made of Aluminum alloy AA 2219 in T87 condition having 2 mm shell thickness. The skin stringers are of hat section and have a thickness 4 mm. The numbers of stiffeners provided are 40 in longitudinal direction and 12 in circumferential direction. Four cut outs are provided at the main conical support structure to avoid the extensive external protrusion of propellant tanks. FE analyses carried out considering quarter symmetry. Ansys 14.5 [4] commercial FEM based software is used for analyzing the structure. Four node shell elements SHELL181 are used for meshing the shell structure and 3-D two node beam elements BEAM188 are used for meshing the skin stringers. MASS21 elements are used for lumping the mass of the reentry module, propellant tanks, propellant loaded, engine and helium gas bottles. FE analyses carried out with a longitudinal acceleration of 15 g and lateral acceleration of 5 g. Symmetry boundary conditions are considered at the ends of the conical shell structure modeled. Bottom nodes of the structure are axially supported.

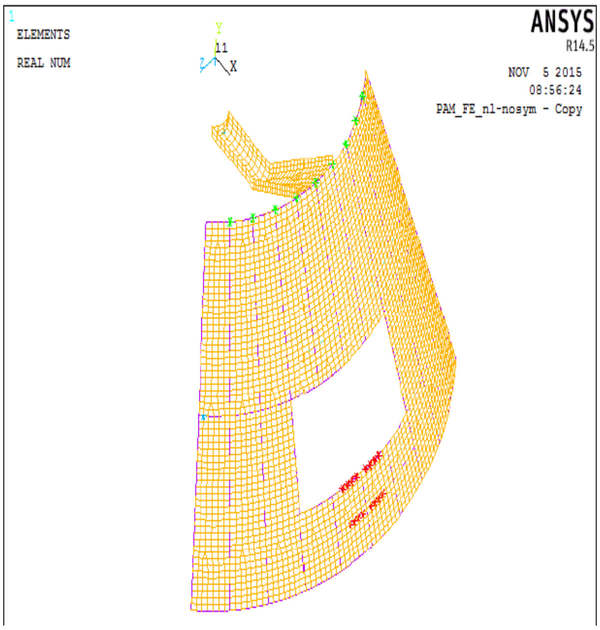

Figure 1 FE model of the propulsion module main conical support structure.

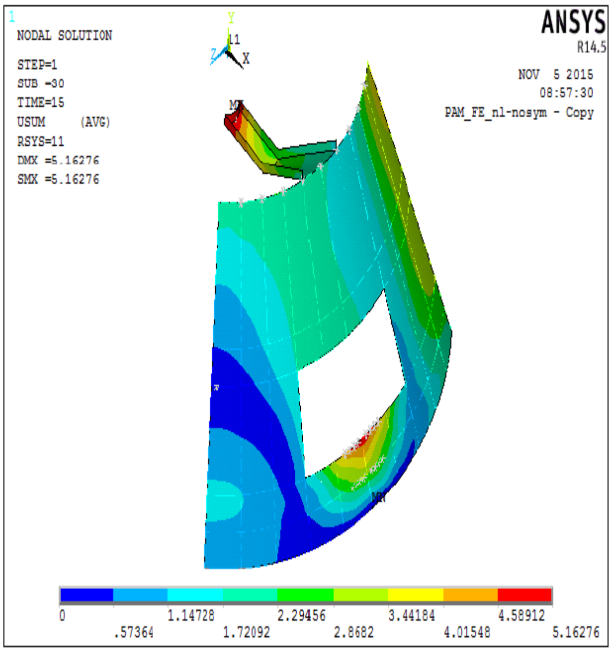

Figure 2 Resultant displacement distribution in propulsion module main conical support structure

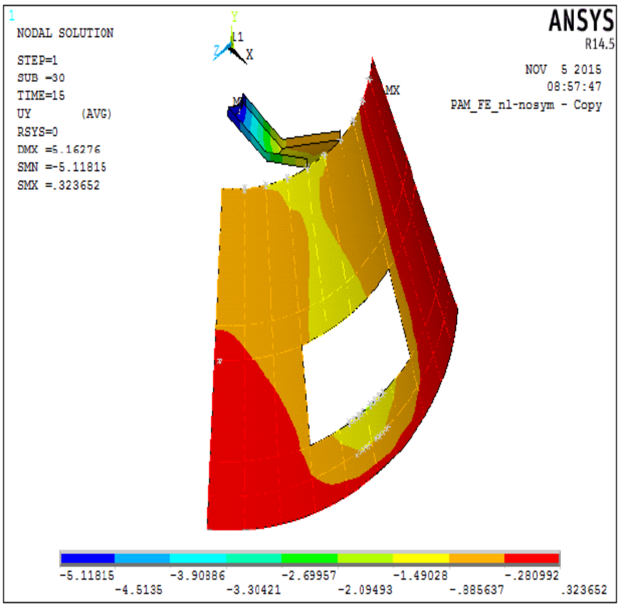

Figure 3 Axial displacement distributions in propulsion module main conical support structure.

