

# Dynamic Response of Liquid Rocket under TAFT Seismic Wave

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**Abstract:** This paper adopts the time course method of ANSYS software to analyze the dynamic response of liquid rocket under the action of TAFT seismic wave, and calculates the displacement and stress before and after the injection of liquid rocket. The results show that under the action of TAFT seismic wave, the liquid rocket swings along the direction of seismic wave action before and after filling. With the increase of the height, the maximum displacement appears in the top of the rocket, and the maximum stress appears in the tail support part. The maximum swing amplitude and the maximum stress are greatly increased than before the filling, especially the swing is divergent, there is a possibility of rocket dumping and structural strength damage.

**Keywords:** TAFT Seismic Wave; Liquid Rocket; Dynamic Response; Displacement; Stress.

## 1. Introduction

Large liquid launch vehicles generally use vertical hot launch, and before launch, the liquid rocket is erected on the launch pad for testing and propellant filling. At this time, if there is an earthquake, the liquid rocket is in the danger of overturning under the action of the seismic waves, which is a major issue concerning the safety of the shooting range, and it is necessary to carry out in-depth research.

Scholars at home and abroad have made in-depth research on the dynamic characteristics of launch vehicles, including the modeling theory and modeling technology of rocket structure dynamics[1][2], Dynamics test technology, kinetic model modification technology, payload coupling response analysis and vibration control technology, kinetic analysis of propellant and tank liquid solid coupling vibration[3][4]And, etc., it has laid a solid foundation for the stability design of rocket load environment design, attitude stability control system design, self-excited vibration (POGO) generated by the coupling of structural vibration and propulsion system. However, there are few research reports on the dynamic characteristics and response of liquid rockets under the action of seismic waves. Liu Caizhi and Tang Guojin studied the seismic response and seismic design of a certain type of carrier rocket [5], The main body of the rocket uses the beam unit model, and only partially adopts the fine 3 D model. The standing state of liquid rocket is similar to that of vertical liquid storage tank, but the seismic research of vertical liquid storage tank is very lasting and deep. Since the 1930s, a series of calculation theories, test techniques and design specifications have been put forward [6][7]. With the development of finite element technology, the numerical simulation method of the reservoir is widely used. Fully considering the influence of various nonlinear factors and liquid-solid coupling, analyze the inherent characteristics and dynamic response of the tank, and calculate the lifting and buckling effect of the tank under seismic action, which can be used as an important reference for the seismic response analysis of the liquid rocket. This paper uses the finite element

analysis software ANSYS to establish a liquid rocket three-dimensional fine model, with the classic TAFT seismic wave input, calculate the liquid rocket before and after propellant injection, obtain the rocket movement trend and stress change under the earthquake action, evaluate the possibility of liquid rocket under the action of TAFT seismic wave danger, provide reference for the safe use of the target range.

## 2. Computational Model

### 2.1. Geometric Model

This paper takes a two-stage liquid carrier rocket as an example, mainly consists of fairing (including payload), instrument module, secondary power system (including secondary oxidant tank, secondary compartment, secondary burner tank), segment (including shell segment and rod segment) and primary power system (including primary oxidant tank, primary tank, primary combustion agent tank). In order to reduce the calculation scale, the fairing (including payload) and the instrument module were ignored in the modeling, and only the main part of the rocket was established. However, the fairing (including payload) and the instrument module were loaded on the short shell of the secondary oxidant tank as mass force in the calculation. When the rocket is erected on the launch pad, it relies on four parts of the short shell of the first burner tank. The liquid rocket geometry model is shown in Figure 1 (a).

In the modeling, the shell is treated according to the light shell, and the middle surface operation is drawn. On the basis of ensuring the authenticity of the model, the calculation efficiency is improved. Establish the propellant model [8] Using the fill command, the inner surface of each tank is filled, and then the liquid propellant model in different liquid filling states is obtained by cutting. Finally, the unneeded liquid propellant part of the tank is removed by inhibiting the operation. In this article, the volume ratio of propellant after filling is 80%, as shown in Figure 1 (b).

