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# **Analysis of Slosh Oscillations in a Launch Vehicle**

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**ABSTRACT:** For deep space exploration, normally liquid fuel and oxidizer are used for the propulsion. Normally large containers are used to store these cryogenic liquids. When the tanks are partially full or partially empty, the liquid starts oscillating which generates a side force and that produces vibration and an unstable moment about center of gravity of the vehicle.

The effect of slosh on the natural frequencies of vehicle is studied in this paper. First a finite element model of the structure and its free vibration frequencies and modes are studied. Subsequently, appropriate model for the slosh mass is added and its effect on natural frequencies of the vehicle is studied.

## **I. INTRODUCTION**

The phenomenon of fluid sloshing can be understood as the motion of the free surface of the liquid in a partially filled container. When a partially filled container is subjected to external forces, the effect of sloshing occurs. Sloshing causes additional forces and moments which change the dynamics and stability of the vehicle. Liquid sloshing on one side affects the flow dynamics, on the other side it may also be detrimental for the container. With regards to a liquid propellant launch vehicle, the effects of slosh [1] show negative effects such as additional fluid strike, tank vibration, pressure drop, structural damage and control system failure.

When the fluid interacts with the walls of the container, the energy exchange takes place between the two and the fluid can show different types of motions. The fluid can have motions like planar, rotational, chaotic, etc. depending upon the external excitation.

The basic problem of liquid sloshing involves the estimation of hydrodynamic pressure distribution, moments, forces and natural frequencies of the free surface of the liquid. The above mentioned parameters directly affect the dynamic stability and performance of a moving container. The slosh dynamics of propellant tanks can be represented by an equivalent mass pendulum-spring-dashpot mechanical model. The parameters of this equivalent model, identified as slosh mechanical model parameters, are slosh frequency, slosh mass, and pendulum hinge point location.

With cryogenic propellants have virtues of high specific impulse and easy availability, especially liquid hydrogen and oxygen due to which they are commonly used in rocket engines, a point to be noted is that they have low viscosity, meaning even a slight disturbance to the launch vehicle can cause enormous motion of the fluid present, leading to undesirable effects as mentioned above [2].

## **II. LITERATURE REVIEW**

Solving the problem of slosh involves the estimation of physical properties such as forces, moments, hydrodynamic pressure and the natural frequencies of the free-liquid surface. These parameters have a direct influence on the dynamic stability of the spacecraft [3]. Liquid oscillations in spinning fuel tanks produce very different response characteristics compared to those of non-spinning fuel tanks [4]. A liquid sink model was developed by Thomson [5], which included small and passive sources of energy dissipation, but it failed because of the extraordinarily high mass fraction of fuel to the total mass of the launch vehicle. Weihs and Dodge [6] illustrated that the free surface effect in containers can be left out in case of small depths in the container. A 3-D pendulum model was proposed by Green, et al., [7]. They proposed a rotary oscillator concept to simulate the torque resonance in tangential and radial directions. This rotary oscillator model was superimposed on the pendulum model to provide the overall response of liquid oscillation in the tank.

Analytical solutions are limited to regular geometric tank shapes such as cylindrical, and rectangular. The nature of sloshing dynamics in cylindrical tanks is better understood than for prismatic tanks. However, analytical techniques for predicting large-amplitude sloshing are still not fully developed. Such loads are extremely important in the design stage of supporting structures and internal components of vehicle tanks.

Development of a more accurate model currently lies in a more generalized model incorporating masses, springs and dampers. Translational and rotational motion about three axes in a rectangular coordinate system allows the sloshing mass to move with less restriction. Parameters describing the model include the inertia tensor of the fuel, spring constants, and damper coefficients. Refinement of these parameters allow for the most accurate simulation of fuel slosh [8].

Glenn Research Center (GRC) scientists have been researching the behavior of fluids in 1-g and low gravity since the 1950s [9], with a focus in safely and efficiently managing cryogenic propellants. Research into essentially all areas of Cryogenic Fluid Management (CFM) has been conducted at GRC, including acquisition, stratification, thermal control, pressurization, transfer, and slosh. Various ground and flight experiments, many of which occurred before modern numerical modeling was possible, have been conducted by GRC to test the various technologies associated with CFM.

Baffles of various configurations have been devised which add a small amount of damping to the system and mainly affect the magnitude of the slosh forces and the amplitude of the liquid motion. If a shift in the range of the fluid natural frequencies is desired, a more effective method is to divide the tank into sub-tanks by means of radial or concentric walls, which has led to interest in the ring sector tank and its variations.

### III. OBJECT OF THE WORK

The focus of this project is to analyze the effect of propellant slosh in a generic liquid propellant launch vehicle and obtain the elastic modes and rigid modes at different levels in the storage tank. The emphasis is on the analysis of this slosh motion in a rigid cylindrical container, present in the launch vehicle and to observe and determine the overall effect of this motion on the launch vehicle.

Two conditions are taken into account to determine the behavior of the launch vehicle, i.e., when the level of the fuel in the tank is at eight-five percent (85%) of the height of the fuel tank and at fifty-five percent (55%) of the height of the fuel tank. The fuel tank is chosen to be in a cylindrical shape with a flat bottom and the boosters of the rocket are not taken into consideration to avoid complexity in the problem.

### IV. MATHEMATICAL BACKGROUND

This study is conducted assuming that the tank is rigid in nature, the fluid is homogeneous, non-viscous and incompressible in nature and that the fluid field is irrotational.

The natural frequencies, mode shapes, potential functions, free surface displacements, and forces and moments are known for a variety of geometries. During slosh in a cylindrical container, the lower part of the liquid shows oscillatory motion as though only the liquid in the vicinity of the free surface. As the frequency of oscillation of free surface increases, the motion penetrates to a lower depth in the container. For liquid depth (h) to diameter (d) ratio ( $h/d > 1$ ), the liquid natural frequencies may be considered independent of liquid depth. In the case of a circular cylindrical tank, the orthogonality condition for trigonometric functions ensures that antisymmetric motion is the only class of motion which contributes to the net horizontal force and the moment exerted by the liquid on the container [10].

#### Governing Equation:

Consider a cylindrical tank with its axis vertical, the z axis of an r,  $\Theta$ , z and filled to a depth 'h' with an ideal fluid. The final equation considering the boundary conditions is as follows:

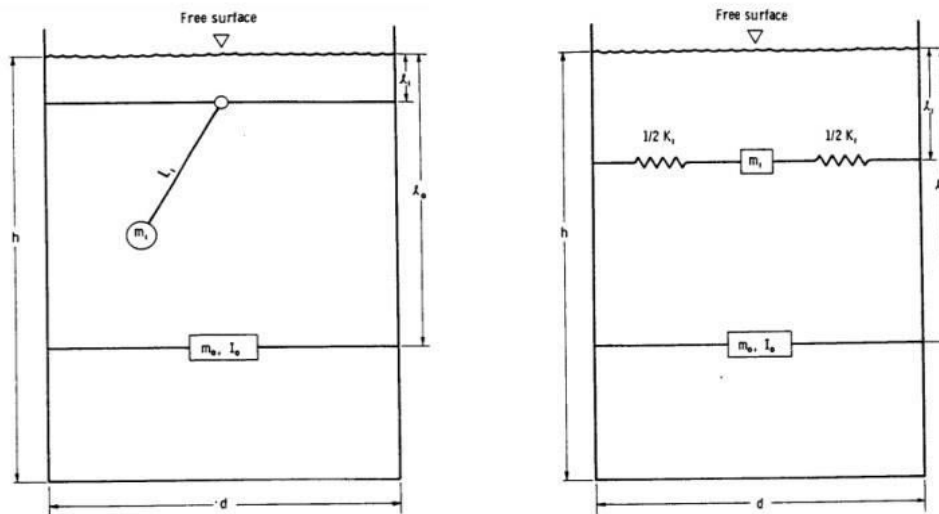
$$I_o + m_o l_o^2 + m_1 l_1 = I_{rigid} + m_T \left( \frac{h}{2} \right)^2 - \frac{m_T * d * d}{8} \left[ 1.995 - \frac{d}{h} \left( \frac{1.07 \cosh * 3.68 \frac{h}{d} - 1.07}{\sinh 3.68 \frac{h}{d}} \right) \right];$$

where:

