Dynamic Response of the Rocket Body under Seismic Excitation

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Abstract. In order to study the influence of seismic excitation on the rocket body during the propellant injection and launch waiting state of a certain rocket, the dynamic response analysis of the rocket structure was carried out, and the seismic response spectrum analysis and time-history analysis were respectively used to solve the structural dynamic response. SolidWorks was used to establish a simplified three-dimensional model of the rocket body, and ANSYS Workbench was imported to solve the static stress, modal frequency and mode of the rocket. Time-history analysis of El-centro seismic wave data was carried out, and Fourier transform was applied to frequency domain spectrum for seismic response spectrum analysis. Cloud maps of structural equivalent stress, displacement and strain were obtained. After numerical verification, the results show that the rocket meets the safety requirements of seismic resistance, and more research methods are verified for the optimization of the rocket body.

Introduction

In the waiting state of liquid rocket for launch, environmental humidity, temperature, vibration and impact brought by the outside world and other factors affect its effectiveness to varying degrees, especially in the face of natural disasters such as earthquake [1], there are many difficulties in ensuring the safety of rocket before launch. The aseismic performance of the rocket structure directly affects the personal and property safety. Therefore, it is necessary to verify the overall safety of the rocket and analyze the seismic dynamic response of the rocket structure.

Under the action of earthquake excitation, J.M. Spritzer [2] studied several limit states such as hydrostatic ring stress, uplift, bottom stress and buckling of large surface storage tanks, as well as two stability mechanisms of shear and capsizing. Hamid Kazem [3] studied the finite element model of oil refinery storage tank, analyzed and calculated the dynamic characteristics and failure mode of the model under earthquake excitation. H.E. Estekanchi [4] proposed a Endurance Time method for evaluating the seismic performance of storage tanks. The finite element analysis results show that the method is reasonable in accuracy and has strong applicability in seismic response calculation of steel tanks. According to the research status, the simulation method of vibration response of the rocket body under seismic excitation is relatively simple and lacks comparative advantages, which cannot better reflect the vibration characteristics of the structure.

In this paper, the response spectrum analysis and time-history analysis respectively on the arrow to evaluate structural response under earthquake excitation, establish a finite element three-dimensional solid model, static stress analysis, structure vibration characteristic is obtained by using the modal analysis, determine the natural frequency and vibration mode of structure, through seismic response spectrum analysis from the Angle of the frequency domain calculation peak response of the structure of the arrow, using time-history analysis method from the Angle of time domain calculation of structural response, comparison of advantages and disadvantages for the methods of the differences and results.
Comparison of Seismic Response Analysis Methods

Response Spectrum Analysis Method

Response spectrum method is widely used in seismic response analysis. Since the response spectrum analysis is the basis of the modal overlapping addition, it will relate to each other and influence of multi-degree of freedom vibration are divided into the single degree of freedom vibration each other has nothing to do, and then to solve the multiple single degree of freedom vibration, the system is linear superposition principle requirement, so the response spectrum method is only applicable to linear systems. In response spectrum analysis, it is necessary to first solve the natural vibration characteristics of natural frequency, modal mode and other structures. The seismic response spectrum is designed reasonably, the damping of the structure is determined, the modal coefficients of each order and the structural response are calculated, and the peak response of the structure is finally solved by using the mode combination method [5].

Time-history Analysis

Time-history analysis, or transient dynamic response, is a technique to analyze the dynamic response process of structures under the action of loads varying with time. The input data is the load as a function of time, and the whole process of internal force and deformation state of the structure changing with time is solved by integral operation, and other output quantities such as displacement or stress and strain changing with time are output, so as to check and calculate the seismic bearing capacity and displacement and deformation of the structure. Time-history analysis in theory is the most accurate structural seismic response analysis method, but its complexity, the analysis and seismic random response structure in the performance of the seismic under the action of a specific, is not universal, so just take it as a general validation of response spectrum method rather than a direct design method using [6].

Finite Element Simulation

Description of Rocket Body

This type of rocket is two-stage propulsion. The arrow body is 32.9m high, 3.35m in diameter, and has a take-off mass of about 241t. The endian section is located at the end of the first-stage arrow body. In the process of model establishment, binding contact is used to simulate bolt connection and weld connection for each component, which has little impact on the results and can be ignored. After simplification, the arrow body was imported into ANSYS software, and the whole arrow was meshed, which was divided into 3800990 nodes and 1584358 units. The whole arrow model is shown in Fig. 1.

