Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 13, No. 1, 2024

Analysis of the Dynamic Response of A Liquid Rocket Under Seismic Waves

Shiji Chen[1], Xueren Wang[1], Jiazhao Chen[1, *], Xuan Zhang[2], Jiexin Weng[2]

[1]PLA Rocket Force University of Engineering, Xi'an, 710025, China
[2]Inner Mongolia Power Machinery Research Institute, Hohhot 010000, China
[*] Corresponding author: Tingjing Geng, jazhch@sina.com

Abstract: By adopting time history method in software ANSYS, dynamic response of a liquid rocket was analyzed when it was suffered from earthquake wave TAFT and EI, and the displacement and stress of the rocket were calculated. The result showed that the liquid rocket swung along the acting direction of the earthquake wave. The higher the position of rocket, the larger the swing, and the maximum displacement located on the top of the rocket, and the maximum stress located at the support places on the rear part. The higher the earthquake magnitude, the larger the swing, and the larger the maximum equivalent stress. The rocket has the possibility to fall down and damage in structure under a strong earthquake over 7 grade.

Keywords: Seismic waves; liquid rocket; dynamic response; Displacement; Stress.

1. Introduction

Large liquid launch vehicles are usually placed vertically on the launch pad for a series of tests and propellant refueling before launch. If a strong earthquake occurs at this time, is there a danger that the liquid rocket will capsize under the action of seismic waves? This is a major issue related to the safety of the shooting range, and it is necessary to conduct in-depth research.

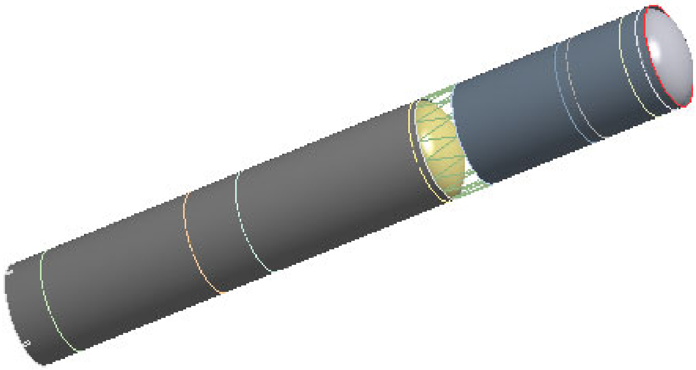
Scholars at home and abroad have carried out in-depth and persistent research on the seismic resistance of buildings and storage tanks[1][2], and the seismic research on vertical liquid storage tanks has been carried out since the 30s of the 20th century, and a series of calculation theories, test techniques and design specifications have been proposed[3][4]. With the development of finite element technology, numerical simulation methods are widely used to analyze the seismic response of the reservoir, fully considering the influence of various nonlinear factors and liquid-solid interaction, analyzing the inherent characteristics and dynamic response of the reservoir, and calculating the lifting and buckling effects of the reservoir under seismic action. Scholars at home and abroad have also conducted in-depth research on the dynamic characteristics of launch vehicles, including rocket structural dynamics modeling theory and modeling technology[5][6], dynamic test technology, dynamic model correction technology, payload coupling response analysis and vibration control technology, and dynamic analysis of liquid-solid interaction vibration between propellant and storage tank[7][8].It lays a solid foundation for the design of rocket load environment, attitude stability control system, and self-excited vibration (POGO) stability design 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 seismic waves, and Liu Caizhi and Tang Guojin studied the seismic response and seismic design of a certain type of carrier rocket in the erection state[9], the main body of the rocket adopts the beam element model, and only the part adopts the fine three-dimensional model. The erection state of liquid rockets is similar to that of vertical liquid storage tanks, and the seismic research results of vertical liquid storage tanks can be used as an important reference for seismic response analysis of liquid rockets. In this paper, the finite element analysis software ANSYS is used to establish a three-dimensional fine model of a liquid rocket, taking the typical TAFT seismic wave and EI seismic wave as input, considering the influence of liquid-solid interaction, using the time history method to calculate the dynamic response of the liquid rocket under the action of seismic waves, obtaining the motion trend and stress change of the rocket under the action of earthquake, and evaluating the possibility of danger of the liquid rocket under the action of TAFT wave and EI wave, so as to provide a reference for the safe use of the shooting range.