' $I_o$ ' is the moment of inertia of the fixed mass ( $\text{kg.m}^2$ )

- ' $m_0$ ' is the mass of fixed element (kg)
- ' $l_0$ ' is the distance of fixed mass from free surface (m)
- ' $m_1$ ' is the mass of the first element from free surface (kg)
- ' $l_1$ ' is the distance of first element from free surface (m)
- ' $m_T$ ' is the total mass of fluid (kg)
- ' $I_{rigid}$ ' is the rigid moment of inertia ( $kg \cdot m^2$ )
- ' $d$ ' is the diameter of the cylindrical tank (m)
- ' $h$ ' is the height of the cylindrical tank (m)

For reference to the above equation, the cylindrical tank is analyzed as an equivalent mechanical model. A complete mechanical analogy for transverse sloshing must include an infinite number of oscillating masses, one for each of the infinite sloshing modes. A detailed analysis shows that the size of each of these pendulums or spring-mass elements decreases rapidly with increasing mode number. Thus, it is generally acceptable to include only the pendulum or spring-mass corresponding to the fundamental mode in the mechanical model. The model parameters may be calculated directly from the sloshing force and moment analysis [11]. The two mechanical models to demonstrate the slosh in cylindrical containers is shown below [11]:



The diagram on the left shows the pendulum analogy of slosh in cylindrical tanks and the diagram on the right shows the spring-mass analogy of slosh in cylindrical tanks.

The Finite Element Analysis (FEA) for this problem was done using MSC NASTRAN (solver 103). CAD Geometry, which was created in CATIA was imported in the Hypermesh software, where MMKS (mm,kg,N,s) were considered. Mid mesh, an automated mesh generation tool in Hypermesh was used to create the mesh on the geometry. The material property 'MAT1' card image was selected, signifying that the material is linear and isotropic. The physical properties of aluminum were entered.

Analysis was done on the cylindrical container in three conditions, where the container was considered empty, 55% filled and 85% filled. Properties of mesh element were imported using the 'PSHELL' card. The thickness is given to be 15mm (about 0.59 in). Similarly, for masses  $m_1$  and  $m_0$ , the property cards 'PELAS' and 'PMASS' were used to define the properties of tank filled at 55% and 85%.

**V. RESULTS AND DISCUSSIONS**

Comparison of elastic modes of partially filled tank (at 85% and at 55%) with that of empty tanks:

Sl. No.	Elastic Mode no.	Frequency for empty tank (Hz)	Frequency for 85% filled tank (Hz)
1	1	2.836987	1.627085
2	2	2.837527	1.627396
3	3	7.45249	4.987472
4	4	7.453972	4.988432
5	5	10.7111	8.802945
6	6	13.50775	10.75866
7	7	13.5115	10.76103
8	8	15.69096	13.49053
9	9	15.69244	13.49609
10	10	16.08263	16.35694

Table 1: Elastic modes of empty tank and 85% filled tank (mesh size 11)

It is observed that the frequencies of the partially filled tank are lower than the frequencies of the vehicle with empty tank until the 10th mode of natural frequency where frequency of the vehicle with slosh/fuel mass is higher than the vehicle with empty tank.

Sl. No.	Elastic Mode no.	Frequency for empty tank (Hz)	Frequency for 55% filled tank (Hz)
1	1	2.864779	1.696936
2	2	2.864965	1.697058
3	3	7.52533	4.624184
4	4	7.525576	4.624462
5	5	10.81415	9.932235
6	6	13.64092	9.932622
7	7	13.64207	9.93296
8	8	15.8294	16.04255
9	9	15.83136	16.04463
10	10	16.22516	16.28004

Table 2: Elastic modes of empty tank and 55% filled tank (mesh size 10)

It is observed that for a 55% filled fuel tank, the frequencies of the vehicle with empty tank have higher values than the frequencies of the partially filled tank. Until the eighth mode of vibration is reached, where frequencies of the vehicle with slosh/fuel mass have greater value than the previous.

