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Comparison Analysis of Modes Before and After Liquid Rocket Filling

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ABSTRACT

Taking the two-stage liquid rocket as an example, we use the ANSYS calculation software to consider the fluid-solid coupling after propellant filling, calculate the modes under the first and last two conditions of propellant filling, and obtain the first 20 natural frequency and vibration pattern of the liquid rocket, which provide reference for the safe use of the target range. The calculation results show that the natural frequency of the liquid rocket system decreases after propellant filling compared with that before filling, the modes of order 1 and 2 are low frequency vibration, the natural frequency amplitude changes significantly, while the natural frequency above order 6 is basically stable. Therefore, attention should be paid to eliminating the low frequency vibration source in the environment, and more attention should be given after filling. The 1 and 2 modes of the front and back liquid rockets are swinging, while the liquid rocket structure; the filling propellant will not affect the first 4 modes, but will only change the vibration plane.

KEYWORDS

Liquid Rocket; Mode Analysis; ANSYS; Natural Frequency; Vibration Type.

1. INTRODUCTION

Large liquid launch vehicles generally adopt vertical thermal launch, and are erected on the launch pad before launch for testing and propellant filling. What is the change in the vibration mode before and after the injection of propellant, whether it may be dangerous under external incentive, is a major problem affecting the safe use of the target range.

Jia Wencheng, Wang Penghui, Zhang Yongliang and others studied the full mode test technology of large carrier rockets[1], A large number of full-arrow mode parameters are obtained, which provides an important basis for rocket design and dynamic analysis. Qiu Qibao and Wang Jianmin studied the progress of dynamic test simulation of spacecraft structure and pointed out[2], With the development of the spacecraft, structure size or more and more big, or structure is more and more light, flexible deformation is more and more big, makes the full size ground dynamic test is more and more difficult, and the numerical analysis method for dynamic analysis of complex structure system is simple and economic, to master the structure mode distribution characteristics and used to guide the test and improve the test efficiency is very helpful. Cui Gaowei, Hong Liangyou and Zhang Dongmei used the method of liquid to study the influence of modal parameters of launch vehicle[3], Provide a reference for the design of launch vehicles. After the liquid rocket fills the propellant, it is equivalent to a large liquid storage tank, so the problem of fluid-solid coupling must be considered. Zhou Sida and Liu Li studied the analysis method of fluid-solid coupling of the carrier rocket storage tank[4], Provide reference for rocket design. In this paper, ANSYS software is used to analyze the mode of large liquid launch vehicle, calculate the first twenty order mode of the structure and propellant fluid solid coupling system, and obtain the spontaneous vibration frequency and formation before and after the rocket filling, so as to provide reference for the safe use of the rocket shooting range and accident prevention.

2. COMPUTATIONAL MODEL

2.1. Geometric Model

With the example of a two-stage liquid carrier rocket, the geometric model of the second stage power system (including secondary oxidant tank, secondary compartment, secondary burner tank), stage segment (including the shell segment and the pole segment) and the primary power system (including primary oxidant tank, primary compartment and primary burner tank), as shown in Fig. 1. In order to reduce the calculation scale, the fairing (including payload) and the instrument chamber structure are ignored, but the fairing (including payload) and the instrument chamber are loaded on the front short shell of the secondary oxidant box as mass force during the calculation.

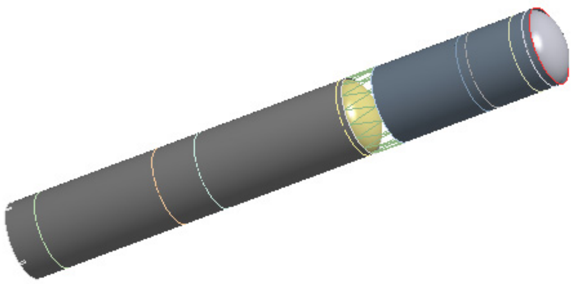
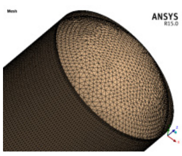
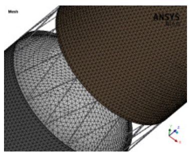


Figure 1. Geometric model of a two-stage liquid rocket

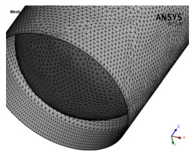
In order to simplify the model, the structural details such as truss, frame, rivets and screws are ignored in the modeling, and the shell is all treated according to the light shell, as shown in Fig. 2. The surface of the shell was performed in the modeling [5], In the numerical calculation, the shell thickness is still retained, which reduces the number of units and improves the calculation efficiency on the basis of ensuring the authenticity of the model.