2. Computational Model

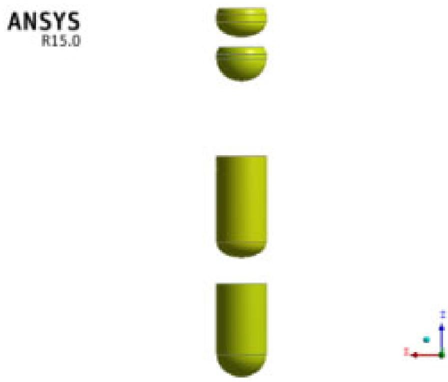
2.1. Geometric model

In this paper, a two-stage liquid launch vehicle is taken as an example, which is mainly composed of a fairing (including payload), an instrument compartment, a second-stage power system (containing a second-stage oxidant tank, a second-stage inter-tank section, and a second-stage burner tank), an interstage section (including an interstage shell section and an interstage rod section) and a first-stage power system (including a first-stage oxidizer tank, an inter-tank section, and a first-stage combustion tank). In order to reduce the scale of the calculation, the fairing (including the payload) and the instrument compartment were ignored in the modeling, and only the main part of the rocket was established, and the fairing (including the payload) and the instrument compartment were loaded on the short shell in front of the secondary oxidizer tank as mass force during the calculation. When the rocket is erected on the launch pad, it is supported on the launch pad by four parts on the short shell behind the first stage incendiary tank. The liquid rocket geometry is shown in Fig.1(a).

During modeling, the shell is treated as a smooth shell, and the middle surface is extracted, which reduces the number of elements and improves the calculation efficiency on the basis of ensuring the authenticity of the model. To build a propellant[10], the fill command was used to fill the inner surface of each tank, and then the liquid propellant model under different filling states is obtained by cutting, and finally the unwanted part of the liquid propellant in the tank is removed by suppression. In this paper, the post-filling propellant filling volume ratio is set to be 80%, as shown in Figure 1(b).



(a) Rocket geometry



(b) Propellant geometry

Figure 1. Geometric Model of Structure

2.2. Finite element model

In this paper, the shell element SHELL181 is selected to mesh the shell structure, and the connecting rod of the interstage section is divided by the beam element BEAM188. In the process of meshing, in order to obtain the better quality elements, the element size was controlled to 0.05m, and a total of 149406 nodes and 148037 elements were obtained.

The liquid-filled part is divided by FLUID30 units. In order to make the structure-fluid element grid co-node, the outer surface of the fluid structure in the four propellant tanks was selected, and the control size was also set to 0.05m, and finally the finite element model of the liquid rocket under the condition of 80% liquid filling was obtained. A total of 1038233 nodes and 666136 units were obtained under the working condition after filling, of which 888827 nodes and 518099 units were obtained in the liquid part.

3. Calculation Settings

3.1. Material Properties

The first and second stage shells of the rocket are made of aluminum alloy, the interstage rod is alloy steel, the oxidizer is nitrous tetroxide, and the combustion agent is metamethylhydrazine, and the material properties are shown in Table 1 and defined in the ANSYS material library.

Table 1. Material Property of Liquid Rocket

Material	Parameter	Numeric value
Aluminum alloy	Modulus of elasticity E/MPa	7×10^4
	Yield limit σs/MPa	400
	Poisson's μ	0.33
	Density ρ/kg/m^3	2270
Alloy steel	Modulus of elasticity E/MPa	2×10^5
	Yield limit σs/MPa	450
	Poisson's μ	0.3
	Density ρ/kg/m^3	7850
Nitrous tetroxide	The density of the liquid is ρ/kg/m^3	1446
	The velocity of sound in liquids is v/m/s	1013
Metamethylhydrazine	The density of the liquid is ρ/kg/m^3	793
	The velocity of sound in liquids is v/m/s	1444

3.2. Constraints and Load Conditions

In the finite element model of the liquid rocket, the four rectangular areas with symmetry in the center of the first stage tail are taken for imprint calibration, which restricts the movement of all units in the x, y and z directions and the rotation around each axis in the imprint area.