### VI. MODE SHAPES

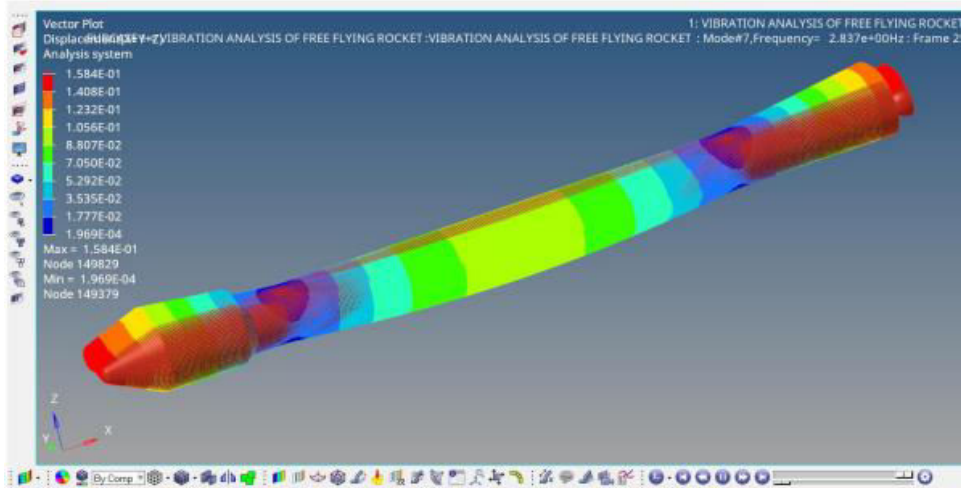


Fig: First elastic mode shape of the empty tank

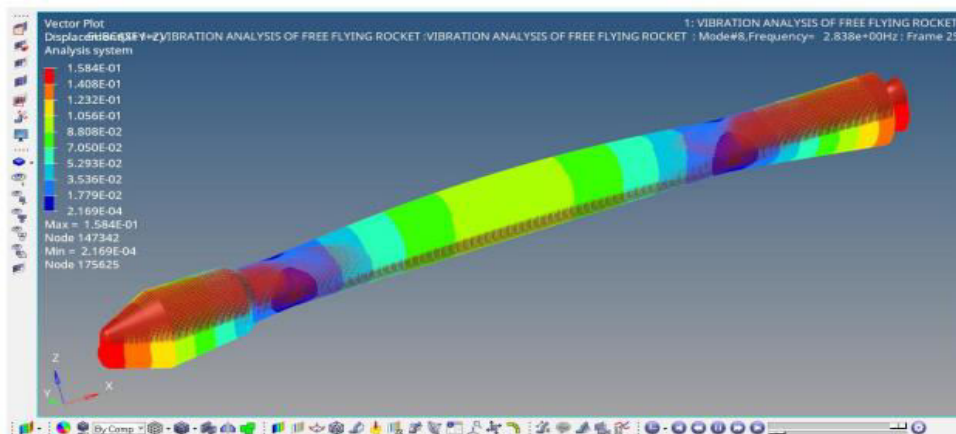


Fig: Second elastic mode shape of the empty tank

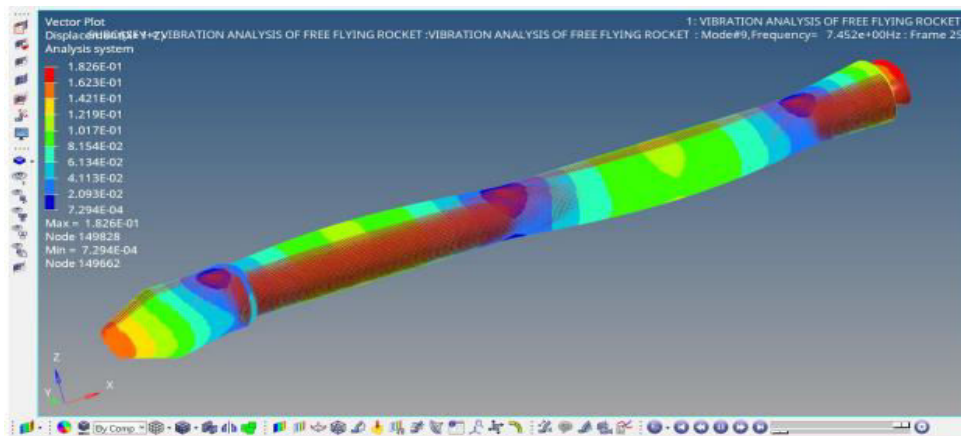


Fig: Third elastic mode shape of the empty tank

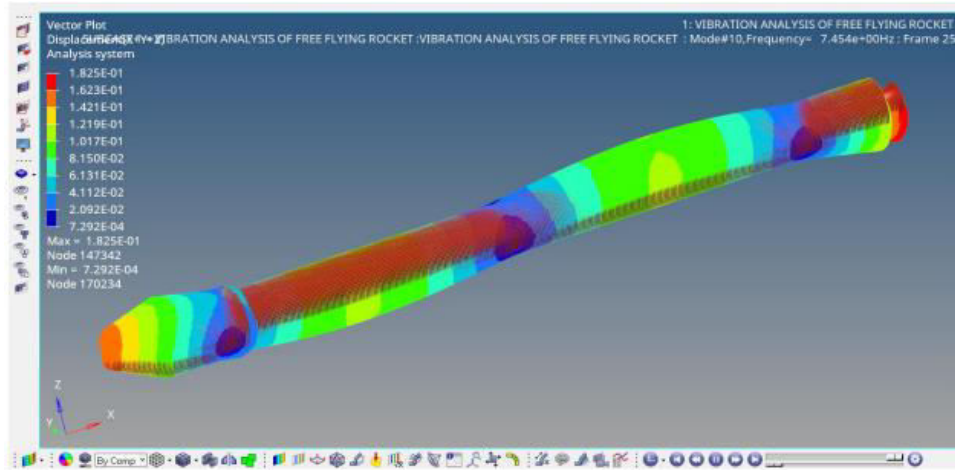


Fig: Fourth elastic mode shape of the empty tank

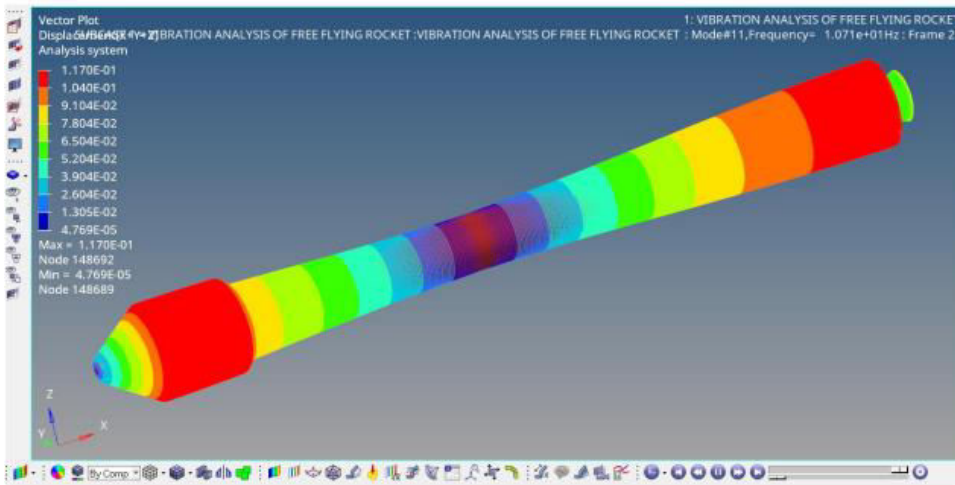


Fig: Fifth elastic mode shape of the empty tank