(a) Secondary top



(b) Interbar bar



(c) Bottom of level 1

Figure 2. FEM of Some Partial Structure

Due to propellant in the tank after filling, propellant should be added to the model of modal calculation[6]. Suppose the volume ratio of propellant in the tank is 80%. First, use the fill command to select the inner surface of each tank, and then the liquid propellant model at 80% of the filled state is obtained by cutting. Finally, remove the unnecessary propellant part of the tank is operation to get the model of the desired propellant, as shown in Fig. 3 (a).

2.2. Finite-element Model

According to the structural characteristics of the rocket model, the shell unit SHELL181 is used to mesh the shell, and the connecting rod between the stages belongs to the slender beam structure, so the beam unit BEAM188 is used for the division. During the mesh division, to obtain relatively good quality cells, the cell size was controlled to 0.05m, as shown in Fig. 2.

The propellant part is divided by FLUID30 unit, which is the unit of fluid medium in flow-solid coupling problem. In order to connect the grid of the structure-fluid cell, the outer surface of the fluid structure in the four propellant tanks is selected, and the control size is also set to 0.05m to obtain the finite element model of liquid rocket after filling. The number of nodes and cells of the FEM model before and after injection is shown in Table 1. The finite element model of the first-stage combustion agent is shown in Fig.3 (b).

(a) Geometric model of the propellant (b) Finite element model of the primary burner

Figure 3. The propellant calculation model Calculation Model of Propellant

Table 1. Quantity of Node and Unit of Calculation Model Before and After Fueling

operating mode	monolithic construction		Projector part	
	Number of nodes	number of cells	Number of nodes	number of cells
Before filling	149406	148037	\	\
After filling	1038233	666136	888827	518099

3. SETTING OF THE BOUNDARY CONDITIONS

3.1. Material Properties

Table 2. Material Property of Liquid Rocket

Material	Parameter	Numeric value
Alufer	Elastic modulus, E / MPa	7×10^4
	yield limit σ_s/MPa	400
	Poisson ratio μ	0.33
	Density of ρ / kg / m^3	2270
Alloy steel	Elastic modulus, E / MPa	2×10^5
	yield limit σ_s/MPa	450
	Poisson ratio μ	0.3
	Density of ρ / kg / m^3	7850
Dinitrogen tetroxide	Liquid density is ρ / kg / m^3	1446
	Sound speed v / m / s in the liquid	1013
Dimethylhydrazine	Liquid density is ρ / kg / m^3	793
	Sound speed v / m / s in the liquid	1444

In this paper, two structural materials of aluminum alloy and alloy steel are used in the model. The shell material is aluminum alloy, the intermediate rod is alloy steel, the oxidant is nitrous oxide, and the combustion agent is dimethylhydrazine. The material properties are shown in Table 2 and defined in ANSYS material library.

3.2. Constraints and Load Conditions

Before the rocket, the short shell is supported on the launch pad, and in the finite element model of the liquid rocket, take the four rectangular areas on the tail, limit the movement of all units x, y, z and the rotation around each axis, as shown in Fig. 4.

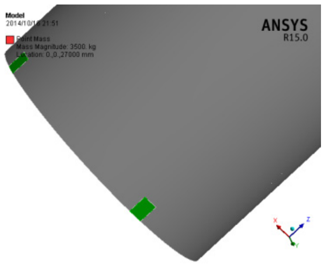


Figure 4. Clamped Constraint

And the load is then applied. Before liquid rocket filling, it is empty. After filling, the liquid accumulation ratio in each tank is 80%. In the upright state, the rocket is only affected by its own gravity, the hydrostatic pressure of the internal propellant, and the front and rear mass load, so three loads are applied here:

(1) Gravity acceleration. Select all units and, in the z direction, apply the gravitational acceleration (Acceleration of Gravity) g =9.8m / s^2;

(2) Hydrostatic water pressure. The hydrostatic pressure (Hydrostatic Pressure) is applied to the surface of the four tanks, defining the propellant density in the combustion agent tank and oxidant tank respectively, and defining the height of the liquid level in each tank so that the filling volume meets the volume ratio of 80%.