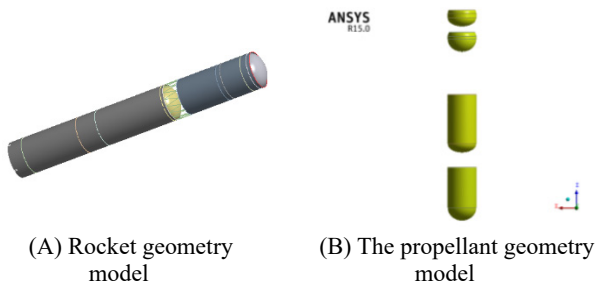


Fig 1. Phase analysis of arrangement

## 2.2. Finite-element Model

In this paper, the shell unit SHELL181 is selected to grid the shell structure, and the connecting rod of the stage segment is divided by the beam unit BEAM188. In the grid division process, in order to obtain the cells with better quality, the cell size was controlled to 0.05m, yielding a total of 149406 nodes and 148037 cells.

The filled portion was divided using FLUID30 units. 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, which finally obtains the liquid rocket finite element model under 80% liquid filling condition. After filling, a total of 1038,233 nodes and 666,136 units were obtained, including 888,827 nodes and 518,099 units in the liquid part.

## 3. Computational Settings

### 3.1. Material Properties

The first and second stage shell of the rocket is made of aluminum alloy, the stage bar is alloy steel, the oxidant is nitrous oxide, and the combustion agent is dimethylhydrazine. The material properties are shown in Table 1 and defined in ANSYS material library.

Table 1. Material properties of liquid rockets

Material	Parameter	Numeric value
alufer	Elastic modulus, $E / \text{MPa}$	$7 \times 10^4$
	yield limit $\sigma_s / \text{MPa}$	400
	Poisson ratio $\mu$	0.33
	Density of $\rho / \text{kg} / \text{m}^3$	2270
alloy steel	Elastic modulus, $E / \text{MPa}$	$2 \times 10^5$
	yield limit $\sigma_s / \text{MPa}$	450
	Poisson ratio $\mu$	0.3
	Density of $\rho / \text{kg} / \text{m}^3$	7850
dinitrogen tetroxide	Liquid density is $\rho / \text{kg} / \text{m}^3$	1446
	Sound speed $v / \text{m} / \text{s}$ in the liquid	1013
dimethylhydrazine	Liquid density is $\rho / \text{kg} / \text{m}^3$	793
	Sound speed $v / \text{m} / \text{s}$ in the liquid	1444

### 3.2. Constraints and Load Conditions

Before the imminent launch, the rocket is supported on the launch pad by the short shell of the first stage burner tank, which is treated as fixed support. In the finite element model of the liquid rocket, the four rectangular areas on the center symmetry of the first stage are calibrated to limit the movement of all units  $x$ ,  $y$  and  $z$  in the direction and the rotation around each axis.

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 four loads are applied here:

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

(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 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 the payload and instrument chamber).

(4) Earthquake wave. The time course method is used for seismic response analysis and the time domain acceleration input method for seismic wave loading. Select the TAFT seismic wave with relatively complete records, belonging to the magnitude 7 strong earthquake. A 5s acceleration sequence including the maximum acceleration peak was intercepted and loaded from the support site X direction. The time-course figure and spectrum map of the seismic waves are shown in Figure 2.

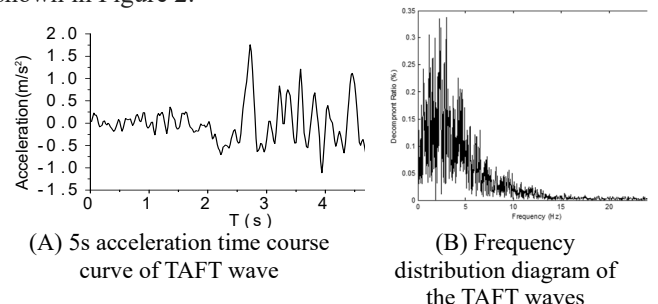


Fig 2. The TAFT seismic wave

### 3.3. Fluid-solid Coupling Setting

In the calculation, 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 at the same time is in the free liquid level, so the control command flow must be imposed on 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 contact surface between propellant and air in each tank is defined as face1, and the free order is applied on the face1. Because the tank is filled with three atmospheres, it is necessary to define the

pressure of 0.3MPa above the free liquid level. Finally, add gravity to the model, select all units and define the gravity acceleration of 9.8 m/s<sup>2</sup>.