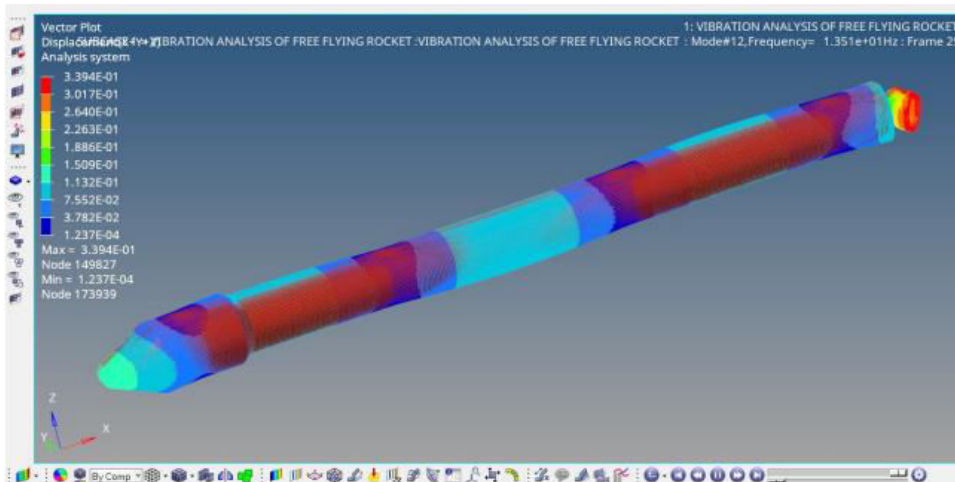


Fig: Sixth elastic mode shape of the empty tank

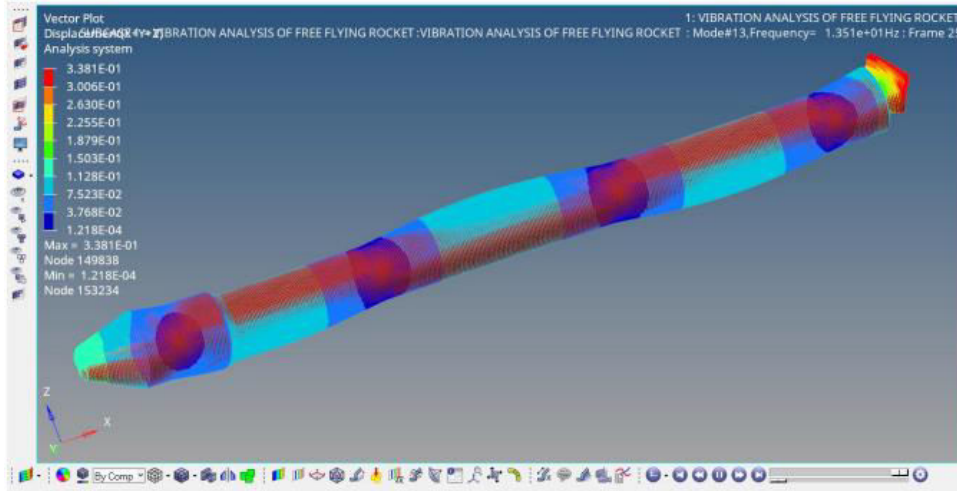


Fig: Seventh elastic mode shape of the empty tank

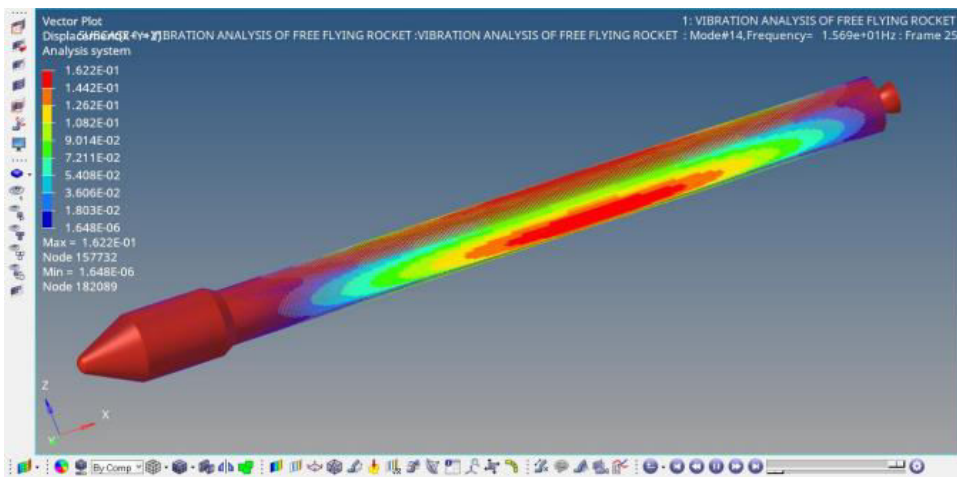


Fig: Eighth elastic mode shape of the empty tank

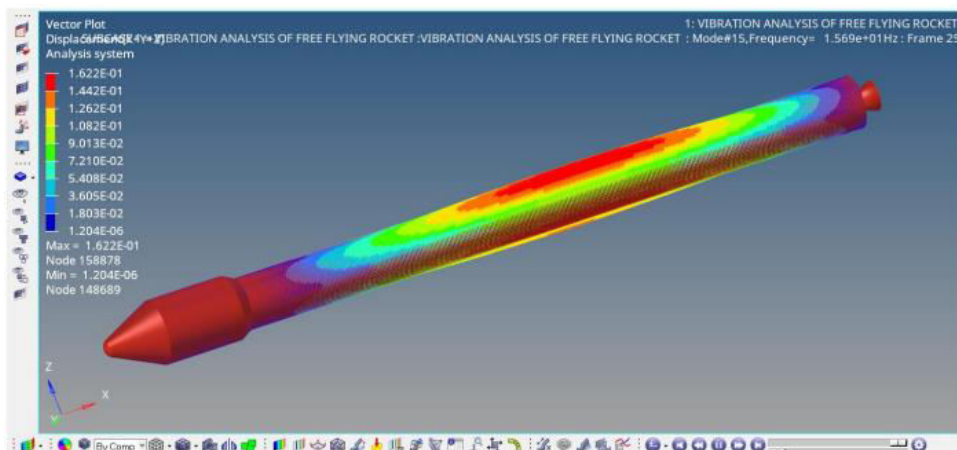


Fig: Ninth elastic mode of the empty tank



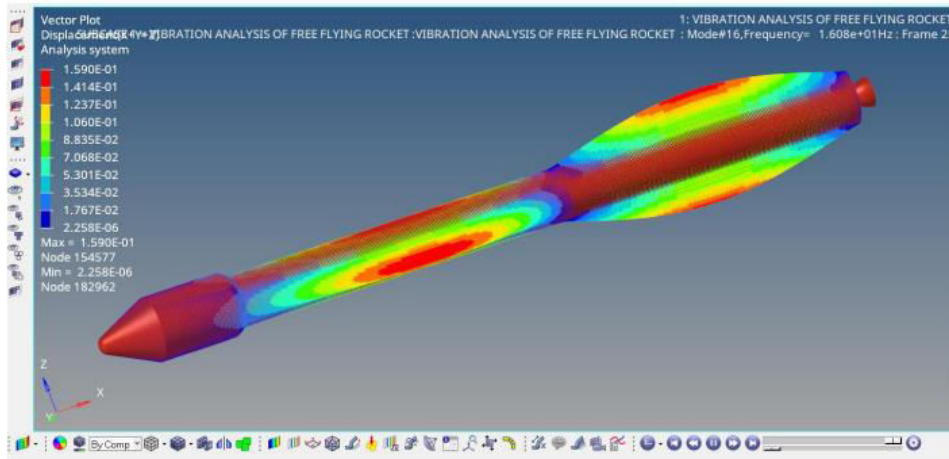


Fig: Tenth elastic mode of the empty tank

