Design and FE Analysis of Anti-Slosh Baffles for Fourth Stage of PSLV

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Abstract--- *Polar Satellites Launch Vehicle (PSLV) is the work horse of ISRO. It is used to launch 1000 kg satellites in polar orbits and upto 1600 kg satellites in low earth orbits. PSLV is a 4 stage vehicle weighing 315 tonnes. It uses liquid propulsion for second and fourth stages. The fourth stage propulsion tank is made up of Titanium Alloy (Ti6Al4V)(1335 mm dia). The configuration of tank is monocoque, with a common bulkhead to separate the fuel and oxidiser. The top compartment is used for fuel and bottom compartment is filled with oxidiser. Anti-slosh baffles (Ring Baffles) are used in both compartments to suppress slosh .Sloshing is a common phenomenon in partially filled liquid container. The rocket motor cases, filled with liquid propellants are left with an internal ullage volume (free volume) for the pressuring gas to stabilise. This creates a free surface of liquid. Sloshing is defined as the oscillation of the free surface of a liquid in a partially filled container due to external disturbances. Baffles are essentially "plates" fixed inside the container to arrest sloshing. The slosh waves, during the causes of travel, hits the plates breaks and dies out. This reduces the slosh forces on the walls of container. Presently the ring baffles are supported from top flange of tank for launching satellites up to 1200 kg. For this propellant loading is upto 2.5 t. Now a PS4 stage is reconfigured with 0.8 t loading to launch 500 kg satellites. In this tank the liquid levels are less. Hence ring baffles are supported from bottom flange of tank to reduce the total mass of the baffle system. So in this paper Structural design, Finite Element analysis and Modal Analysis are carried out.*

I. Introduction

THE Indian Space Research Organisation (ISRO) is the research and development wing of Department of Space (DOS) and is responsible for the execution of the National space programmes. The PSLV, work horse of ISRO, consists of four stages to inject the 900 kg class Indian Remote Sensing Satellite into a 900 km Sun-Synchronous circular polar orbit. The second and fourth stages (PS2 and PS4) are liquid stages, with PS4 using 2.5 t of Mono Methyl Hydrazine (MMH) and Mixed Oxides of Nitrogen (MON3) as propellants [1].

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The propellant tank of PS4 stage of PSLV is monocoque with a common bulkhead (dome) used to separate the fuel (MMH) and oxidiser (N_2O_4-Nitrogen Tetroxide), is made of Titanium Alloy (Ti6Al4V). The configuration of the tank is cylindrical (1335 mm dia.) with ellipsoidal domes.

The rocket has to be controlled and oriented through the most optimised trajectory to launch a satellite. If slosh (oscillation of free liquid surface) occurs, the control system requirements become large and proportionately the mass of the rocket also will increase. This will reduce the mass of satellite launched to the space. One kg of Geostationary satellite costs about 20 lakh rupees in International markets. Hence slosh is suppressed to the maximum extent using antislosh baffles, fixed inside the propellant tanks. Ring baffles, the most economical type of baffles when the ratio (*damping /mass of baffle*) is studied, are supported from top of PS4 tank. In the new design of propellant tank (L0.8 version), the propellant loading is reduced and the liquid levels are lowered. The baffles are supported from the bottom of the tank (Fig. 2), which reduces the mass of the total baffle assembly and also to prevent excessive oscillations.

II. Slosh

Sloshing, the *'Periodic oscillations of the free surface of a liquid in a partially filled container due to external disturbances'* [5]. The propellant tanks with liquid propellants are left with an intentional ullage volume for the pressuring gas to stabilise and for thermal expansions of propellants.