Then the load is applied. The liquid rocket is empty before refilling, and after the refueling is completed, the filling volume ratio in each tank is 80%. In the erect state, the rocket is only affected by its own gravity, the hydrostatic pressure of the internal propellant, and the mass load before and after, so four loads are applied here:

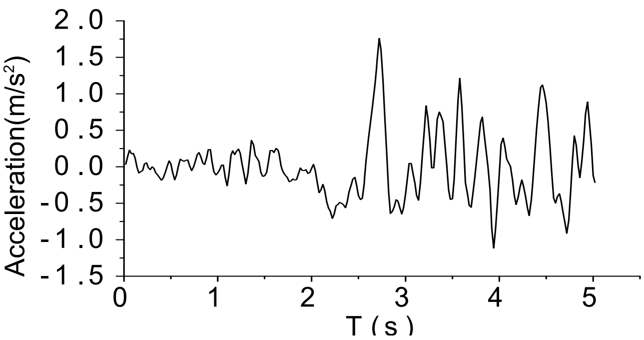
(1) Acceleration of Gravity. Select all elements, and apply the acceleration of gravity in the inertial load g=9.8m/s^2 in the z-direction;

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

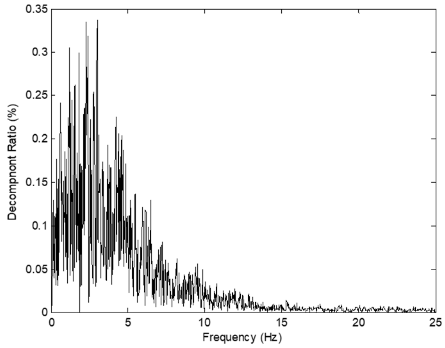
(3) Mass load. In the z-direction, define the mass load on the front frame of the secondary oxidizer tank so that its resultant force is equal to the equivalent mass force of the fairing (as well as the payload and instrument compartment).

(4) Seismic waves. In this paper, the time history method is used in the seismic response analysis, and the acceleration input method in the time domain is used for seismic wave

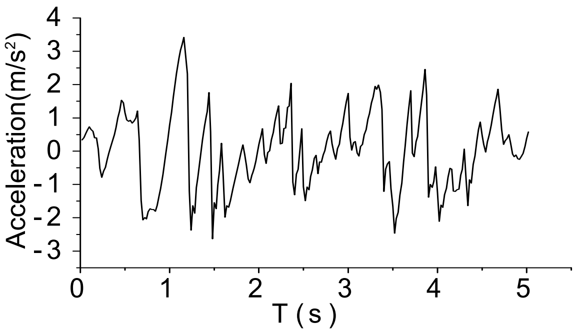
loading. In this paper, TAFT waves and EI waves, which are relatively well recorded, are selected as TAFT waves and EI waves, which belong to magnitude 7 strong earthquake seismic waves, while EI waves belong to magnitude 8 strong earthquake seismic waves. In this paper, the 5s acceleration sequence, including the maximum acceleration peak, is intercepted and loaded from the x direction of the support part. The time history curve and spectrogram of the seismic wave are shown in Fig.2.



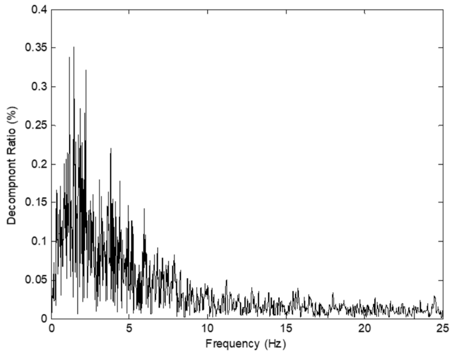
(a) 5s acceleration time history curve of TAFT wave



(b) TAFT wave frequency distribution



(c) 5s acceleration time history curve of EI wave



(d) Frequency distribution of EI waves

Figure 2. Earthquake Wave TAFT and EI

3.3. Fluid-structure interaction settings

In the calculations, the flow field element and the structural element require coupling degrees of freedom at the contact surface, and the contact surface between the liquid propellant and the air in the individual tanks is a free liquid surface, so a control command must be applied to these two surfaces.

(1) Define the fluid-structure interaction surface, select the nodes on the contact surface between the structural element and the fluid element, select the acoustic field element associated with these nodes, and apply the FSI command to realize the degree of freedom coupling on the contact surface of the structure and the fluid element;

(2) To define the free liquid level, first define the contact surface between the propellant and the air in each tank as face1, and apply the free command on face1, because the tank is filled with a protective gas of 3 atmospheres, it is necessary to define the pressure above the free liquid level as 0.3MPa. Finally, add gravity to the model, select all the elements and define the gravitational acceleration as 9.8m/s2.