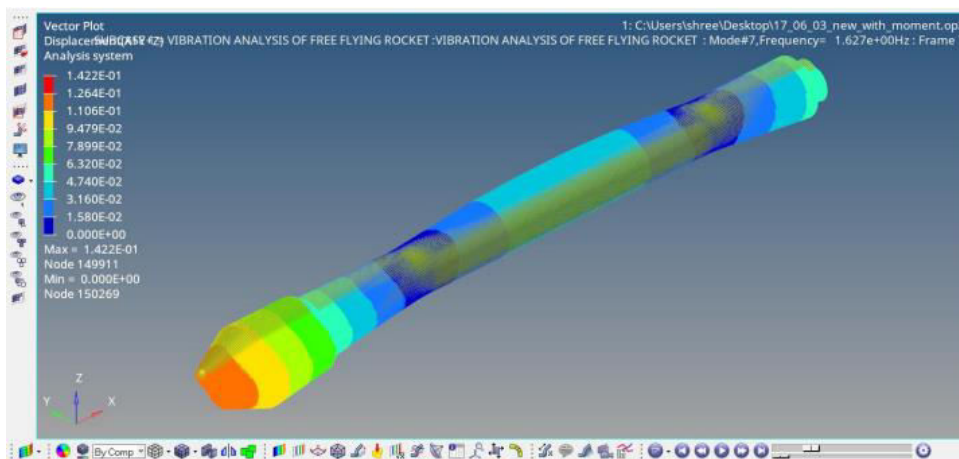


Fig: First elastic mode for 85% filled tank

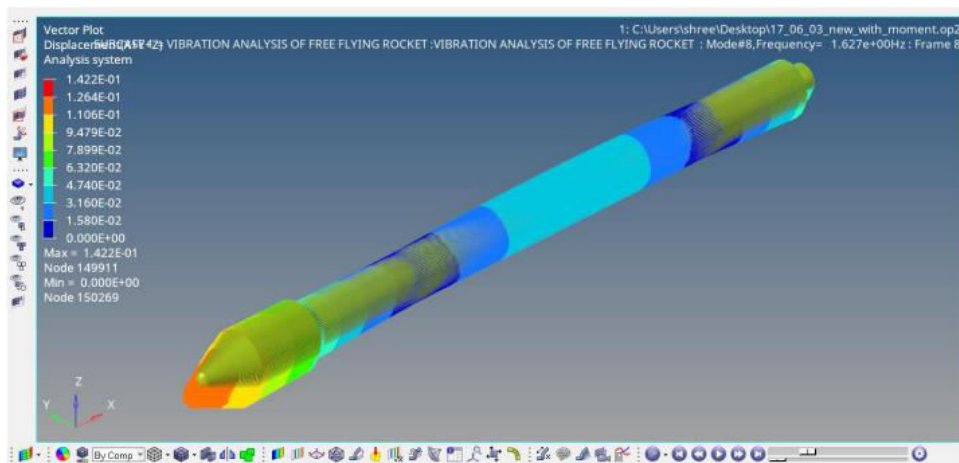


Fig: Second elastic mode for 85% filled tank

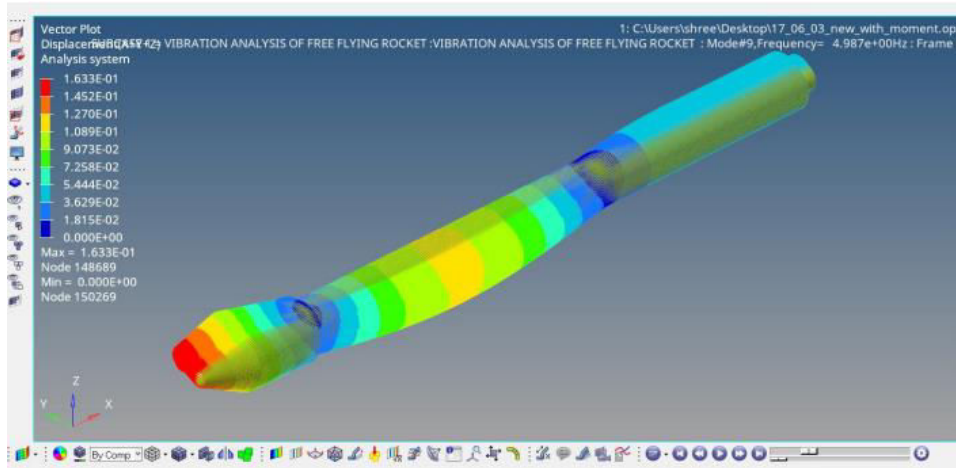


Fig: Third elastic mode for 85% filled tank

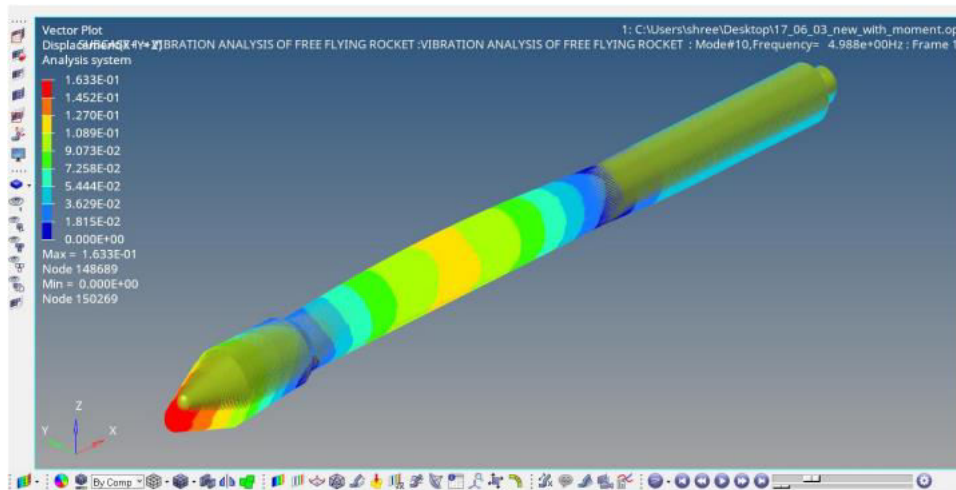


Fig: Fourth elastic mode for 85% filled tank

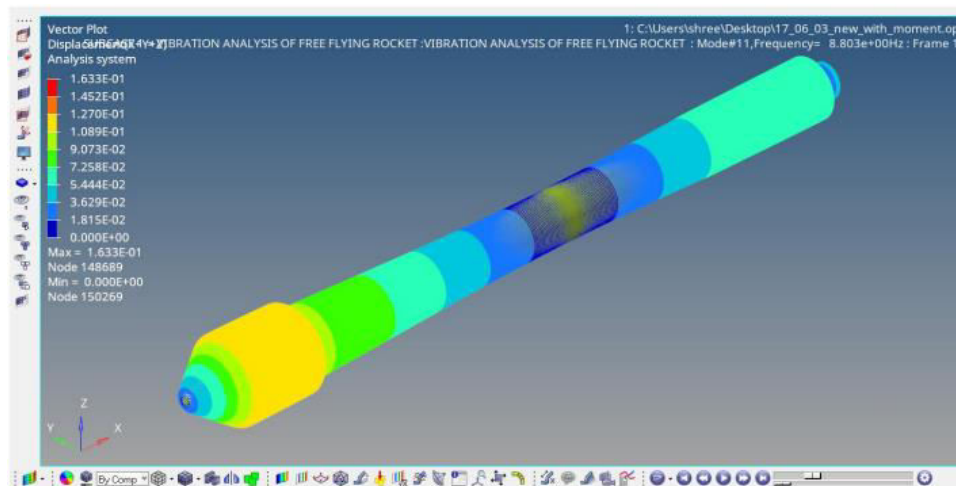
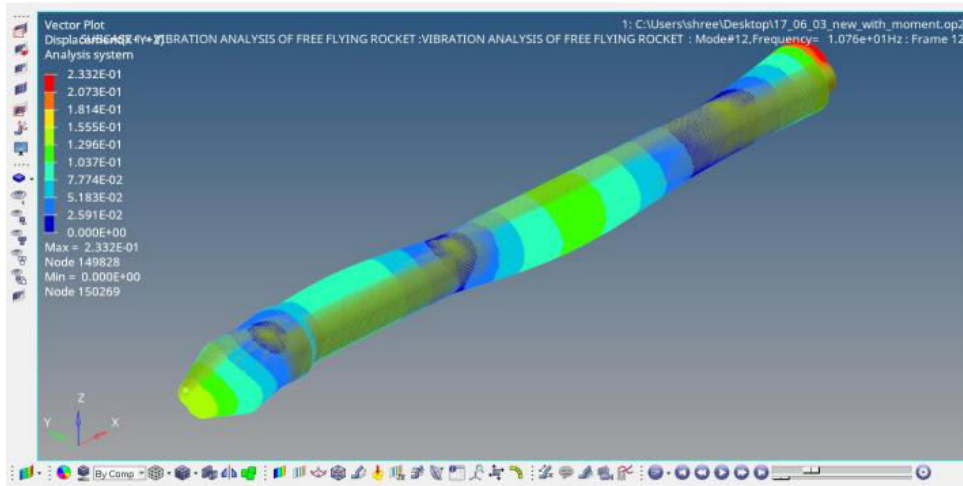
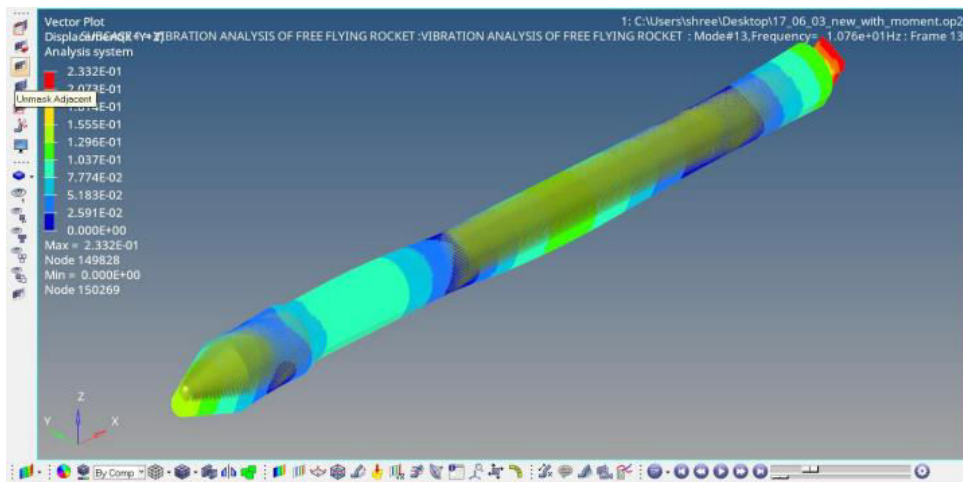