### 3.4. Calculate the Step Size Setting

In ANSYS, the Newmark time integration method is used to solve the governing equation at discrete time points, and the initial step size is determined according to the following formula:

$$\Delta t_{initial} = \frac{1}{25 f_{response}} \quad (1)$$

Among,  $f_{response}$  Represents the frequency of the highest order mode pattern of interest when studying the structure.

After modal analysis of the first and last filling conditions, the highest frequencies of order 1 and 2 are 4.05023Hz and 1.6342Hz respectively. According to formula (1), the initial time steps before and after filling are 0.01s and 0.025s respectively.

## 4. Analyses of the Calculation Results

In this paper, the dynamic response of the structure under the TAFT seismic wave before and after filling is calculated. The loading time of the seismic wave is 5s, and the stress and displacement of the structure within 5s are obtained.

### 4.1. Movement Trend of the Rocket under the Action of TAFT Wave Before Injection

The displacement data of the liquid rocket under the action of TAFT wave before filling is calculated. According to the analysis, the liquid rocket swings along the x axis. In 5s, the swing changes from small to large, the maximum swing is about 0.06m, and the swing period is about 0.8s. And the swing amplitude was not stable during the 5s action time.

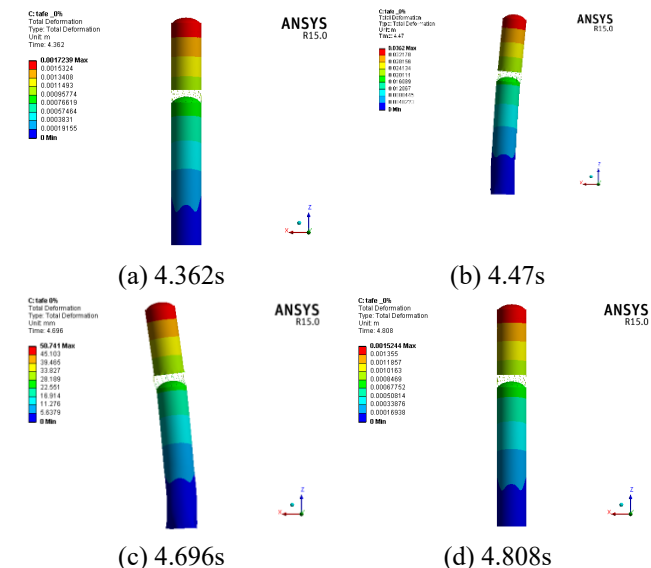


Fig 3. Total Displacement Nephogram of Rocket Under Earthquake Wave TAFT Before Fueling

In order to analyze the displacement change of the overall structure of the liquid rocket in the time course, the total displacement at the beginning, trough, peak and the end of the stable swing is studied, as shown in Figure 3, corresponding to the four moments of 4.362s,4.47s,4.696s,4.808s. The overall amplitude of the change at 4.467s and 4.696s.

According to the figure, the maximum displacement of the liquid rocket appears at the top of the liquid rocket at 4.362s and the size is only 0.0017m, so the overall structure is basically vertical, that is perpendicular to the xy plane; at 4.47s, the top of the liquid rocket is about 0.0362m and swinging negatively to the x-axis; at 4.696s, the top of the liquid rocket is the maximum displacement and the size is about 0.0507m to the x-axis; at 4.808s, the overall structure of the liquid rocket returns to vertical again. Therefore, in a swing period, the total displacement of the liquid rocket before the action of TAFT wave increases with the increase of height, and the maximum value appears at the top and the minimum value at the bottom. Combined with the cycle characteristics, it is true in the whole time period.

From the maximum displacement, it can be seen that the liquid rocket before filling is not large under the action of TAFT wave, which will not endanger the stability of the rocket, but the swing within 5s is not stable and there is a divergence trend. If the seismic wave lasts long enough, there is still the possibility of danger.

