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Design and Modal Analysis of Cryogenic Rocket Propellant Tank

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ABSTRACT

Cryogenic rocket propellant tank is a pressure vessel for storing fuel or oxidizer of rocket stages. Generally, Liquid Hydrogen is used as fuel for cryogenic stages. The Fuel is stored at very low temperature at 20 K. Vibration analysis of cryogenic propellant tanks is significant in addition to the pressure analysis. Intense of vibrations are high during start and shut down of the rocket engine. The vibration levels generate major problems in propellant tank and its internals. Hence estimating the frequency levels at various possible modes is essential. Design and modal analysis of the Liquid hydrogen propellant tank is carried out in ANSYS workbench 15.0 in this work. Frequencies at six mode variations are taken and frequency ranges are compared.

Keywords : Cryogenic pressure vessel, Liquid hydrogen tank, Pressurization, Tank design, Modal analysis.

I. INTRODUCTION

A. Rocket Engine

A rocket engine is a type of jet engine that uses only stored rocket propellant mass for forming its high speed propulsive jet. Rocket engines are reaction engines, obtaining thrust in accordance with Newton's third law. Most rocket engines are internal combustion engines, although non-combusting forms (such as cold gas thrusters) also exist. Vehicles propelled by rocket engines are commonly called rockets. Since they need no external material to form their jet, rocket engines can perform in a vacuum and thus can be used to propel spacecraft and ballistic missiles.A cryogenic rocket engine is a rocket engine that uses a cryogenic fuel or oxidizer, that is, its fuel or oxidizer(or both) is gases liquefied and stored at very low temperatures.The most common rocket engine is the chemical type in which hot exhaust gases are produced by chemical combustion. The chemicals or propellants are of two types, fuel and oxidizer corresponding to gasoline andoxygen in an automobile engine. Both are required for combustion. They may be solid or liquid chemicals.

B. Cryogenic

Cryogenics originated from two Greek words "kayos" which means "cold or freezing" and "genes" which means "born or produced".Cryogenics is the study of very low temperatures or the production of the same. Liquefied gases like liquid nitrogen and liquid oxygen are used in many cryogenic applications.

C.Cryogenic RocketStage

During World War II, when powerful rocket engines were first considered by the German, American and Soviet engineers independently, all discovered that rocket engines need high mass flow rate of both oxidizer and fuel togenerate a sufficient thrust.

At that time oxygen and low molecular weight hydrocarbons were used as oxidizer and fuel pair. At roomtemperature and pressure, both are in gaseous state. Hypothetically, if propellants had been stored as pressurized gases, the size and mass of fuel tanks themselveswould severely decrease rocket efficiency.
Therefore, to get the required mass flow rate, the only option was to cool the propellants down to cryogenictemperatures (below −150 °C, −238 °F), converting them to liquid form. Hence, all cryogenic rocket engines are also,by definition, either liquid-propellant rocket engines or hybrid rocket engines.

Various cryogenic fuel-oxidizer combinations have been tried, but the combination of liquid. Hydrogen (LH2) fuel and the liquid oxygen (LOX).

Oxidizer is one of the most widely used. Both components are easily and cheaply available, And when burned have one of the highest entropy releases by combustion, producing specific Impulse up to 450 s, \(effective exhaust velocity 4.4 km/s).

Cryogenic Engines are rocket motors designed for liquid fuels that have to be held at very low "cryogenic" temperatures to be liquid - they would otherwise be gas at normal temperatures. Typically Hydrogen and Oxygen are used which need to be held below 20°K (-423°F) and 90°K (-297°F) to remain liquid.

The engine components are also cooled so the fuel doesn't boil to a gas in the lines that feed the engine. The thrust comes from the rapid expansion from liquid to gas with the gas emerging from the motor at very high speed. The energy needed to heat the fuels comes from burning them, once they are gasses. Cryogenic engines are the highest performing rocket motors. One disadvantage is that the fuel tanks tend to be bulky and require heavy insulation to store the propellant. Their high fuel efficiency, however, outweighs this disadvantage.

