Dynamic Response and Vibration Isolation Analysis of Very Large Floating Building under Wave Action

Jian Zhang, Xiang Wang, Pingping Yuan and Hanghang Wang

College of Civil Engineering and Architecture, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu Province, 212000, China

*Corresponding author’s e-mail: justwangxiang@163.com

Abstract. Taking the buildings above the very large floating structures as research object, the finite element software ANSYS/AQWA was used to carry out hydrodynamic analysis of the single module very large floating structure, and the motion response parameters were obtained. A common multi-layer steel frame structure model and a multi-layer steel frame structure model with three-dimensional vibration isolation bearings were established by using SAP2000, and dynamic time history analysis was carried out for these two steel frame building models. Studies have shown that the motion response of the very large floating structures under the action of waves can not be ignored for the upper building. After the vibration isolation bearing is added to the floating buildings, the natural vibration period of the upper steel frame structure is significantly extended, the inter-layer shear force is slightly reduced, and the inter-layer shear force, inter-layer displacement and floor acceleration are increased. Compared with the installation of vibration isolation bearings for land buildings, the vibration isolation of offshore floating buildings is not effective.

1. Introduction

The very large floating structures (VLFS) is a new type of offshore structure that can be used as a rocket launching platform, a sea transit base, and even developed for use in offshore cities. In recent years, a lot of research have been done on the hydroelastic and multi-float connectors of very large floating structures, but the research on the upper buildings of very large floating structures has just begun. Based on the three-dimensional hydroelastic theory, Wang and Riggs [1] calculated the motion response and hydrodynamic load of super-large floating single-module and multi-module, and studied the influence of connector stiffness on multi-module the very large floating structures response. Li et al. [2] studied several offshore structures that were connected by single connectors through connectors, and determined the location of the structure where damage occurred at the earliest stage under dangerous conditions. Zhang and Qi [3] calculated the hydrodynamic coefficients and wave loads of each floating body under 8 wave directions and 46 regular frequencies based on VLFS models of different modules. Y. Totsuka and Ishigaki [4] establish the elastic model of the flight control tower and the floating structures, and analyses the vibration of the building control tower by inputting different wave loads. Three-dimensional vibration isolation steel frame structure is a structure with three-dimensional vibration isolation bearings between the upper structure and the foundation, which can prolong the period of the structure, and absorb vibration energy by using the isolation berings. At present, the main vibration isolation structures are multi-storey masonry structure and reinforced concrete structure, while the application of steel structure is relatively less. Li and Wang [5] studied that the vertical vibration acceleration of floor slab was significantly reduced when the structure with three-dimensional and multi-functional vibration isolation
bearings was subjected to subway vibration load, and the horizontal vibration isolation of short and long span directions had better effect. Wang and Zhou [6] studied the frame structure with three-dimensional vibration isolation bearings under subway vibration. The results show that the acceleration isolation rate reaches 50%-70%.

2. Hydrodynamic analysis based on ANSYS/AQWA

2.1. Hydrodynamic
Hydrodynamic calculation and analysis module in software AQWA is based on the three-dimensional potential flow theory and meshes the floating structure model on wet surfaces. According to the three-dimensional potential flow theory, the velocity potential satisfies the Laplace equation [7] in the basin.

\[ \nabla^2 \phi = 0 \] (1)

The velocity potential can be linearly decomposed into a diffraction potential and a radiation potential:

\[ \phi = \phi_R + \phi_D \] (2)

\[ \phi_D = \phi_0 + \phi_7 \] (3)

\[ \phi_R = iw \sum_{j=1,6} \xi_j \phi_j \] (4)

In the formula (2) to (4), \( w \) represents the wave circle frequency, \( \xi_j \) represents the amplitude of six degrees of freedom, \( \phi_j \) represents the unit radiation potential, \( \phi_0 \) represents the incident wave velocity potential, and \( \phi_7 \) represents the object's disturbance to the incident wave.