FE analyses carried out for the propellant tanks simulating the pressure loads and inertia loads.

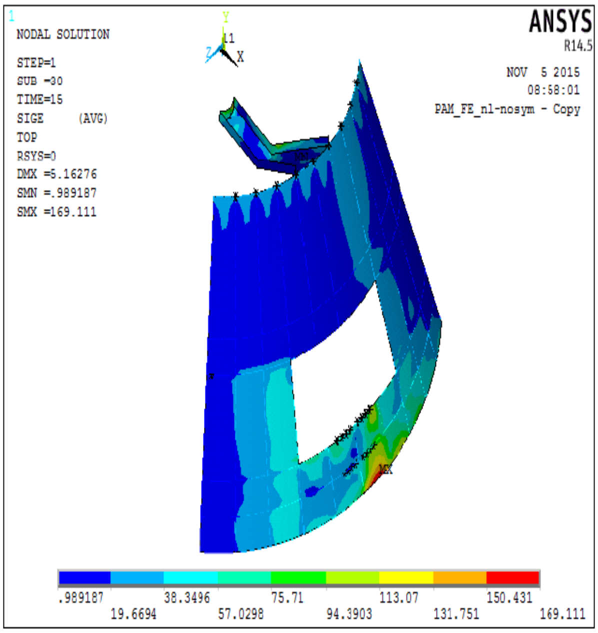

Figure 4 Von Mises stress distribution in propulsion module main conical support structure.

Fig. 1 shows the FE model. The radial displacement distribution in main conical support structure is shown in Fig. 2 Axial displacement distribution in propulsion module main conical support structure is shown in Fig .3. The von Mises stress distribution in propulsion module main conical support structure is shown in Fig. 4. Modal analysis of the main conical support structure is carried out with masses of re-entry module, engine, propellant tanks and gas bottle lumped at the attachment locations. FE model used for modal analysis is shown in Fig. 5. The first natural frequency noticed is 20 Hz and it is sufficiently away from the fundamental frequency associated with the launch vehicle. The first mode of modal analysis is shown in Fig. 6

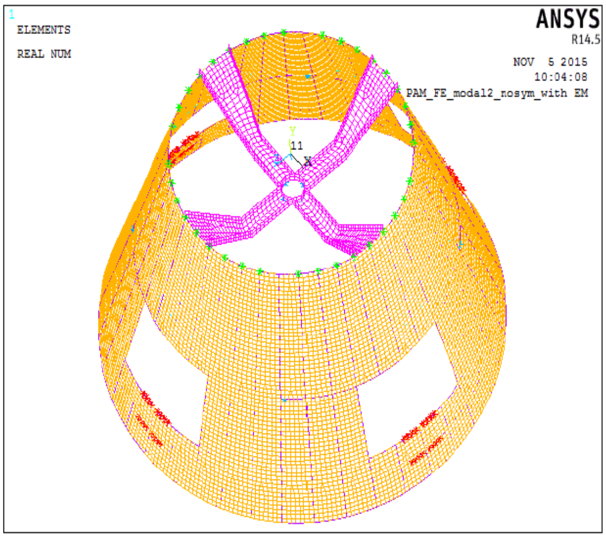

Figure 5 FE model for modal analysis of propulsion module main conical support structure.

Since both of the tanks are made of 1 mm thick Ti6Al4V ELI sheets and both are having the same maximum expected operating pressure, the MON3 tank which is having the higher diameter (there by more critical) is selected for FE analyses