The Space Shuttle's main engines used for liftoff are cryogenic engines. The Shuttle's smaller thrusters for orbital maneuvering use non-cryogenic hypergolic fuels, which are compact and are stored at warm temperatures. Currently, only the United States, Russia, China, France, Japan and India have mastered cryogenic rocket technology.

D. Construction of Cryogenic Rocket Stage

Cryogenic rocket stage comprises independent propellant tanks for fuel and oxidizer which feeds to the engine. Stage also comprises pressurization system required to ensure the net positive suction head at the turbo pump inlet of the engine.

The major components of a cryogenic rocket engine are the combustion chamber (thrust chamber), pyrotechnic ignite, fuel injector, fuel cryopumps, oxidizer cryo pumps, gas turbine, cryovalves, regulators, the fuel tanks, and rocket engine nozzle.

In terms of feeding propellants to combustion chamber, cryogenic rocket engines (or, generally, all liquid propellant engines) work in either an expander cycle, a gas-generator cycle, a staged combustion cycle, or the simplest pressure-fed cycle.

The cryo pumps are always turbo pumps powered by a flow of fuel through gas turbines. Looking at this aspect, engines can be differentiated into a main flow or a bypass flow configuration.

In the main flow design, all the pumped fuel is fed through the gas turbines, and in the end injected to the combustion chamber. In the bypass configuration, the fuel flow is split; the main part goes directly to the combustion chamber to generate thrust, while only a small amount of the fuel goes to the turbine.

C25 stage and CUSP are the cryogenic upper stages of LVM3 and LVM2 launch vehicles respectively. Liquid hydrogen and Liquid oxygen are used as propellants for these stages.

It is essential pre-requisite that these propellant tanks are to be thermally insulated in order to reduce boil-off losses of the propellant and minimize heat in leak into the tanks. Insulation also prevents the pressure build up inside the tank. During flight, launch vehicle will be subjected to aero-dynamic heating. A Single layer of insulation will not meet all the flight requirements. Hence a composite layer of Insulation is designed. Being upper stage, mass saving is one of the main criteria. Hence an optimum insulation mass with the required properties will enable maximum payload addition.

II. METHODS AND MATERIAL

A. Vibration and Problems of Vibration

If the displacement of an object continues with respect to time, repetitive in nature, it is termed as vibration. Simply, repeated cyclic oscillations of a system are known as Vibrations.

Vibrations are broadly classified with respect to many means like the direction in which the system vibrates nature of the vibration, source of vibration etc.

Free vibration is the natural response of a structure to some impact or displacement. The response is completely determined by the properties of the structure, and its vibration can be understood by examining the structure's mechanical properties. For example, when you pluck a string of a guitar, it vibrates at the tuned frequency and generates the desired sound. The frequency of the tone is a function of the tension in the string and is not related to the plucking technique.

Forced vibration is the response of a structure to a repetitive forcing function that causes the structure to vibrate at the frequency of the excitation. For example, the rear view mirror on a car will always vibrate at the frequency associated with the engine's RPMs. In forced vibration, there is a relationship between the amplitude of the forcing function and the corresponding vibration level. The relationship is dictated by the properties of the structure.

Random vibration is very common in nature. The vibration you feel when driving a car result from a complex combination of the rough road surface, engine vibration, wind buffeting the car's exterior, etc. Instead of trying to quantify each of these effects, they are commonly described by using statistical parameters. Random vibration quantifies the average vibration level over time across a frequency spectrum.

Sinusoidal vibration is a special class of vibration. The structure is excited by a forcing function that is a pure tone with a single frequency. Sinusoidal vibration is not very common in nature, but it provides an excellent engineering tool that enables us to understand complex vibrations by breaking them down into simple, one-tone vibrations.