![Figure 1. A three-dimensional model of rocket body structure.](image)

Material Properties and Boundary Conditions

The main materials of the arrow body are high-strength aluminum alloy models 2014 and 2024, and the physical characteristics of the main components are listed in Table 1. The arrow is connected with
the ground support platform by four supports of the endian section, and is erected on the support platform as a fixed constraint of displacement.

Table 1. Material physical characteristics of main components of the rocket body.

<table>
<thead>
<tr>
<th>Body parts</th>
<th>Material name (aluminum alloy)</th>
<th>Modulus of elasticity [N/mm²]</th>
<th>Density [kg/m³]</th>
<th>Poisson's ratio</th>
<th>Yield strength [N/mm²]</th>
<th>Compression strength [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank tube section</td>
<td>2014-T4</td>
<td>72400</td>
<td>2800</td>
<td>0.33</td>
<td>290</td>
<td>425</td>
</tr>
<tr>
<td>Interstage section</td>
<td>2024-T4</td>
<td>72400</td>
<td>2780</td>
<td>0.33</td>
<td>325</td>
<td>470</td>
</tr>
<tr>
<td>Endian</td>
<td>2024-T4</td>
<td>72400</td>
<td>2780</td>
<td>0.33</td>
<td>325</td>
<td>470</td>
</tr>
<tr>
<td>Transition girth weld</td>
<td>2219-T31</td>
<td>72000</td>
<td>2840</td>
<td>0.33</td>
<td>250</td>
<td>360</td>
</tr>
</tbody>
</table>

Static Analysis and Modal Analysis

The static stress simulation was carried out by loading the whole arrow body in the negative direction of Y-axis. The maximum stress of the arrow body was 203.37MPa, which mainly acted on the fulcrum of the endian section and was less than the yield strength of the material to meet the strength requirements.

Modal analysis is a numerical technique for calculating structural vibration characteristics, which include natural frequency and mode, can avoid structural design resonance and predict the vibration form of the structure under different loads [7]. Modal analysis is the basis of other dynamic analysis. Based on the modal solution results, the characteristics of the first 10 modes' frequencies and modes are summarized, as shown in Table 2.

Table 2. The 10th order modal frequency and vibration mode characteristics of the rocket body.

<table>
<thead>
<tr>
<th>Number</th>
<th>Modal Frequency [Hz]</th>
<th>Modal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.56997</td>
<td>The upper part of the XY plane arrow body oscillates along the X axis</td>
</tr>
<tr>
<td>2</td>
<td>0.5701</td>
<td>The upper part of the arrow body in the YZ plane oscillates along the Z axis</td>
</tr>
<tr>
<td>3</td>
<td>2.6104</td>
<td>The center of the XY plane arrow is swinging at 45 degrees forward along the X axis</td>
</tr>
<tr>
<td>4</td>
<td>2.611</td>
<td>The middle part of the arrow body in the YZ plane oscillates at 45 degrees forward along the Z axis</td>
</tr>
<tr>
<td>5</td>
<td>5.7371</td>
<td>The arrow body twists around the Y axis and distends</td>
</tr>
<tr>
<td>6</td>
<td>6.5251</td>
<td>Y - direction vibration, deformation of the upper part of the arrow</td>
</tr>
<tr>
<td>7</td>
<td>6.5316</td>
<td>Y - direction vibration, deformation of the upper part of the arrow</td>
</tr>
<tr>
<td>8</td>
<td>6.6966</td>
<td>It vibrates in the Y direction, and the body compresses</td>
</tr>
<tr>
<td>9</td>
<td>7.7267</td>
<td>It vibrates in the Y direction, and the arrow expands</td>
</tr>
<tr>
<td>10</td>
<td>8.0174</td>
<td>In the YZ plane, the center of the arrow body swings in the s-shape in the negative direction of 45 along the Z axis</td>
</tr>
</tbody>
</table>

The structural frequency is concentrated in the range of 0.5 ~ 8.1Hz. Due to the existence of similar modal modes, the total deformation of the corresponding modes is only analyzed specifically for the 1st, 3rd, 5th, 8th, 9th and 10th modes, which are arranged from left to right and from top to bottom, as shown in Figure 2.