3.4. Calculate the step size setting

In this paper, the seismic response analysis uses the time history method, and the Newmark time integration method is used in ANSYS to solve the governing equations at discrete time points, and the initial step size is determined by the following formula:

$$\Delta t_{initial} = \frac{1}{25 f_{response}} \tag{1}$$

where $f_{response}$ denotes the frequency of the highest-order mode shape that is of interest when studying the structure.

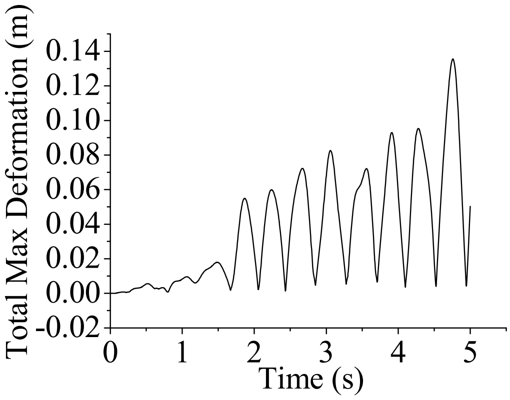
The modal analysis of the structure of the two working conditions before and after filling is carried out, and the highest frequencies of the first and second modes are 4.05023Hz and 1.6342Hz, respectively, and according to equation (1), the initial time steps before and after filling are 0.01s and 0.025s, respectively.

4. Analysis of Calculation Results

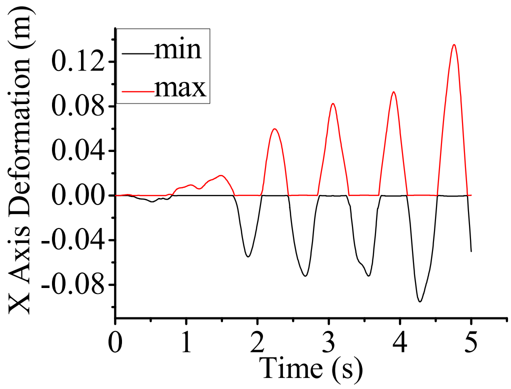
In this paper, the dynamic response of the structure of the liquid rocket after filling under the action of TAFT seismic wave and EI seismic wave is calculated, and the loading time of seismic wave is 5s, and the stress and displacement time history curves of the structure within 5s are obtained.

4.1. Trend of the movement of the rocket under the action of the TAFT wave

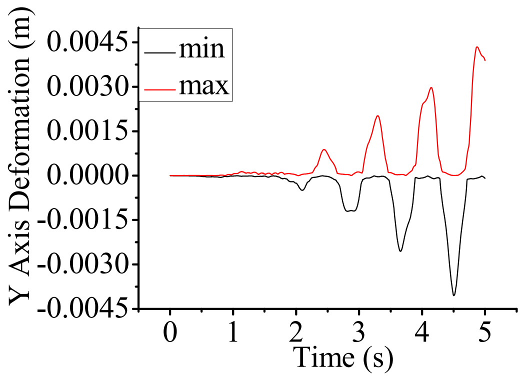
After numerical calculations, the time history curves of the overall maximum displacement of the liquid rocket under the action of TAFT wave and the time history curves of the maximum and minimum displacement in the x, y and z directions are obtained respectively, as shown in Fig.3, where the red line represents the time history curve of the maximum displacement and the black line represents the time history curve of the minimum displacement.



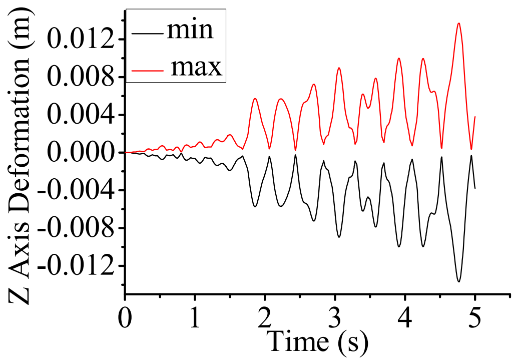
(a) Total displacement time history curve