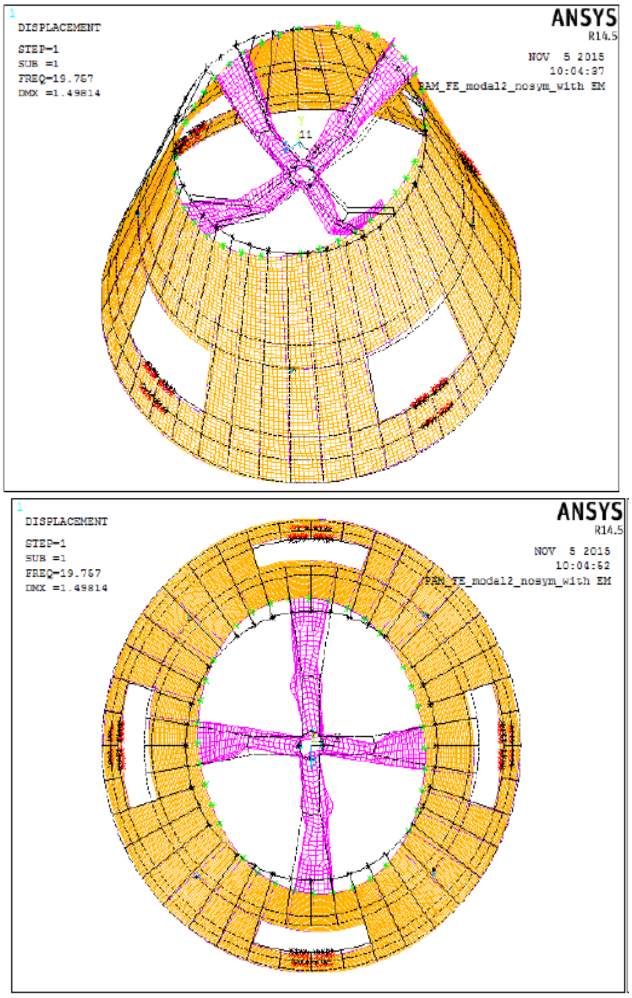

Figure 6 First natural frequency mode of propulsion module main conical support structure

The FE model of the propellant tank is shown in Fig. 7. PLANE82 2D eight noded axisymmetric structural solid elements are used for meshing geometry. The internal pressure input is 1.87 MPa (proof pressure test requirement). The displaced configuration is shown in Fig. 8.

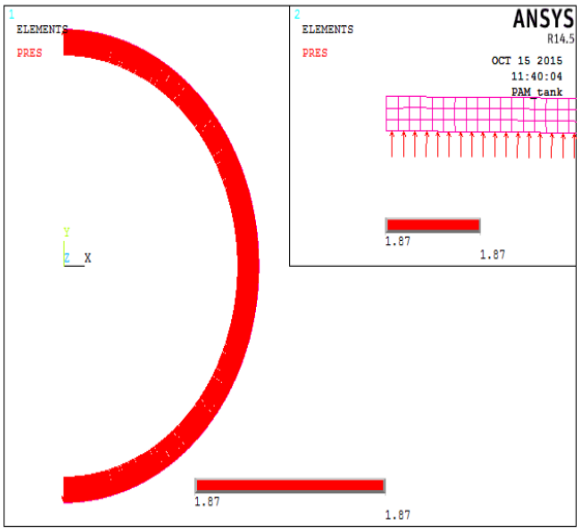

Figure 7 FE model of the propellant tank in propulsion module

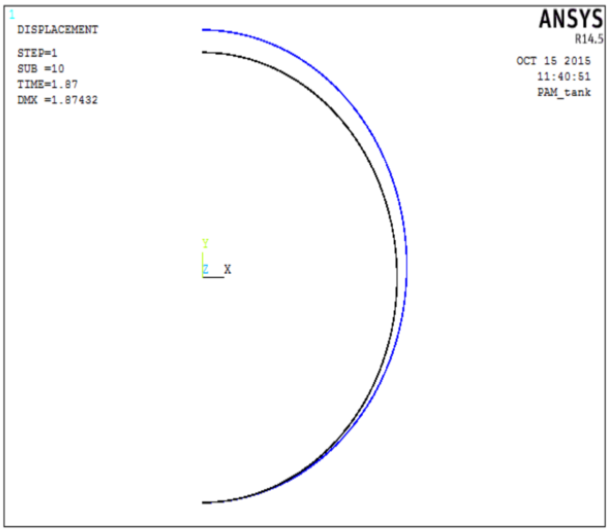

Figure 8 Displaced configuration of the propellant tank under internal pressure

The von Mises stress distribution under proof pressure is shown in Fig. 9. The total strain distribution at proof pressure is given in Fig. 10. The FE analyses extended to ultimate pressure to see that there is no possibility of bursting even at ultimate pressure. The von Mises stress distribution under ultimate pressure is shown in Fig. 11. FE analyses repeated with the inertia loads acting on the propellant tank with internal pressure. The von Mises distribution in the propellant tank with inertia loads at proof pressure is shown in Fig. 12.