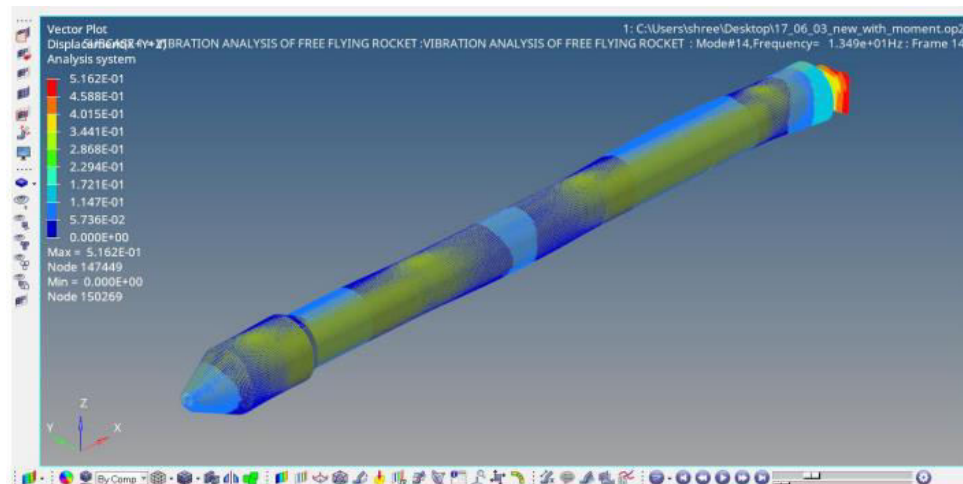
Fig: Fifth elastic mode for 85% filled tank