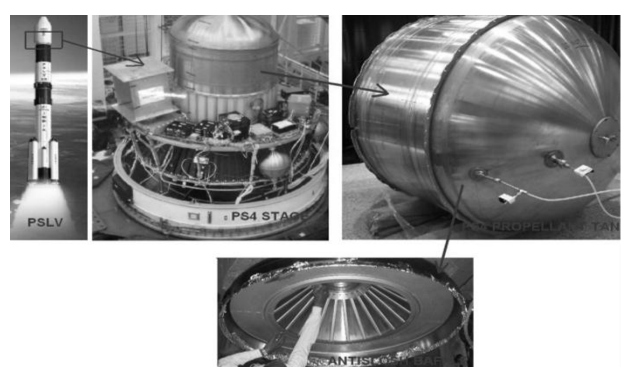


Fig.1: The Details of Existing Baffles

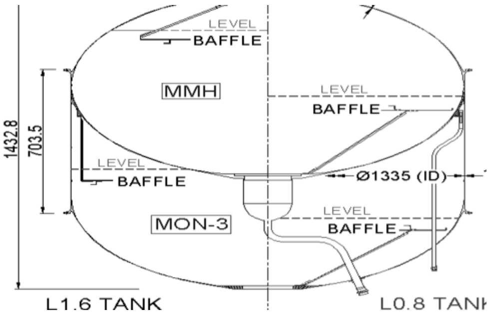


Fig. 2 Present and Modified Configurations

A. Effect of Sloshing

Slosh creates forces on the walls of the container. This causes instability to the vehicles. Also, slosh disturbances produce structural oscillations. At any moment, if a structural frequency coincides with an adjacent one, they may resonate and become unstable. Also sloshing disturbs the free volume (Ullage Volume) of tank causing flow disturbances. At any stage, if slosh occurs towards the depletion of a liquid, it may result in starvation of propellant to the engine and thrust oscillations will result.

B. Need for Suppressing Sloshing

Slosh creates forces on the walls of liquid container. This force causes instability to the vehicles, because the vehicle in its course of flight is a "free-free" pendulum. Hence more "control system propulsion" requirements arise to control the vehicle, which proportionately increases the stage mass and is adverse. Hence slosh should be suppressed to the minimal extent possible.

C. Formulation of Slosh

Initially, a *"Vehicle Stability Analysis"* is carried out. This is done by mathematical modelling of the vehicle. This gives a picture of how much "Damping" is required at various heights of vehicle to cater the control system design requirements.The slosh phenomena in a vehicle is modelled initially to study and assess the wave patterns, slosh pressures, amplitudes etc. This gives a picture of the slosh behavior of the liquids at each instant. From slosh modelling, the slosh pressure, width of baffles etc. are derived to suppress the slosh (damp) to the required levels. The baffles and supports are suitably configured and positioned inside the propellant tanks. Structural design and analysis of the baffles are carried out to assess the deflections and stresses.[3]

III. BAFFLES

Baffles are essentially "*hindrance plates*" fixed inside the container to arrest or reduce sloshing (Fig. 1). The slosh waves, during the course of travel, hit the plates, break and die out. This reduces the slosh forces on the walls of container and persistence of sloshing. Three types of baffles are commonly used. They are: Cruciform baffles, Vertical baffles and Horizontal (Ring) baffles. The baffle dimensions are obtained from slosh analysis of the vehicle. Usually the ring baffles are fixed below a height of 10% of tank radius from free surface of liquid [2]. This depth has been found out to be the most effective for damping from experimental studies. The baffles can be positioned at the required level by Supporting from top of tank, Fixing to side walls of container & Supporting from bottom.

A. Structural Design Inputs

Propellant loading - 800 kg, Tank used- L1.6 version, Slosh damping ratio for MMH > 5% & for MON3 > 3.5%, Damping duration is 40 Seconds, Material chosen for baffle -AFNOR 7020/ Ti6Al4V.