(b) Time history curve of displacement in the x-direction



(c) Displacement time history curve in the y-direction



(d) Time history curve of displacement in the z-direction

Figure 3. Displacement Time History Curve of Rocket Under Earthquake Wave TAFT

As can be seen from Fig.3(b) and Fig.4(c), the maximum and minimum displacements of the liquid rocket in the x and y directions alternate under the action of EI waves, but the displacement amplitude in the y direction is much smaller than that in the x direction. As can be seen from Fig.3(d), the curves of the maximum displacement and the minimum displacement in the z-axis are symmetrical with respect to z=0, so it is inferred that the liquid rocket oscillates periodically in the x-direction, with a maximum swing amplitude of about 0.14m and a swing period of about 1.8s. There is a slight shift in the oscillating plane relative to the xz plane during the oscillation, which is caused by the shaking of the liquid propellant under the action of seismic waves after filling.

The analysis of the displacement data shows that the swing amplitude of the liquid rocket increases with the increase of altitude under the action of TAFT wave, the maximum displacement appears at the top, and the minimum displacement appears at the bottom, and the swing amplitude does not tend to be stable within 5s, but has a divergent trend. If the seismic wave lasts longer, the swing will be greater, eventually toppling the rocket. Therefore, in order to prevent the danger of the missile under the action of a strong earthquake, the restraint of the rocket on the crest on the tower should not be prematurely lifted.

The reason why the swing of the rocket has a tendency to diverge in 5s is that the components in the spectrum of seismic waves that are similar to the natural frequency of the rocket are relatively strong, which is easy to cause the rocket to resonate.

4.2. Stress analysis of rockets under the action of TAFT waves

Fig.4 shows the time history curve of the equivalent stress force of the rocket under the action of the TAFT wave. The analysis of the stress data shows that the maximum equivalent stress of the liquid rocket under the action of TAFT wave occurs in the tail support part, and the stress in the area near the secondary and interstage rod sections is also larger, and although the interstage rod section is subjected to greater tensile and compressive stress, it is not the maximum stress part. It can be seen from Fig.4 that the maximum equivalent stress in the whole time history is about 310MPa, which is less than the yield limit of the material itself, but when the safety factor is 1.5, its structural strength reserve coefficient is 0.86, which is less than 1, so the strength failure of the liquid rocket structure will occur under the action of TAFT wave.

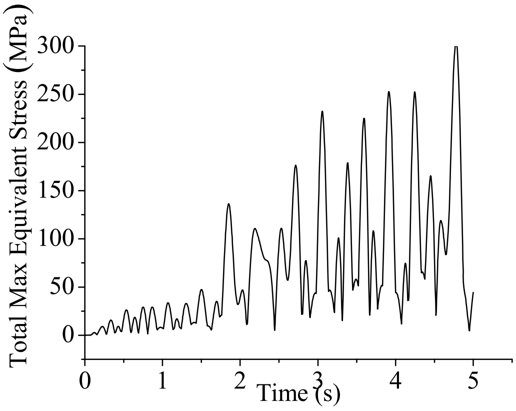
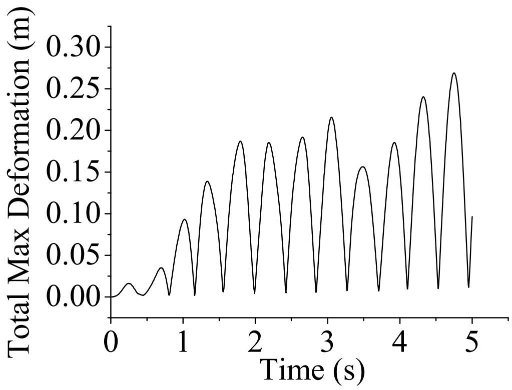


Figure 4. Maximum Equivalent Stress Time History Curve of Rocket Under Earthquake Wave TAFT

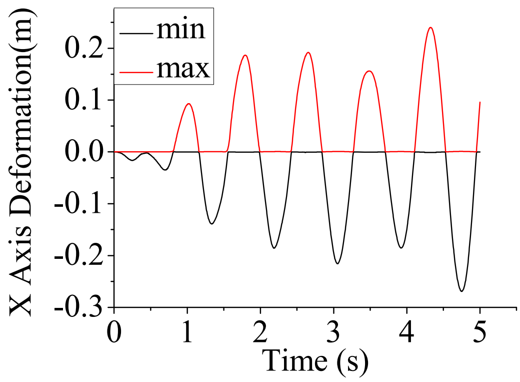
It can also be seen from the figure that the maximum equivalent stress does not tend to stabilize in 5s, and if the seismic wave lasts longer, the structural damage will be greater.