Wear and tear of machine parts depends on the levels of vibration. Vibration affects the accuracy of the system. During vibration, unwanted noise will be created at the time of rotating, moving, and reciprocating. Main source of vibrations is the unbalanced forces.

B. Natural Frequency and Resonance

The natural frequency is the frequency at which a system oscillates when it is disturbed. The natural frequency is important for many reasons:

- All things in the universe have a natural frequency, and many things have more than one.
- To know object’s natural frequency know its vibration.
- To know an object’s vibration know the kinds of waves created.
- To create objects with natural frequencies that match the waves you want.

Resonance:

In physics, resonance is a phenomenon that occurs when a vibrating system or external force drives another system to oscillate with greater amplitude at a specific preferential frequency. Frequencies at which the response amplitude is relative maximum are known as the system's resonant frequencies, or resonance frequencies. At resonant frequencies, small periodic driving forces have the ability to produce large amplitude oscillations.

Every system has its own natural frequency in which it vibrates. If the natural frequency of the system matches the frequency of the induced vibrations, then resonance will occur which leads to failure. Hence estimating the natural frequency is essential.

C. Model Description

Cryogenic rocket propellant tank for storing liquid hydrogen is taken as model. It is made oftitanium alloy (Ti-6Al-4V).The tank is Dome radius of tank is 2504mm. Length of propellant tank is 4894mm.Thickness of propellant tank 6mm. Propellant tanks having a pressurization system withtitanium gas bottles as storage of helium.

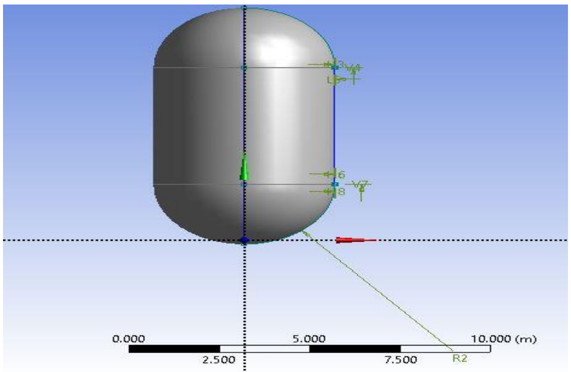

Figure 1. Front view- Model of propellant tank

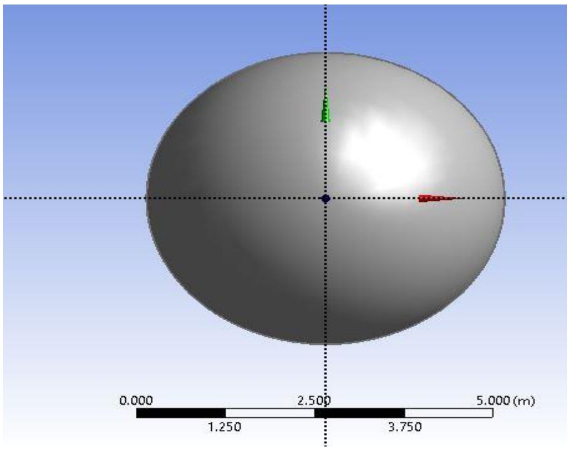

Figure 2. Top view- Model of propellant tank

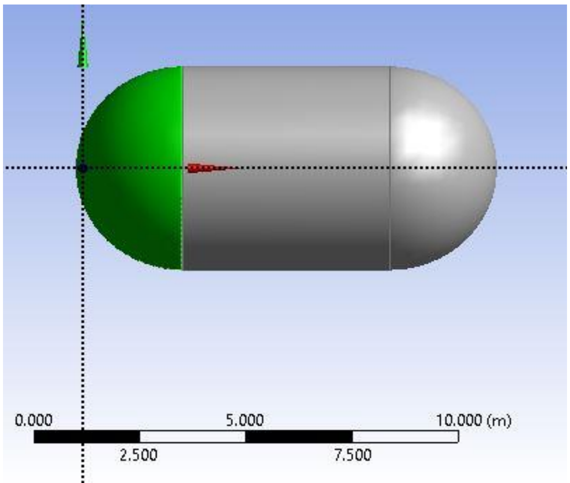

Figure 3. Side view- Model of propellant tank

D. Material Properties

The variable material properties of high grade Titanium alloy are considered for the design of propellant tank.