Table 1: Property Comparison

Material Properties	Aluminium Alloy - AFNOR 7020	Titanium Alloy - Ti6Al4V
Yield Stress	280 N/mm^2	840 N/mm^2
UltimateTensileStress	350 N/mm^2	920 N/mm^2
Modulus of Elasticity, E	71,000 N/mm^2	1,05,000 N/mm^2
Specific Gravity	2.8	4.5

B. Slosh Loads on Baffle

The slosh pressure varies *'Sinusoidally'* over the surface of ring baffle. It takes a *'Cosh'* variation axially over the vertical supports. The loads on Horizontal baffles are 2.62 KPa (MMH) , 3.01 KPa (MON3) and on Vertical baffles are 1.72 KPa (MMH) , 2.81 KPa (MON3).

C. Configuration of Baffles from Slosh Analysis

The structural design is carried out using the classical equations available in *"Roark's Formula for Stresses and Strain"*. Formula for curved beams loaded normal to the plane of curvature is used [6].

Table 2: Baffle Details

Details	MMH(mm)	MON3 (mm)
Liquid high from tank ring seat	379	332
Baffle immersion	69	60
ID / OD of baffles	775 / 1250	890 / 1210
Width of baffles	237.5	160

D. Configuration Designed: MMH Baffle

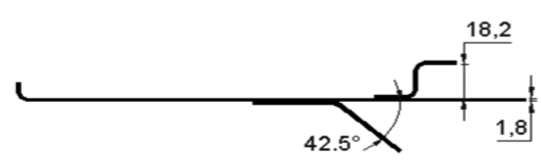


Fig. 3: Configuration for MMH

The designed configuration of MMH Baffle system according to Table 3 is shown in Fig. 3.

Table 3: Design results from Excel program MMH (Al.alloy) baffle

No. of Segments	12 Seg.	24 Seg
Moment of inertia (mm^4)	38226	38226
Bending moment (kNm)	279.95	72.34
Twisting moment (kNm)	-2.3×10^{-11}	-9.6×10^{-11}
Deflection (mm)	-0.002	-9.5×10^{-05}
Bending stress (N/mm^2)	0.007	0.002

E. Configuration Designed: MON3 Baffle

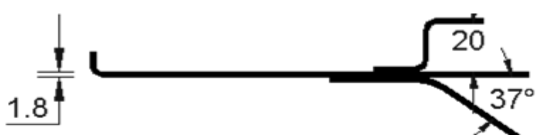


Fig. 4: Configuration for MON3

Fig. 4 showing MON3 configuration as per Table 4.

Table 4: Design Results from Excel Program- MON3 (Al. alloy) Baffle

No. of Segments	12 Seg.	24 Seg
Moment of inertia (mm^4)	46425.9	46425.9
Bending moment (kNm)	319.32	81.89
Twisting moment (kNm)	-3.6×10^{-11}	-1.7×10^{-10}
Deflection, (mm)	-0.0024	-9.9×10^{-05}
Bending stress (N/mm^2)	0.006	0.002

The material chosen for the baffles is Aluminium alloy AFNOR 7020 because the mass of the baffle system will be less in comparison with Titanium Alloy.

F. Finite Element Model

A 3D shell model (360^0) with element SHELL181 is created. For supports from top, BEAM 188 is used for supports [4]. The thickness of baffle plate, Z-Section, the top support ring and channel are given as real constants. Two materials are studied: Titanium alloy and Aluminium alloy. Nodes at bottom support rings where bolts are coming are arrested (All DOF = 0) to simulate bolting to Aft End ring of tank. Top surface is free to deflect. Varying slosh pressures on horizontal baffle and channels are given as macros for both fluids.

G. Results of FE Analysis (Al. Alloy)

The MMH & MON3 baffle assemblies are designed using 1.8 thick Al alloy AFNOR 7020 sheets. It is a rivetted construction (Figure 5 & 6). The bottom support rings can be formed from 3 thick sheets or machined out of suitable rings. The assembly is fixed inside the tank using screws. FE analysis & Modal analysis are carried out to assess the natural frequency of baffle assembly. The interaction of structural oscillations, plumbing vibrations and liquid slosh oscillations with baffle oscillations (frequency) are studied for difftrent cases. Adequate frequency separation is ensured after the design and modal analysis data to avoid resonance and consequent damages.