(3) Mass load. In the z direction, the mass load is defined on the front frame of the secondary oxidant box, so that the resultant force is equal to the equivalent mass force of the fairing (and payload and instrument chamber).

3.3. Cooperation Mode

To maintain the continuity of the model, the head of the enclosure, the head of the container, respectively, as shown in Fig. 5.

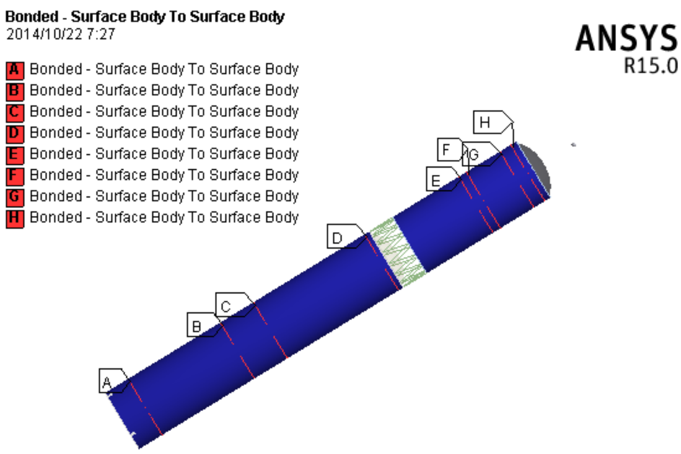


Figure 5. Contact Setting

4. CALCULATION RESULTS AND ANALYSIS

4.1. Implementation of Fcoupling and Algorithm Selection

In the mode calculation of the filling condition, the flow-solid coupling problem needs to be considered. The flow field unit and the structure unit need the coupling degree of freedom in the contact surface, and the contact surface of the liquid propellant and air in each tank belongs to the free liquid level, so the control command flow must be applied to these two surfaces.

(1) Define the flow-solid coupling surface, select the nodes on the contact surface between the structure unit and the fluid cell, then select the sound field units associated with these nodes, and apply the fsi command to realize the degree of freedom coupling on the contact surface of the structure-fluid cell;

(2) Define the free liquid level. First, the propellant and air contact surface in each tank in the model is defined as face1, and the free order is applied on the pace 1. Because the tank is filled with three atmospheres, the pressure is defined to be 0.3MPa above the free liquid level. Finally, add gravity to the model, select all units and define the gravity acceleration of 9.8m / s^2.

In the mode calculation, the mode extraction of the liquid rocket before filling adopts the reduction method. First, some nodes in the structure are selected as the main degree of freedom, and the mode and frequency of the structure are found through the degrees of freedom, and then the mode is extended to obtain the overall degree of freedom. Considering that the FLUID30 cell stiffness matrix is asymmetric, the mode extraction of liquid rocket after filling is asymmetric.

4.2. Natural Frequency Computation Results and Analysis

After the mode calculation of the liquid rocket structure by ANSYS, the top twenty order mode of the liquid rocket structure is obtained under the two working conditions. The natural frequency values are shown in Table 3 and Fig. 6.

Table 3. Top 20th order modes of liquid rocket under two working conditions

Order	1	2	3	4	5
Before filling	4.0523	4.0525	18.004	18.005	20.943
After filling	1.6342	1.6422	5.4656	5.483	10.543
Order	6	7	8	9	10
Before filling	23.051	23.051	23.728	23.735	24.916
After filling	15.637	16.026	16.148	16.15	16.192
Order	11	12	13	14	15
Before filling	24.918	25.652	25.657	26.26	26.348
After filling	16.192	16.193	16.193	16.606	16.606
Order	16	17	18	19	20
Before filling	26.348	26.556	26.557	26.601	26.63
After filling	16.668	16.668	16.698	18.96	18.97

(1) As can be seen from the chart, the frequency value of the two working conditions increases with the increase of the order, and the spontaneous vibration frequency of each order of the liquid rocket after filling decreases compared with before filling.