4.3. Analysis of the movement trend of rockets under the action of EI waves

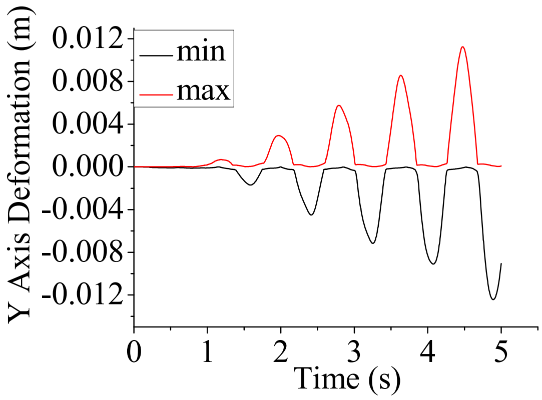
After numerical calculations, the time history curves of the overall maximum displacement of the liquid rocket under the action of EI wave and the time history curves of the maximum and minimum displacement in the x, y, and z directions are obtained respectively, as shown in Fig.5, where the red line represents the time history curve of the maximum displacement and the black line represents the time history curve of the minimum displacement.



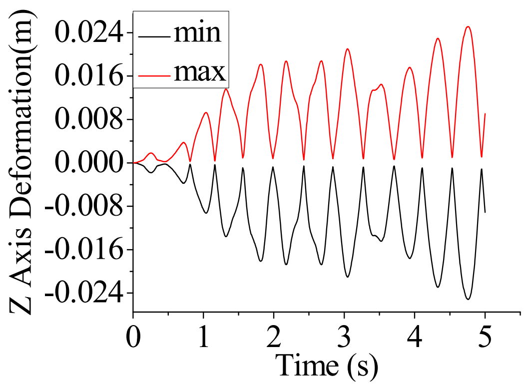
(a) Total displacement time history curve



(b) Time history curve of displacement in the x-direction



(c) Displacement time history curve in the y-direction



(d) Time history curve of displacement in the z-direction

Figure 5. Displacement Time History Curve of Rocket Under Earthquake Wave EI

As can be seen from Fig.5(b) and Fig.5(c), the maximum and minimum displacements of the liquid rocket in the x and y directions alternate under the action of EI waves, but the displacement amplitude in the y direction is much smaller than that in the x direction. As can be seen from Fig.5(d), the curves of the maximum displacement and the minimum displacement in the z-axis are symmetrical with respect to z=0, so it is inferred that the liquid rocket also oscillates periodically in the x-direction, and the oscillation plane has a slight offset relative to the x-plane during the oscillation. The maximum swing is about 0.26m, and the swing period is about 0.9s. Compared with the swing of the rocket under the action of TAFT wave, the swing amplitude of the rocket under the action of EI wave is larger and the period is shorter, which indicates that the swing is more violent.

The analysis of the displacement data shows that the swing amplitude of the liquid rocket also increases with the increase of altitude under the action of EI wave, with the maximum displacement at the top and the minimum displacement at the bottom. Similarly, the swing amplitude is not stable within 5s, and there is a tendency to diverge, and if the seismic wave lasts longer, the liquid rocket will eventually be toppled.

4.4. Equivalent stress analysis of rockets under the action of EI waves

Fig.6 shows the time history curve of the maximum equivalent stress of a liquid rocket under the action of EI waves.

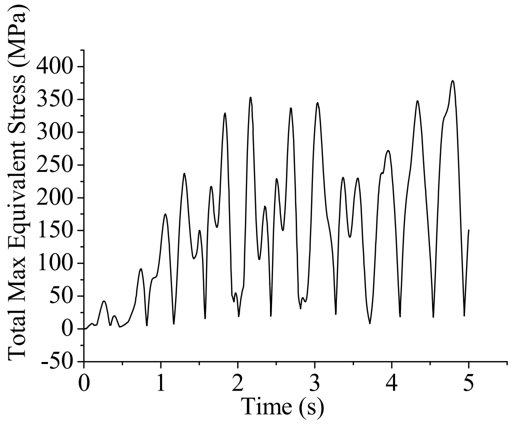


Figure 6. Maximum Equivalent Stress Time History Curve of Rocket Under Earthquake Wave EI

It can be seen from Fig.6 that the maximum stress value of the liquid rocket under the action of EI wave is about 390MPa, which is close to the yield limit of the material itself, although there is no shaping deformation, when the safety factor is 1.5, the safety reserve coefficient of the structure is 0.6, which indicates that the structure of the liquid rocket will be damaged under the action of EI wave after filling, and it should be strengthened in the design.