### 4.2. Stress of the Rocket under the TAFT Wave before Refueling

It can be seen from the previous section that the liquid rocket swings along the x axis under the action of TAFT wave, and the equal effect force of the initial, trough, peak and end of a cycle is shown in Figure 4, and the corresponding time is 4.362s,4.47s,4.696s,4.808s respectively. For observation, the overall magnitude of change at 4.47s and 4.696s was also magnified 51 times.

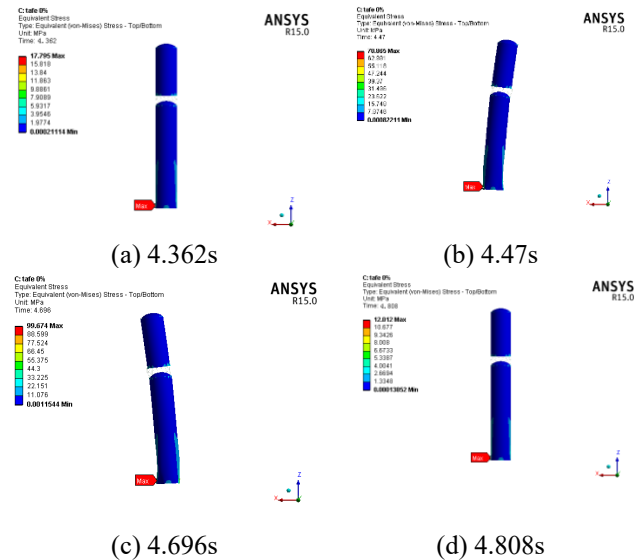


Fig 4. Equivalent Stress Nephogram of Rocket Under Earthquake Wave TAFT Before Fueling

As can be seen from the figure, at four moments, the maximum stress of the liquid rocket appears near the fixed branch, and the maximum stress value of the liquid rocket swings to the maximum displacement is about 99.7MPa.

Through the analysis of all stress data, the maximum value of equal effect force in the whole time period is about 105MPa. When the safety factor is 1.5, the structural strength reserve coefficient is 2.5, which is high safety and no strength damage and instability damage occurs.

### 4.3. Movement Trend of the Rocket under the Action of TAFT Wave after Injection

According to the analysis of displacement data, under the

action of TAFT wave, the overall vibration form of the liquid rocket after filling is also swinging horizontally along the xz plane. In 5s, the swing changes from small to large but the stable swing is not formed, the maximum swing is about 0.14m, and the period after swing is about 1.8s. In order to analyze the displacement change of the overall structure of the liquid rocket after filling, the total displacement cloud map of the initial, trough, peak and end of the swing period is given, as shown in Figure 5, and the corresponding time is 4.1s,4.28s,4.76s,4.944s. The overall amplitude of change at the two peak moments of 4.28s,4.76s was amplified 23-fold for observation.

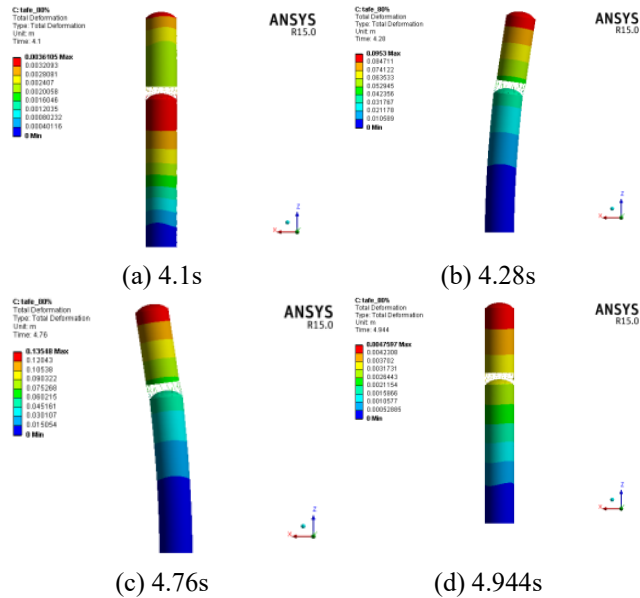


Fig 5. Total Displacement Nephogram of Rocket Under Earthquake Wave TAFT After Fueling

As can be seen from the figure, the overall structure of the liquid rocket is basically vertical, namely perpendicular to the xy plane; at 4.28s, the top displacement value of the liquid rocket is the smallest, about 0.0953m, swinging negatively to the x-axis; at 4.76s, the top displacement value of the liquid rocket is the largest, about 0.1355m, swinging positively to the x-axis; at 4.944s, the overall structure of the liquid rocket returns to the vertical state. Figure shows that the displacement values increases with increasing height.