MATERIAL	***Ti-6Al-4V***
Titanium	***90%***
Aluminium	***6%***
Vanadium	***4%***
Poission's ratio	***0.340***
Youngs modulus	***115-120GPa***

TABLE1. MATERIAL PROPERTIES

Grade 5, also known as Ti6Al4V, Ti6Al4Vor Ti 64, is the most commonly used alloy. It has a chemical composition of 6% aluminum, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen, and the remainder titanium. It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties (excluding thermal conductivity, which is about 60% lower in Grade 5 Ti than in CP Ti). Among its many advantages, it is heat treatable. This grade is an excellent combination of strength, corrosion resistance, weld and fabric ability. "This alpha beta alloy is the workhorse alloy of the titanium industry. The alloy is fully heat treatable in section sizes up to 15 mm and is used up to approximately 400 °C (750 °F). Since it is the most commonly used alloy – over 70% of all alloy grades melted are a sub grade of Ti6Al4V; its uses span many aerospace airframe and engine component uses and also major non aerospace applications in the marine, offshore and power generation industries in particular. Applications: Blades, discs, rings, airframes, fasteners, components. Vessels, cases, hubs, forgings, Biomedical implant.

E. Introduction of Modal Analysis

A modal analysis is a technique used to determine the vibration characteristics of structures:

- Natural frequencies – at what frequencies the structure would tend to naturally vibrate
- Mode shapes – in what shape the structure would tend to vibrate at each frequency.
- Mode participation factors – the amount of mass that participates in a given direction for each mode.
- Typical excitation signals can be classed as impulse, broadband, swept sine, chirp, and possibly theirs. Each has its own advantages and disadvantages.
- The analysis of the signals typically relies on Fourier analysis. The resulting transfer function will show one or more resonances, whose characteristic mass, frequency and damping can be estimated from the measurements.
- The animated display of the mode shape is very useful to NVH (noise, vibration, and hardness) engineers.
- The results can also be used to correlate with finite element analysis normal mode solutions.

Benefits of modal analysis

- Allows the design to avoid resonant vibrations or to vibrate at a specified frequency (speaker box, for example).
- Gives engineers an idea of how the design will respond to different types of dynamic loads.

- Helps in calculating solution controls (time steps, etc.) for other dynamic analyses.

F. Procedure Of Finding Frequency In Mathematically

Longitudinal vibrations are produced in the rocket. Steps of finding frequency given below,

Stiffness matrix[K]= AE\L $\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$

Mass matrix[m]= ρAL/6 $\begin{bmatrix} 1 & 2 \\ 2 & 1 \end{bmatrix}$

Finite element equation

$$\{P\} = \{[K]-[m]\omega^2\}\{u\}$$

Solve equation finding ω (ω is natural frequency)