**Fig: Sixth elastic mode for 85% filled tank**



**Fig: Seventh elastic mode for 85% filled tank**



**Fig: Eighth elastic mode for 85% filled tank**

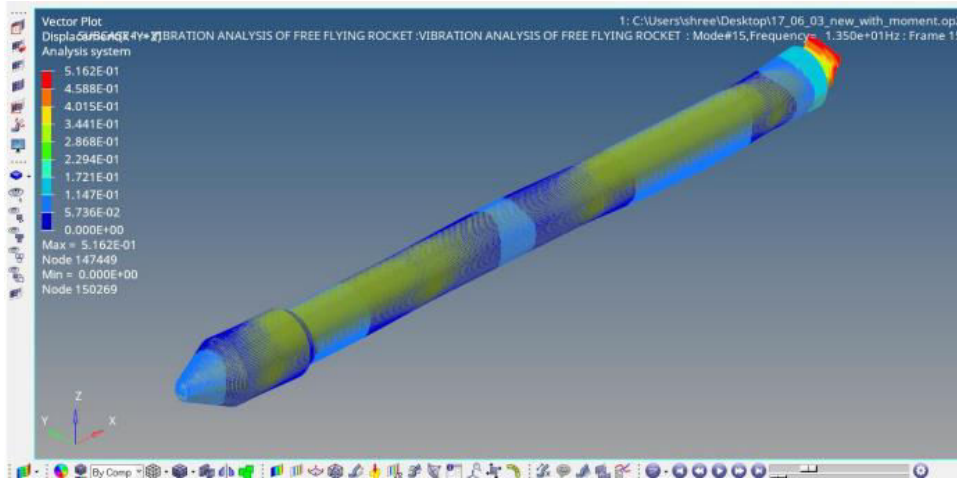


Fig: Ninth elastic mode for 85% filled tank

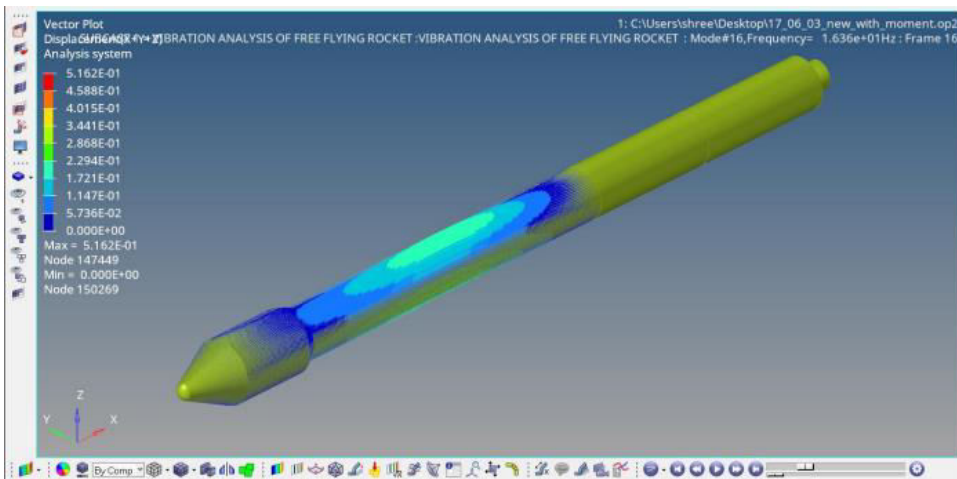


Fig: Tenth elastic mode for 85% filled tank

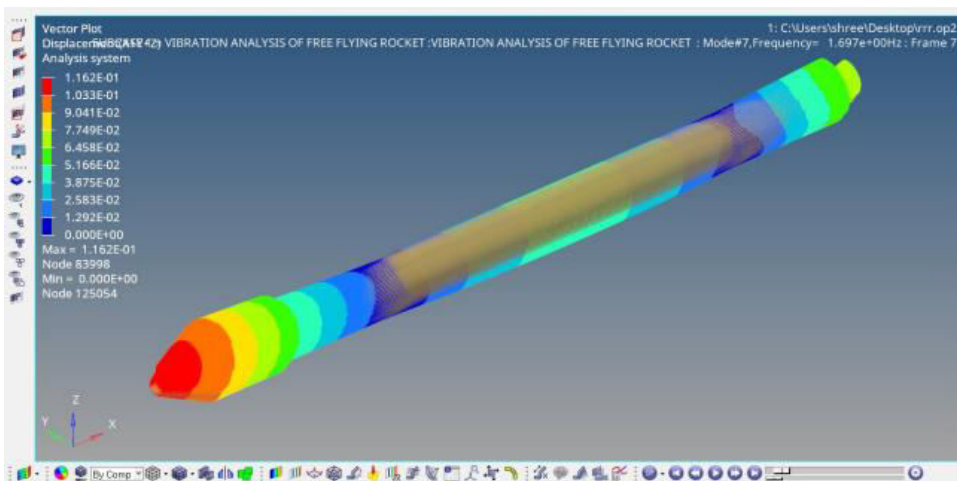


Fig: First elastic mode for 55% filled tank

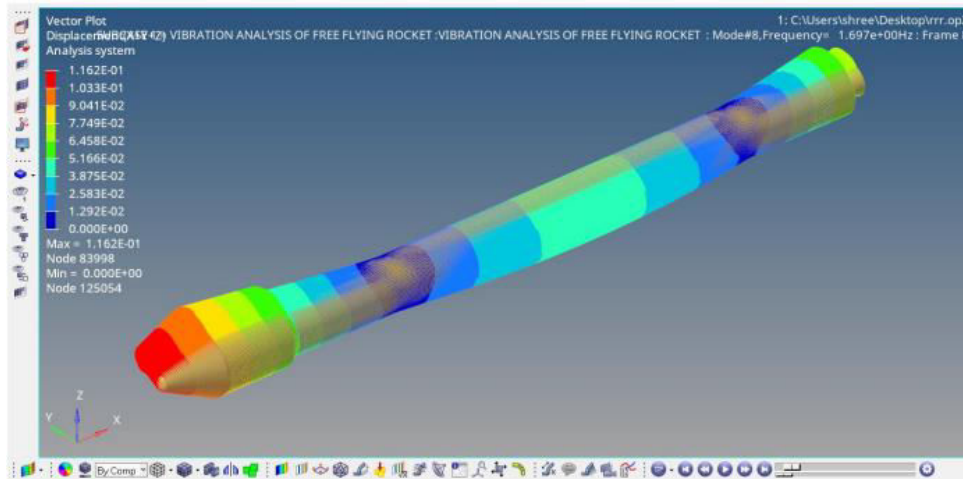


Fig: Second elastic mode for 55% filled tank

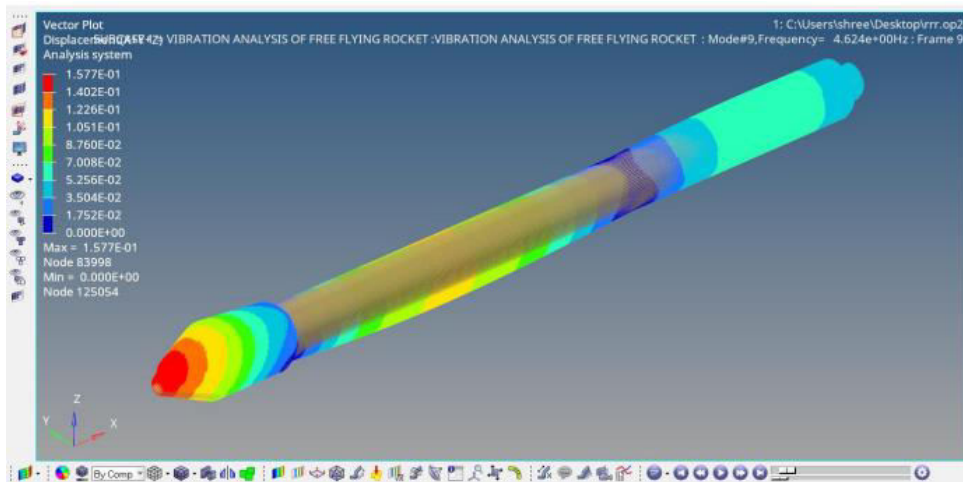


Fig: Third elastic mode for 55% filled tank

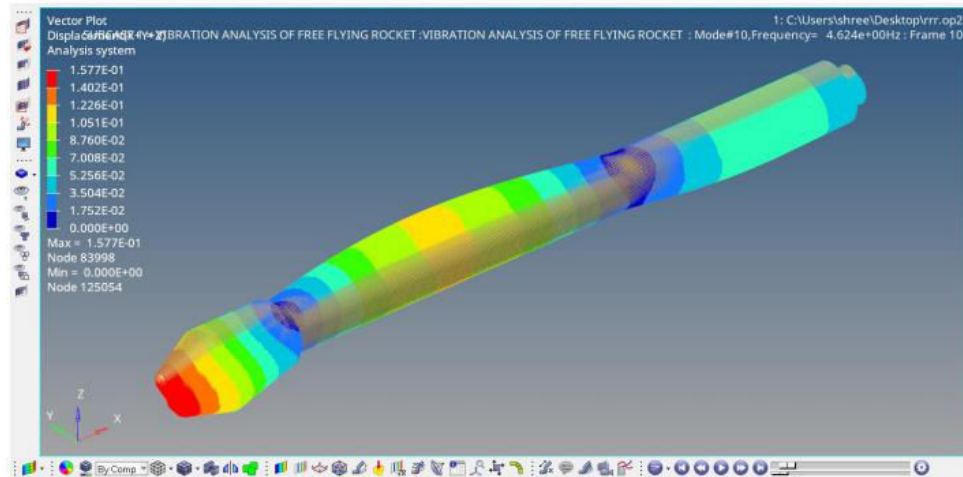


Fig: Fourth elastic mode for 55% filled tank

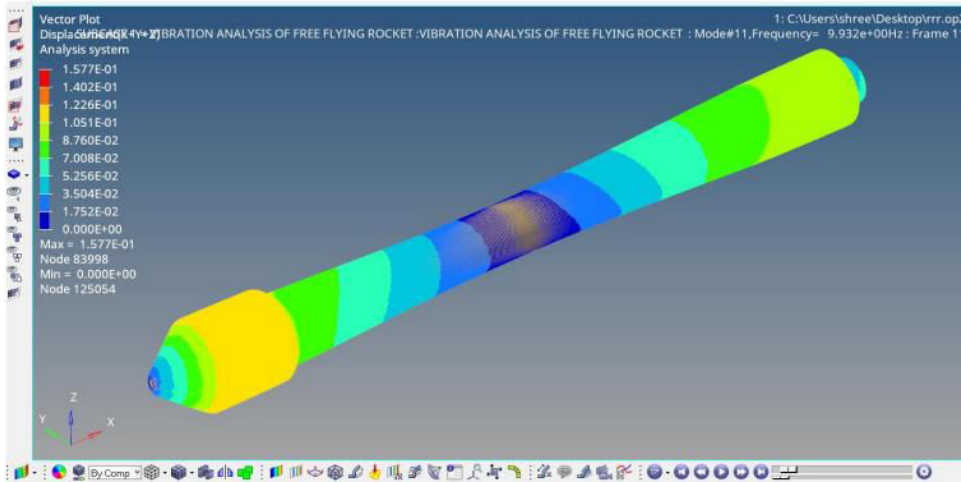


Fig: Fifth elastic mode for 55% filled tank

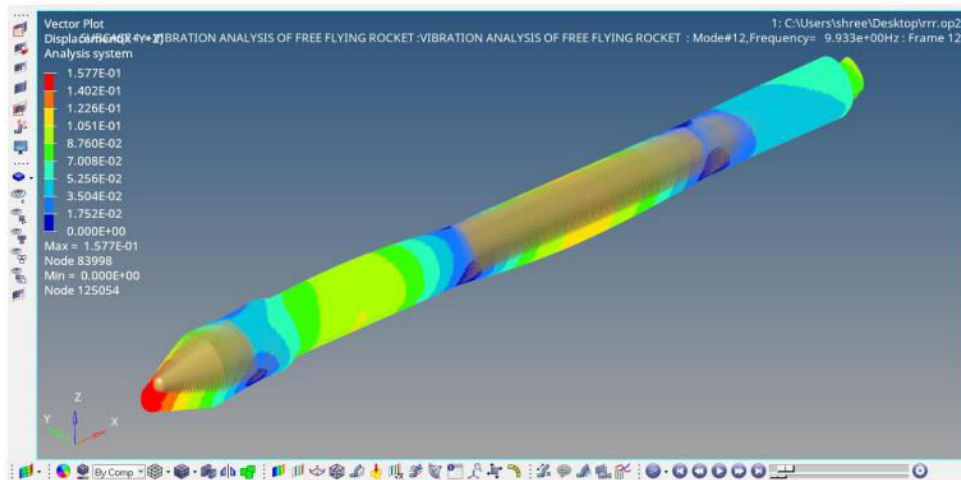


Fig: Sixth elastic mode for 55% filled tank

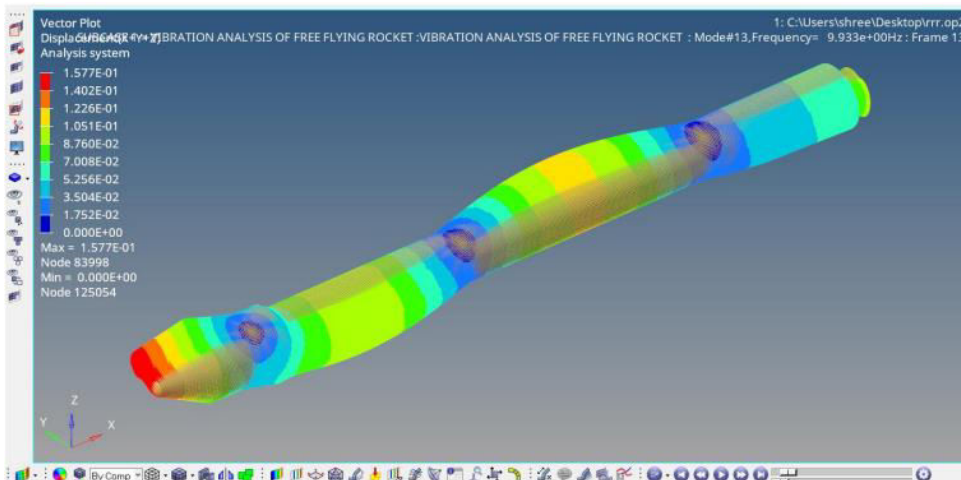


Fig: Seventh elastic mode for 55% filled tank

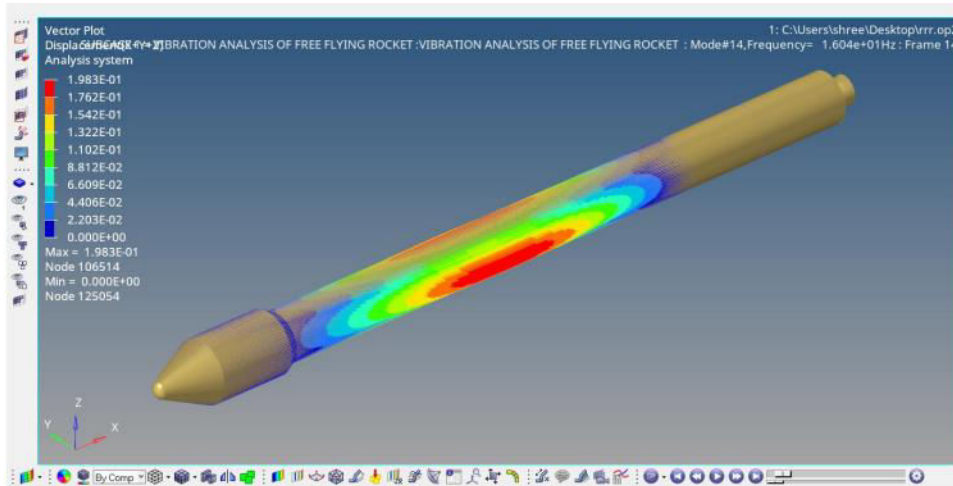


Fig: Eighth elastic mode for 55% filled tank

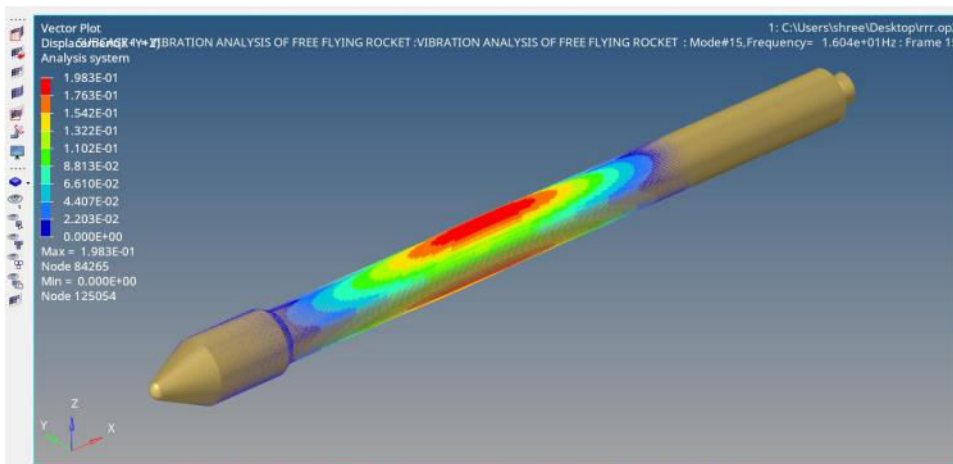


Fig: Ninth elastic mode for 55% filled tank