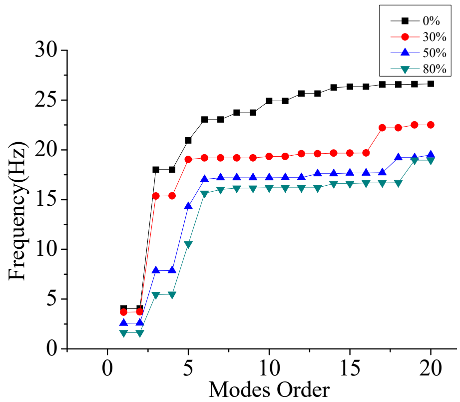


Figure 6. Dot plot of the top twenty order mode of the liquid rocket under two working conditions

We know that the natural frequency of the system is:

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{1}$$

Where f is the natural frequency of the system, ω is the angular frequency, K is the stiffness of the system, and M is the quality of the system.

It can be seen from equation (1) that the stiffness K of the rocket system after filling is basically unchanged, while the mass M increases, so the frequency decreases. The numerical results agree with the theory.

Many scholars have made a deep study on the natural frequency of liquid-solid coupling system, which can be the autovibration frequency of liquid-solid coupling system [7] express as:

$$f_m = \frac{1}{2\pi}\sqrt{\frac{Et_s}{\rho_l R^3}(a_m \frac{R}{H})\frac{I_1(a_m \frac{R}{H})}{I_0(a_m \frac{R}{H})}} \tag{2}$$

Where, f_mIt represents the m-order frequency of the flow system; I_0, I_1It represents the first order and first order Bessel functions of the first class correction;; m represents the frequency order and ρ $\alpha_m = (m - \frac{1}{2})\pi$ $_l$Is the liquid density; R represents the radius of the tank; H is the height of the tank; E is the elastic modulus of the tank material; t_sIs the tank body thickness.

According to Equation (2), with the diameter of the tank unchanged, the liquid level increases, R / H decreases, and the frequency f decreases, which again proves that the numerical calculation results are consistent with the theory.

(2) It can also be seen from the chart that the order 1 and 2 modes are low frequency vibration, and the frequency is lower after filling than before filling, but the amplitude does not change much, $f_1$take part in f_2The difference is small. From order 3, the frequency difference before and after filling increases significantly. The modes of each order after order 6 are basically stable.

Due to the reduction of the automatic vibration frequency of the system after filling, the liquid rocket may resonate under the excitation of the low-frequency vibration, resulting in serious consequences. Therefore, attention should be paid to eliminating the low-frequency vibration sources in the environment during use.

$$\frac{f_{i+1}}{f_i} < 1.2 \tag{3}$$

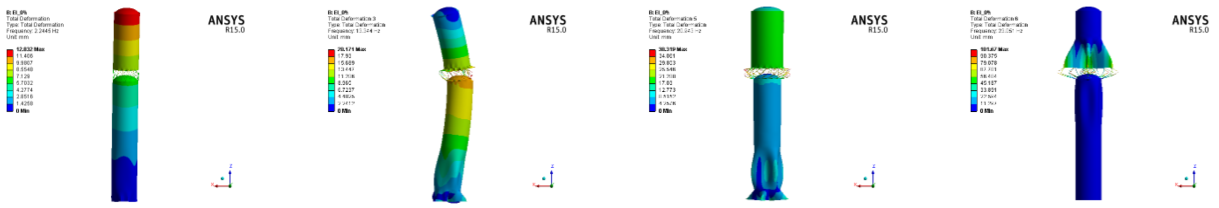
At that time, its mode is the correlation mode [8], The vibration patterns of the associated modes become symmetric or similar. By comparing the spontaneous vibration frequency under the two working conditions:

a) First orders 1 and 2,3 and 4,6~9,10~13 and 14~20 are the correlation modes;

b) orders 1,2,3,4,6 to 18 and 19,20 are associated modes.

4.3. Mode Analysis

According to the correlation modes, the vibration patterns of 1,3,5 and 6 modes under two working conditions are selected for comparison, as shown in Fig. 7 and Fig. 8.