Time period= 2π/ ω

Frequency(f)= $1/t_p$= ω /2π

Where,

ρ = Density, A = Area, L = Length

G. Finite Element Method

The finite element is a mathematical method for solving ordinary and partial differentials equations. Because it is a numerical method, it has the ability to solve complex problems that can be represented in differential equation form. As these types of equations occur naturally in virtually all fields of the physical sciences, the applications of the finite element method are limitless as regards the solution of practical design problems. Due to high cost of computing power of years gone by, FEA has history of being used to solve complex and cost critical problems. Classical methods alone usually cannot provide adequate information to determine the safe working limits of a major civil engineering construction or an automobile or an aircraft. If a tall building, a large suspension bridge or an automobile or a nuclear reactor failed catastrophically, the economic and social cost would be unacceptably high. In recent years, FEA has been used almost universally to solve structural engineering problems. One discipline that has relied heavily on this technology is the automotive and aerospace industry. Due to the need to meet the extreme demands for faster, stronger, efficient and light weight automobiles and aircrafts, manufacturers have to rely on the technique to stay competitive. But more importantly, due to safety, high manufacturing costs of components and the high media coverage that the industry is exposed to, automotive and aircraft companies need to ensure that none of their components fail, that is to cease providing the services that the design intended.FEA has been used routinely in high volume production and manufacturing industries for many years, as to get a product design wrong would be detrimental. For example, if a large manufacturer had to recall one model alone due to a piston design fault, they would end up having to replace up to 10 million pistons. Similarly, if an oil platform had to shut down due to one of the major components failing (platform frames, turrets, etc), the cost of lost revenue is far greater than the cost of fixing or replacing the components, not to mention the huge environmental and safety costs that such an incident could incur. The finite element is a very important tool for those involved in engineering design; it is now used routinely to solve problems in the following areas:

- Structural strength design
- Structural interaction with fluids flows
- Analysis of shock (underwater and in materials)
- Acoustics
- Thermal analysis
- Crash simulations
- Fluid flows
- Electrical analysis
- Mass diffusion
- Buckling problems
- Dynamic analysis
- Electromagnetic evaluations
- Metal forming
- Coupled analysis

Nowadays, even the most simple of products rely on the finite element for design evaluation. This is because contemporary design problems usually cannot be solved as accurately and cheaply using any other method that is currently available. Physical testing was the norm in years gone by, but now it is simply too expensive and time consuming.

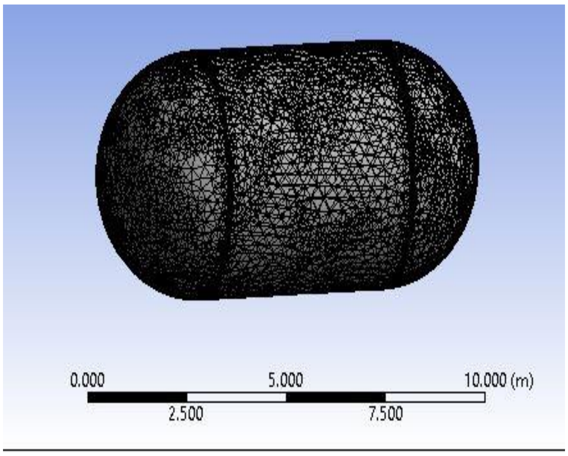

Figure 4. FEA Model of propellant tank

H. Boundary Condition of Modal Analysis

- Both flanges are fixed in x, y and z directions.
- Bulk Temperature is applied as 20K.

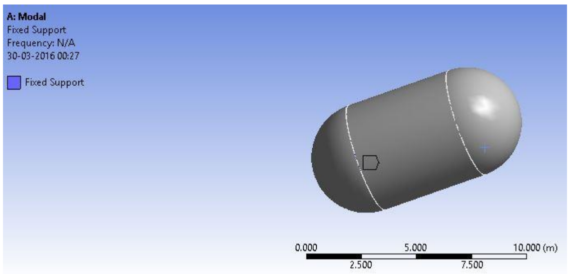

Figure 5. Flanges are fixed

III. RESULTS AND DISCUSSION

Design and modal analysis of the Liquid hydrogen propellant tank is carried out in ANSYS workbench 15.0. Frequencies at six mode variations are taken and frequency ranges are compared.