The Antislosh baffles for MMH and MON3 compartments of PS4 Tank, designed using Aluminium alloy AFNOR 7020 with 24 channel supports are chosen as the final configuration from FE analysis,because of the following reasons: (i) Mass is less, (ii) Stresses are within allowable limits, (iii) Deflections are within allowable limits, (iv) Natural frequency is within acceptable limits, (v) The material and fabrication techniques are readily available. (Table 5)

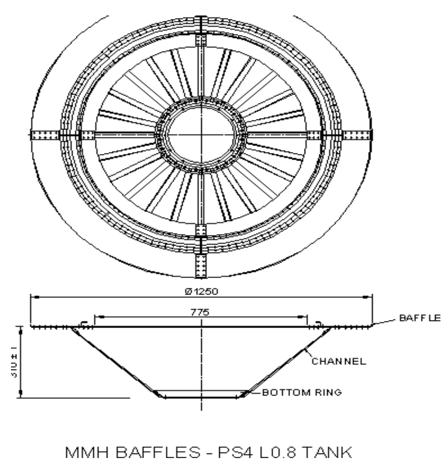


Fig. 5: MMH Baffles for PS4 L0.8 tank

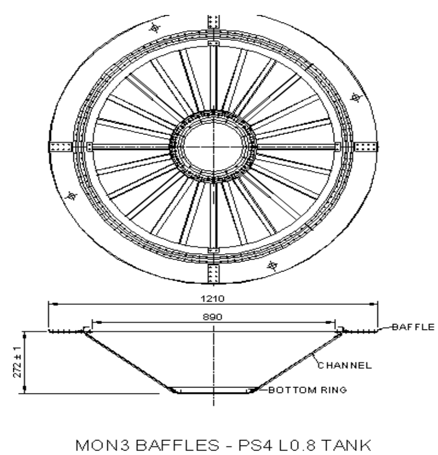


Fig.6: MON3 Baffles for PS4 L0.8 tank

H. Design Check of Fasteners

The butting portions of baffles (channel to support, Z section to plate etc.) are riveted (Figure 7) because they are thin sections and take a large amount of shear stresses. The baffle assembly is bolted to the tank bottom using screws (Figure 8).

Dia 3.2, Aluminium alloy AG5 rivetts and M5 x 0.8 x 16 long, Titanium alloy Ti6Al4V. Screws are used in baffle assembly. A design check of fasteners (rivets and screws) used for the baffle assembly has also been made. Sufficient design margin exists for the rivets (65%) and screws (47%).

Table 5: Design Results from FE Analysis

Baffle	MMH	MON3
Material	Al. alloy AFNOR 7020	Al. alloy AFNOR 7020
No. Of supports	24	24
Thk.(mm)	1.8	1.8
Mounted from	Bottom	Bottom
Von mises stress (N/mm^2)	109.856	99.668
Max.Deflection, mm	12.026	10.242
I mode freq.(Hz)	26.208	30.218
Mass (kg.)	8.1	6.2