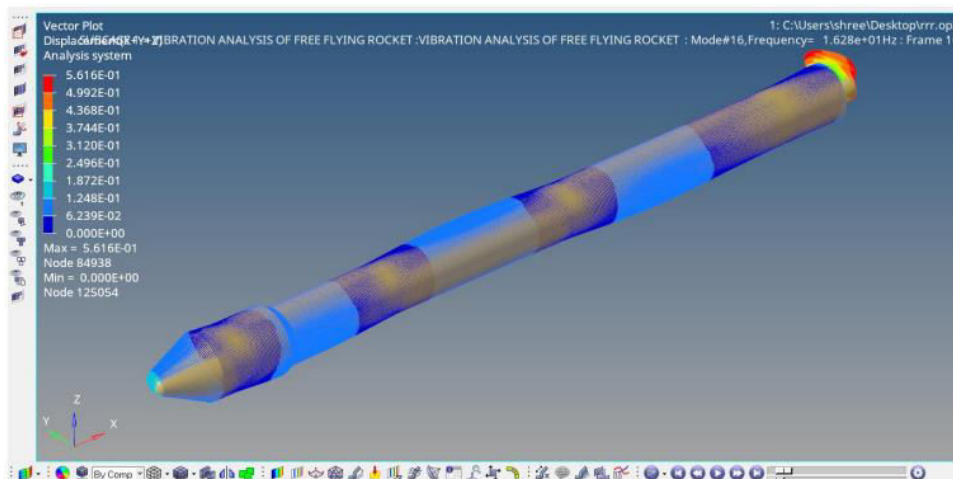


Fig: Tenth elastic mode for 55% filled tank

## VII. CONCLUSION AND FUTURE SCOPE

At higher modes of vibration, it can be concluded that the frequencies with slosh/fuel mass have a greater value and it may lead to failure of the entire launch vehicle. So, it is advisable for the rocket structural engineers to consider these factors and construct the fuel tank where baffles should be designed in a way where they damp the oscillation of the fluid or change the design of tank. Consideration can be made to design tanks such as prismatic tanks or rectangular tanks.

In the future one can use this project for understanding the slosh phenomenon and generating results with more complexities. Aeroelastic response can be noted down of sloshing launch vehicle, one can also consider a tank as an elastic body or one can do a CFD analysis of the fluid in the tank and structural analysis of the rocket, integrate the results for aeroelastic responses with the help of SOL 144 in MSC Nastran.

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