Compared with the equivalent stress of the rocket structure under the action of TAFT wave, the equivalent stress of the rocket under the action of EI wave is larger, and the strength reserve coefficient is smaller, that is, the possibility of rocket destruction is greater.

Analysis of the stress data also shows that the maximum equivalent stress is not stable for 5s, and if the seismic wave lasts longer, the damage will be more severe. In addition, the stress of the interstage rod section and the area near the connection between the second stage and the tail section of the liquid rocket under the action of EI wave is also larger, and the interstage rod section is subjected to a large tensile and compressive stress, with a value of 230MPa, which may cause instability, which should be paid enough attention.

5. Conclusion

The analysis results show that under the action of TAFT seismic wave and EI seismic wave, the liquid rocket oscillates along the direction of seismic wave, and the swing amplitude increases with the increase of rocket height, the maximum swing amplitude appears at the top of the rocket, and the maximum equivalent stress appears near the support part of the rocket tail section. Since the swing amplitude of the rocket is not stable in 5s, there is a tendency to diverge, and if the earthquake lasts longer, the rocket may tipple. The equivalent stress of the tail support part of the rocket is large, and the strength reserve coefficient is less than 1, and the strength failure will occur. The maximum equivalent stress also did not stabilize within 5s, and if the earthquake lasted longer, the damage would be more severe. In addition, the stress of the interstage rod section and its connection with the first and second stages is also large, which should also attract enough attention. The analysis also shows that the maximum displacement and maximum stress under the action of EI wave are larger than those under the action of TAFT wave, that is, the greater the intensity of the seismic wave, the higher the possibility of failure. Therefore, sufficient attention should be paid to the impact of earthquakes in the design of rockets, the selection of shooting ranges and the launch of shooting ranges.

References

[1] Zhou Xiaofu, Kang Yanbo, Zhang Rongqiang, et al. A review of the development trend of modern architecture and seismic technology and modern architecture[J]. Building Science, 2021, 37(1):114-120

[2] Zhang Rulin, Cheng Xudong, Guan Youhai. A review of the current status and development of seismic research on large storage tanks[J]. Sichuan Building Science Research, 2015, 41(1):205-209

[3] Fang Hao, Wu Hao, Wang Duguo. A review of seismic safety issues in liquid storage tanks[J]. Earthquake Defense Technology, 2012, 7(2): 144-151

[4] Zhang Rulin, Cheng Xudong, Wang Huaifeng. Analysis of the influence of vertical seismic action on the seismic response of liquid storage tank [J]. Chinese Journal of Earthquake Engineering, 2017, 39(4): 592-599

[5] Sun Dan, Mao Yuming, Di Wenbin, et al. Development Status and Prospect of Structural Dynamics Modeling Technology for Launch Vehicles[J]. China Aerospace, 2022, Issue 9: 26-30

[6] Wang Jianmin, Wu Yanhong, Zhang Zhong. Three-dimensional modeling technology for full arrow motion characteristics of launch vehicle [J]. Science China, 2014, 44 (1): 50-61

[7] Zhou Sida, Liu Li. Review of fluid-structure interaction analysis methods for launch vehicle tanks[J]. Intensity and Environment, 2010,37(3):52-63

[8] Zhu Changfan, Tang Guoan, Zhang Meiyan. Comparison Algorithm for Liquid-Structure Interaction Analysis of Rocket Considering Propellant Shake[J]. Journal of Dynamics and Control, 2014,12(3):239-242

[9] Liu Caizhi, Tang Guojin. Seismic response analysis and shock absorption design of a certain type of launch vehicle[J]. Journal of National University of Defense Technology,2014,36(4):27-32

[10] Pan Zhongwen, Xing Yufeng, Zhu Liwen. Liquid propellant simulation technology in launch vehicle dynamics modeling[J]. Science China,2010,40(8):920-928