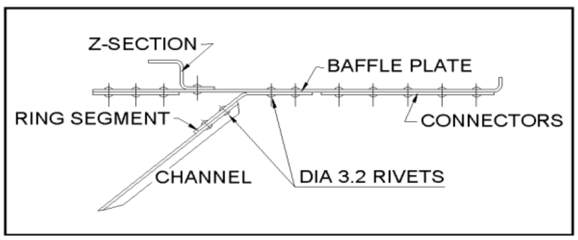


Fig.7: Rivetted Joints in Baffle Assembly

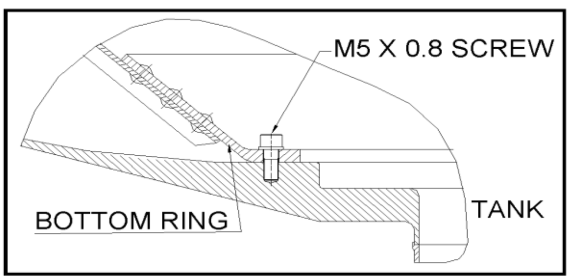


Fig. 6: Bolted joint in Baffle Assembly

I. Experimental Demonstration of Sloshing

Six types of experiments have been conducted as an annexure of the work to demonstrate the phenomenon of Sloshing, instability due to sloshing, wave formation and damping. Small scale models from available vessels are made for the experiments. Baffles of different shape and size are prepared from Aluminium alloy sheets and fixed inside the vessels. The experiments are conducted on wooden platforms, which are excited manually. *The measurement of slosh wave amplitude, frequency, slosh forces, excitation forces, decay rate of waves etc. are not attempted in the model studies due to facility constraints.*

- *Instability Due To Slosh:* Instability due to slosh is explained using a kitchen frying pan. This pan is the most unstable vessel, having a point contact with the surface of rest. The pan is filled with water, kept horizontally on a platform and a disturbance is given externally to create slosh (Fig.7). It can be seen that the vessel continues to rock for a long time even after the external force is released. This is due to the slosh disturbances inside the vessel. The slosh waves exert pressure on the walls of the container and make it unstable. Such disturbances are caused in rocket propellant tanks also due to sloshing of liquid propellants. These disturbances have to be minimised to make the rocket stable for its flight.

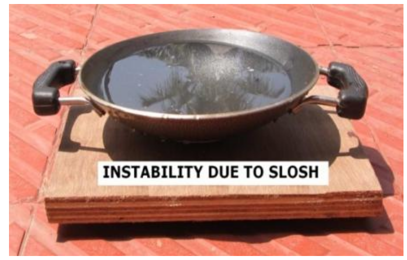


Fig. 7: Experimental Setup to Demonstrate Instability

- *Damping of Slosh Waves When Cruciform and Ring Baffles Are Kept:* Three identical cylindrical vessels have been used for the experiment. One is left without any baffle. In the second vessel, a cruciform (vane) baffle has been kept. In the third one, a ring baffle has been fixed (Fig 8). The vessels are filled with water to the same level and slosh waves are created using a shaker platform. It can be seen that the slosh waves damp out very quickly in the presence of cruciform baffles. It takes some more time to damp out in presence of ring baffle and in tank without baffles, slosh dominates. This very well supports the theory of damping.

Fig. 8 Experimental Setup to Demonstrate Slosh & Damping

- *Damping In The Presence of Vertical Baffles in Hemispherical Tank:* Two identical hemispherical vessels have been used for the demonstration. In one vessel, 8 nos. of vertical baffles have been bonded and the other vessel left free (Fig. 9). In both vessels, water is filled to the same level and shaken simultaneously. It can be seen that slosh dies out quickly in the vessel with vertical baffles. This very well supports the theory of damping in the presence of vertical baffles. In rocket propellant tanks vertical baffles are used for continuous damping of sloshing when propellant depletes during the course of firing. In L40 Propellant tanks of GSLV, these types of baffles are incorporated since they pass through atmospheric region, where slosh disturbances are high.

Fig 9 Experimental Setup to Demonstrate Damping in the Presence of Vertical Baffles

- *Sloshing Vs. Surface Area of Liquid:* Three cylindrical vessels with varying diameters have been used for this experiment (Fig.10). The vessels are filled with water to the same level and slosh is created using the shaker manually. It can be seen that slosh waves die out quickly in the vessel with lowest surface area. The vessel with largest surface area produces the largest slosh wave amplitude. This very well supports the theory that large surface areas of liquids are adverse from slosh point of view.