Response Spectrum Analysis

Response spectrum analysis is a frequency domain analysis technique, whose input is the frequency spectrum of vibration load. In the absence of local seismic spectrum, the seven-stage seismic El-centro wave commonly used in seismic analysis of structures was adopted as the input [8]. After baseline correction and Butterworth filtering, the band pass filtering frequency interval was set as [0.1Hz, 25Hz] to obtain the Fourier transform curve of seismic frequency, as shown in Figure 3. The data in the figure shows that when the frequency is 1.464Hz, the amplitude reaches a maximum of 2.971dB, indicating that seismic waves play the largest role in this frequency, and the main operating frequency is within the range of the first 10 order frequencies of the arrow body. After data fitting and solution, 0.1 damping value was set to obtain the acceleration Spectrum of El-centro wave, and the Spectrum
data was loaded into the Response Spectrum module. The superposition of vibration modes adopted the combination principle of Square Sum and Square Root of each vibration mode (SRSS) [9] to obtain the response of the arrow body under the excitation of this spectrum. The equivalent stress cloud diagram is shown in Figure 4.

Figure 2. Comparison of modes of the rocket body.

Figure 3. Fourier transform curve.

Figure 4. Equivalent stress of seismic spectrum response.

Under the action of the seismic excitation, the maximum equivalent stress of the arrow body is 238.89MPa, which is mainly concentrated at the fulcrum of the tail section, lower than the yield strength of 2024-T4 aluminum alloy 325MPa, meeting the requirements of seismic strength. The maximum positive strain of the rocket structure is 0.00149mm /mm, and the maximum shear strain is 0.00334mm /mm, which is less than the maximum strain value of low-frequency vibration of the rocket body required by Carrier Rocket Engineering [10]. It is within a reasonable range. Based on
comprehensive analysis, this type of rocket meets the seismic resistance requirements of the launch waiting state.

**Time-history Analysis**

Time-history analysis is time-dependent, so inertial force and damping force play an important role in the process of analysis. The equilibrium equation of the dynamic problem is shown in Eq. 1.

\[
[M]\{x''\} + [C]\{x'\} + [K]\{x\} = \{F(t)\}
\]

\[(1)\]

\([M]\) is the mass matrix, \([C]\) is the damping matrix, \([K]\) is the stiffness matrix, \(\{x\}\) is the displacement vector, \(\{F(t)\}\) is the force vector, \(\{x'\}\) is the velocity vector, \(\{x''\}\) is the acceleration vector. The force vector is earthquake acceleration matrix in this paper, El-Centro seismic N-S(north-south), E-W (east-west) and V (vertical) to the peak value of acceleration were 3.487, 2.141, 2.101 m/s\(^2\), overall coordinate system respectively, and the Workbench interface X (horizontal), Z (horizontal) and Y (vertical) that corresponds to, seismic time-history curve as shown in Figure 5.

![Figure 5. El-centro acceleration time-history curve in X, Z and Y directions.](image)

The stress of the Endian node is extracted and the stress distribution is studied, as shown in Figure 6. The Maximum stress is 244.65 MPa in the negative direction of \(Y\)-axis, which is basically consistent with the response spectrum analysis data and slightly larger.

![Figure 6. Endian joint stress.](image)

The seismic time-history response of the arrow body was analyzed by linear solution algorithm, and the displacement response at different nodes was calculated. Node 1 was at the Endian section, node 2 was at the interstage section, and node 3 was at the connection between the secondary combustion agent tank and the short shell, and the displacement time-history was analyzed, as shown in Figure 7.
It can be seen from the analysis results that the displacement range of node 3 is the largest, the X-axis direction reaches 16.19mm, which is the most affected by the earthquake, while the bottom displacement is small. As the height increases, the displacement range of the arrow body becomes larger, and the overall displacement meets the seismic requirements after numerical verification. In addition, since the bending moment and shear force suffered by the fulcrum at the end are not uniform, the peak value is used to check. The simulation results show that the seismic strength is also satisfied.

Conclusion

Through response spectrum analysis and time-history analysis, the stress distribution, displacement deformation, strain, bending moment and shear force are studied intuitively. The results show that the rocket body design is reasonable, the stress and strain distribution is uniform, and the maximum stress is 238.89MPa. The stress of the time-history analysis node reaches 244.65MPa, which is located at the endian section. The absolute displacement of the structure is small, and meets the design requirements. Under the excitation of seven-stage seismic waves, the rocket meets the seismic requirements. In the time-history analysis, the maximum stress and maximum displacement are larger, because the response spectrum analysis is the fitting value, while the seismic wave selected in the time-history analysis has the particularity and instantaneity. The response spectrum analysis is more efficient in the body pre-design, and the time-history analysis is more accurate and effective in the later stage engineering verification of rocket resistance.

References