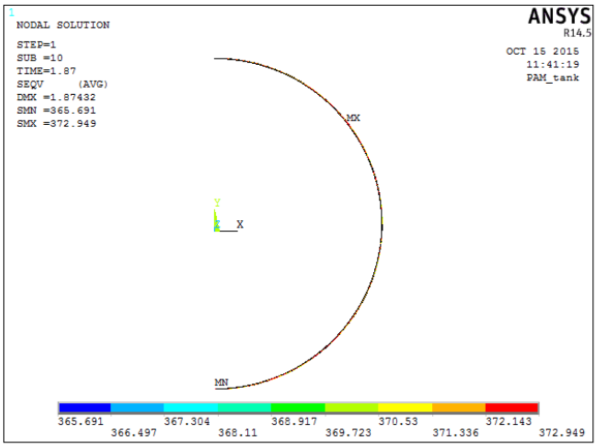

Figure 9 Von Mises stress distribution in the propellant tank under proof pressure

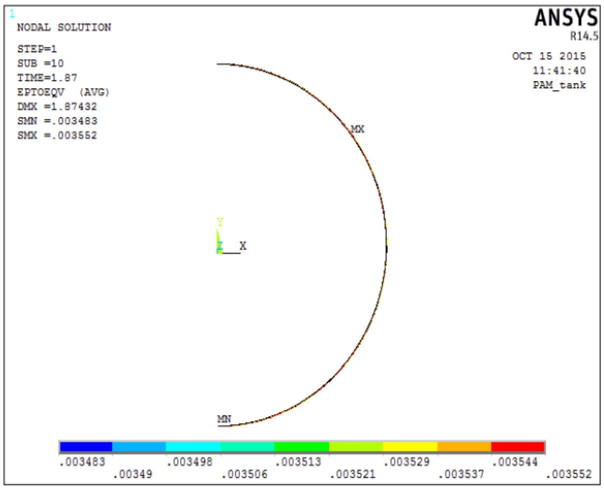

Figure 10 Total strain distribution in the propellant tank under proof pressure

Total estimated dry mass of the stage is 390 kg. The total mass at lift off including propellant loading is 1750 kg.

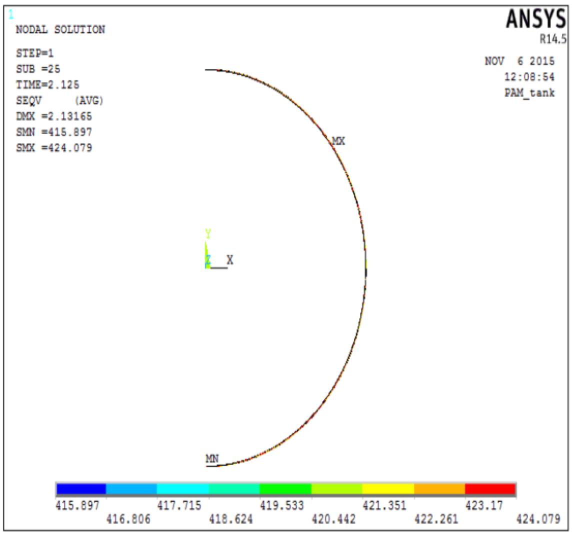

Figure 11 Von Mises stress distribution in the propellant tank under ultimate pressure

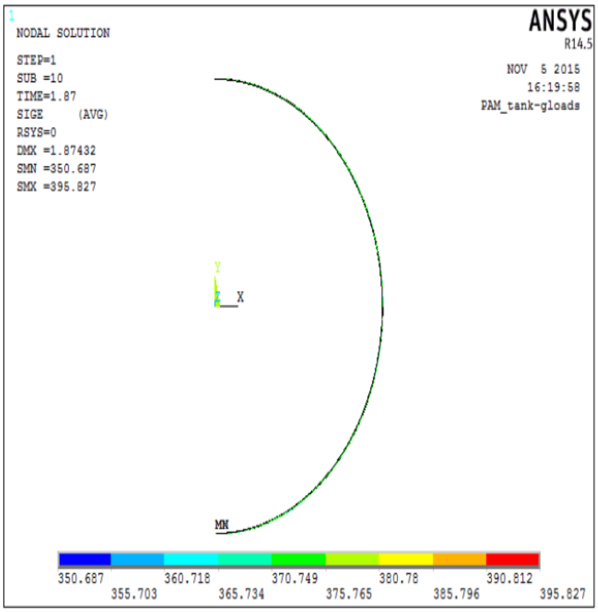

Fig. 12 Von Mises stress distribution in the propellant tank with inertia loads under proof pressure

4. CONCLUSION

The structural configuration scheme of the propulsion module for '2010TK7 sample return mission' is finalized. Preliminary structural design and analyses of propulsion module also carried out. Sufficient margins are available for the analyzed structures. More optimization studies, interface design and assembly details are to be worked out in the detailed design phase. A structural qualification and testing plan is to be generated after detailed design. More optimization studies, interface design and assembly details are to be worked out in the detailed design phase.

5. REFERENCES

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