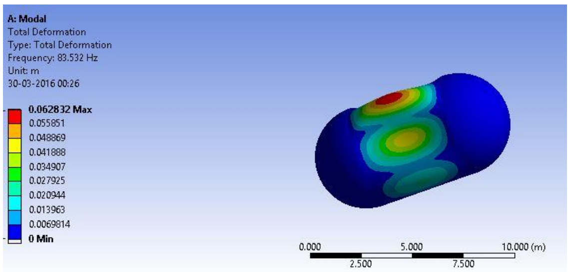

Figure 6. First mode result(83.532Hz)

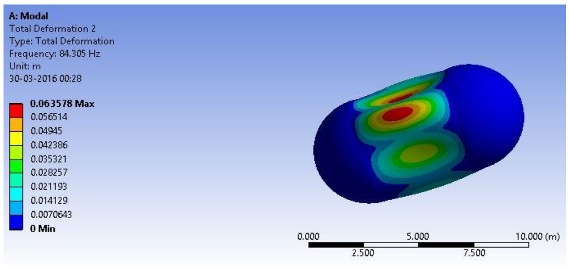

Figure 7. Second mode of frequency (84.305Hz)

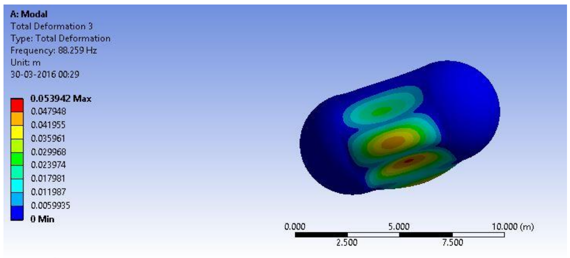

Figure 8. Third mode of result (88.259Hz)

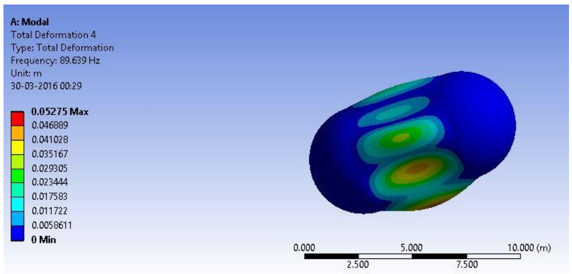

Figure 9. Fourth mode of result (89.639Hz)

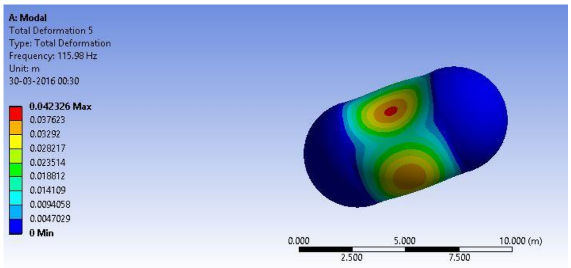

Figure 10. Fifth mode of result (115.98Hz)

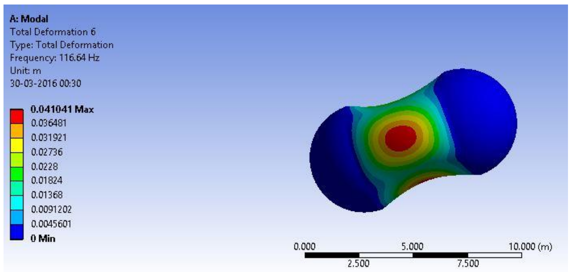

Figure 11. Sixth mode of result (116.64Hz)

Frequency ranges from 83.532Hz, 84.305Hz,88.259 Hz,89.639 Hz, 115.98Hz, and 116.64Hz at each of the six modes respectively.

IV. CONCLUSION

Cryogenic propellant tank is modeled by using Ansys15.0.Ansys modal analysis is carried out in Ansys15.0. The vibration levels generate major problems in propellant tank and its internals. Hence estimating the frequency levels at various possible modes is essential. Frequencies at six mode variations are taken and frequency ranges are compared. This modal analysis is used to design and improve the interface design of the internals assembled to the tank.

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