Fig 10: Experimental Setup to Demonstrate Sloshing vs. Surface Area

- *Sloshing Vs. Viscosity of Liquids:* Kerosene, Water, Cooking oil, Honey has been used for the experiment (Fig. 11). The viscosities of above liquids are in ascending order, honey having the highest viscosity among the four. The same quantity of above liquids has been filled to the same level in 4 identical vessels. Slosh is created by the shaker platform manually. Slosh waves die out quickly on liquid having highest viscosity. It increases proportionately as viscosity reduces. This very well supports the theory that viscosity helps natural damping of a liquid during sloshing.

Fig 11: Experimental Setup to Demonstrate Sloshing vs. Viscosity of Liquids

- *Compartmentalisation to Reduce Sloshing:* Two identical cylindrical bottles are chosen. In one bottle, three vertical perforated baffles are fixed to divide the volume into four (Fig.12). Perforation helps communication of liquid during filling, draining and pressurisation. Both the bottles kept horizontally on the shaker platform and excited manually to the same level. It is demonstrated that Compartmentalisation reduces the slosh wave amplitude and hence the trouble due to sloshing is less in such tanks.

Fig12: Experimental Setup to Demonstrate Compartmentalisation to Reduce Slosh

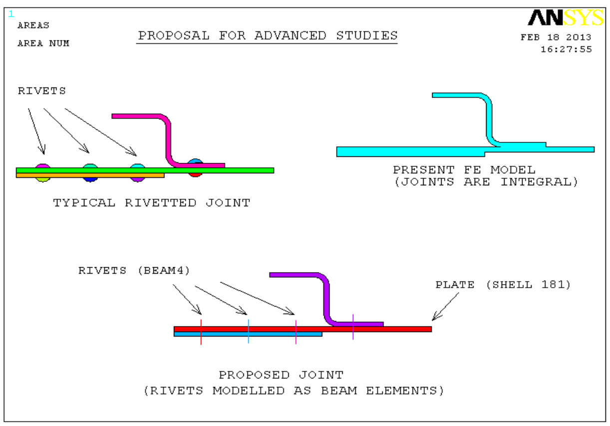
IV. Conclusion

The design and FE analysis details of Antislosh baffle (MMH and MON3) for different configurations, support conditions and materials have been presented. The deflections of the baffles are decided such that sufficient clearances exist between baffle edge and tank wall. The design calculation results give only indicative values. They help in configuring the baffles, estimating initial mass, choosing material and fabrication techniques. The actual support conditions of baffles are different and the pressure loading is also extremely complex as explained. The available classical equations do not support the actual design to full extent. Hence the baffles with support systems are configured and an exhaustive FE analysis is carried out to assess the stresses, natural frequencies, mode shapes and deformations. Macros are written for the application of loads. The results of stress analysis, modal analysis and estimated mass are presented. From this the most optimal configuration is chosen. A design check of fasteners (rivets and screws) used for the baffle assembly has also been made. Sufficient design margin exists for the rivets and screws. The Antislosh baffles for MMH and MON3 compartments of PS4 Tank, designed using Aluminium alloy AFNOR 7020 with 24 channel supports are chosen as the final configuration from FE analysis.

As an annexure of the work, Experimental demonstration of the phenomenon of Slosh, Instability, Wave formation, damping using different type of baffles and effect of Compartmentalisation are carried out using small models and different liquids. Seven types of experiments have been conducted and the inference explained.

V. Suggestion for Future Work

The rivetted joints with rivets have not been modelled in FEM in this paper. It is assumed that the butt joints are integral. Eventhough, due to large amount of friction between the plates, the behaviour of butt joints are almost integral, more accurate stress distribution at joints and rivets can be obtained by modelling the rivets as beam elements. The coefficient of friction between plates after rivetting has to be established by tensile test of riveted specimens. This friction factor has to be applied at the contact elements defined at butt joint after modelling the joint.



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