Under the action of TAFT wave, the total displacement of the liquid rocket is the same as before the filling. The maximum displacement appears at the top, the minimum displacement is at the bottom, and the whole time course according to the cycle characteristics. However, after filling the propellant, the swing of the rocket increases significantly, the cycle is also longer, and the swing within 5s is not stable. This shows that under the action of TAFT wave, the inertial swing of the propellant is strengthened, and there is the possibility of divergence, and finally makes the liquid rocket dump. Therefore, in order to prevent the missile from being dangerous under the action of strong shock, the constraint of the clamp on the launch tower should not be lifted too early.

#### 4.4. Equal Effect Force of the Rocket under the Action of TAFT Wave after Injection

In the analysis of effect forces such as filling conditions, the cloud map of the initial, trough, peak and end of the stability cycle is also selected, as shown in Figure 6, corresponding to 4.1s,4.28s,4.76s,4.944s. For observation, the overall magnitude of change at both peak moments of

4.28s,4.76s was amplified by 23 times.

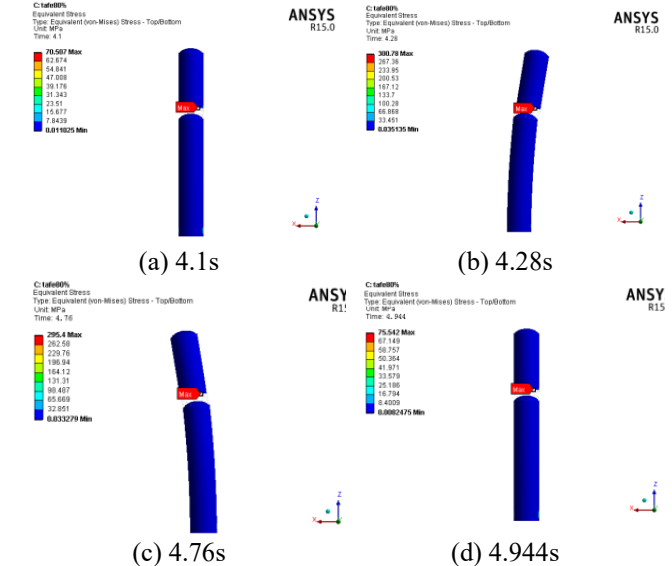


Fig 6. Equivalent Stress Nephogram of Rocket Under Earthquake Wave TAFT After Fueling

It can be seen from the figure that the maximum stress of the liquid rocket after filling appears at the connection between the second stage tail segment and the interstage bar segment. The maximum stress value when the liquid rocket swings to the maximum displacement is about 301MPa, and when the liquid rocket returns to the initial upright state, the maximum stress is about 70~75MPa. Therefore, the maximum stress in the whole swing process appears at the maximum swing moment, the rod section force is large, there is a possibility of instability.

According to further analysis of stress data, the maximum stress value under the action of TAFT wave is about 310MPa, which is located at the full arrow support in the tail section. Although it is less than the yield limit of the material itself, when the safety factor is 1.5, the structural strength reserve coefficient is 0.86 and less than 1, indicating that the strength failure of the liquid rocket structure may occur under the action of TAFT wave.

## 5. Conclusion

The analysis results show that under the action of TAFT seismic wave, the liquid rocket swings along the direction of seismic wave action before and after filling. With the increase of the rocket height, the swing amplitude becomes larger, the maximum swing amplitude appears at the top of the rocket, and the maximum equal effect force appears near the support part at the tail of the rocket. However, before filling, the swing amplitude and equal effect force are small, which will not affect the stability and structural safety of the rocket. After filling, the swing amplitude and equal effect force increase greatly, especially the rocket swing is divergent. If the seismic wave lasts for a long time, the tail support part of the rocket may be damaged, and the rod stress between the stage is also large, so there is a possibility of instability damage.

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