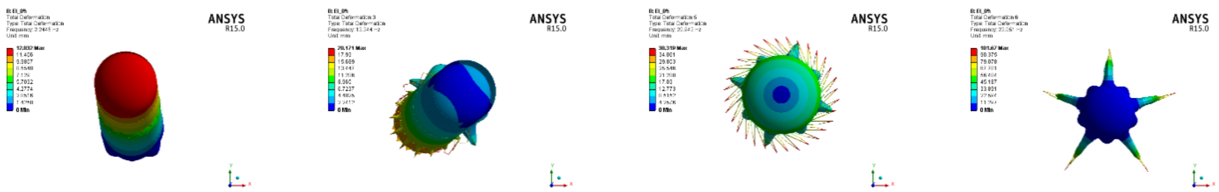


(A) Main view of the first-order vibration pattern

(B) Main view of order 3 vibration pattern

(C) Main view of order 5 vibration pattern

(D) Main view of order 6 vibration pattern



(E) Top view of the order 1 vibration pattern

(F) Top view of the 3-order vibration pattern

(g) Top view of the 5-order vibration pattern

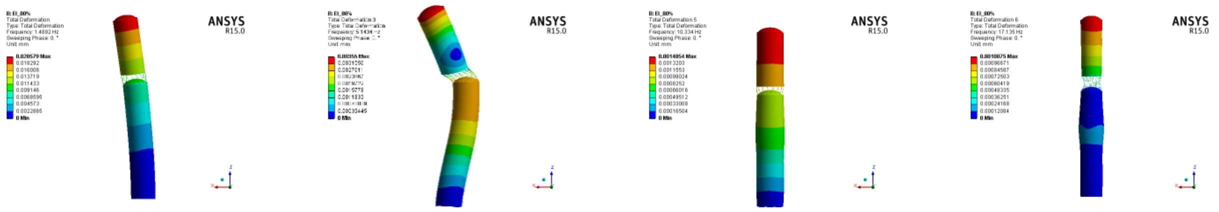
(H) Top view of 6-order vibration patterns

Figure 7. 1, 3, 5, 6 Order M ode graphs of the Liquid Rocket Before Fueling

As can be seen from Fig. 7, the first 1 order type is the swing in the yz plane; the 3 order type is the torsion pendulum in the plane, and the torsion plane has a 45° angle with the xz plane; the 5 order type is the whole twist around the central axis; the 6 order type is the secondary engine and the level lever.

As can be seen from Fig. 8, after the filling, the first order type is the inner swing with a 45° Angle with the xz plane; the third order type is the torsion pendulum in the plane, and the torsion pendulum plane has a certain Angle with the xz plane; the order 5 and the 6th are the upper and lower translations of the overall structure along the central axis.

To sum up, the propellant will not change the order 1 and 3 order type of the liquid rocket, and because order 1 and order 2, order 3 and 4 order are related modes, the amount of propellant will not affect the first 4 order type, but will only change its motion plane. For order 5 and order 6, the motion form changes with the change of the amount of propellant filling. Again, according to the correlation of the modes, the higher order mode of the liquid rocket is related to the amount of propellant filling in the tank.



(A) Main view of the first-order vibration pattern

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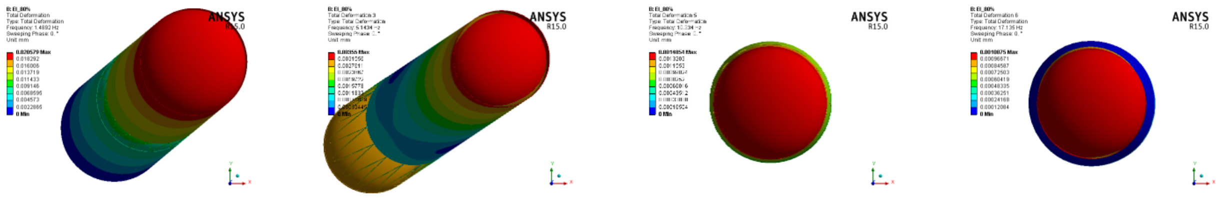
(C) Main view of order 5 vibration pattern

(D) Main view of order 6 vibration pattern



(E) Top view of the order 1 vibration pattern

(F) Top view of the 3-order vibration pattern

(g) Top view of the 5-order vibration pattern

(H) Top view of 6-order vibration patterns

Figure 8. Plot of Order 1,3,5 and 6 of Liquid Rocket after Injection

5. CONCLUSION

The numerical calculation results show that the autovibration frequency of the liquid rocket system decreases after filling the propellant, the 1st and 2nd order mode is low frequency vibration, the amplitude of the first 5th order autovibration frequency changes significantly, while the autovibration frequency above order 6 is basically stable. Attention should be paid to eliminating the use of low-frequency vibration sources in the environment, and more attention should be given after adding propellant.

The 1 and 2 modes of the front and back liquid rockets are swinging, while the liquid rocket structure; the filling propellant will not affect the first 4 modes, but will only change the vibration plane.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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