2.2. Geometric parameters of the wet surface model of the VLFS
The single-module very large floating structure consists of an upper body, two lower floating bodies, and four round columns on each side of the middle. The length, width and height of upper body are 300m, 125m, and 17.5m respectively. The dimensions of the two lower floating bodies are 270m length, 35m in width, and 12.5m height. The middle round column is 27.5m in height and 25m in diameter. The designed draft of the floating body is 28.75m, the designed displacement is 2.975×10^8 kg. The finite element software ANSYS/AQWA was used to establish a wet surface unit model for a single module VLFS, as shown in figure 1. The model is simulated by quadrilateral shell elements (Shell 181), and the finite element model consists of 39,061 quadrilateral elements and 38995 nodes.

2.3. Environmental parameters
According to the environmental data of the south China sea, the water depth of the VLFS is set as 1212m. According to local sea conditions, JONSWAP spectrum was selected to describe sea conditions. The wave period was 12.4s and the effective wave height was 5m. The influence of sea current on the semi-submersible and large-size structure of the super-large floating body is relatively stable, and the analysis does not consider the load of sea current for the moment.
2.4. Hydrodynamic analysis
In this paper, the finite element software ANSYS/AQWA is used to establish a single module VLFS model. Considering the extreme conditions, the floating structure model is analyzed in time domain under the condition of 12.4s period and 5m effective wave height, and the acceleration time history curve of the floating body is obtained, as shown in Figure 2. It can be seen that the acceleration amplitudes of the surge and heave of the floating body are relatively large, and the acceleration amplitudes of the sway are almost negligible. Compared with the time history of seismic acceleration, it can be found that the acceleration period produced by floating body motion is longer, and the acceleration variation is obvious periodically.

3. Vibration isolation analysis of very large floating structure upper building

3.1. Vibration isolation theory
The movement of the super large floating body will generate vibration of the upper building, and the equation of motion [8] of the multi-layer steel frame structure is

\[
[M]{\ddot{U}} + [C]{\dot{U}} + [K]{U} = -[M]{\ddot{U}_g}
\]

in the formula, \(\ddot{U}_g\) represents the acceleration of the deck, \(\{U(t)\}, \{\dot{U}(t)\}\) and \(\{U(t)\}\) represents displacement, velocity and acceleration vectors. \([M]\) and \([K]\) represent the mass matrix and the stiffness matrix, \([C]\) represents the damping matrix.

3.2. Model of steel frame structure
In this paper, a ten-storey steel frame structure is taken as an example, and the finite element software SAP2000 is used to analyze the time history of ordinary steel frame structure and vibration isolation steel frame structure model respectively. The upper structure of the two models is the same, with room opening and depth of 3m and floor height of 3m. Columns are box-shaped with a size of 360 x 360 x 12 x 12, and beams are H-shaped with a cross-section size of 600 x 200 x 10 x 14. The material of columns and beams is Q345 steel, and shell elements are used to simulate floor slabs. The three-dimensional vibration isolation bearings in this paper are composed of common laminated spring and lead core laminated rubber, as shown in Figure 3. In the SAP2000, a rubber isolator connection unit is used to simulate the three-dimensional vibration isolation support by changing the vertical stiffness of the unit. The lead laminated rubber adopts LRB400 bearing, with effective diameter of 400mm, thickness of 73mm, horizontal stiffness before yielding of 8790 kN/mm, equivalent stiffness after 100% shear deformation of 1040 kN/mm, yielding force is 27 N, and horizontal directional damping ratio of 0.2. In addition, the vertical stiffness of the rubber vibration isolating unit is set to 286 kN/mm, and the vertical damping ratio is 0.12.
4. Dynamic analysis of steel frame structure

4.1. Modal analysis

The first nine modes of the two structural models are selected for modal analysis. The natural vibration frequencies of the vibration modes of the vibration isolation and non-isolation structure are shown in Table 1. It can be seen from the results of Table 1 that the natural vibration frequencies of the non-isolated structure is 1.191 to 2.529 times of the natural vibration frequencies of the vibration isolated structure.

Table 1. Natural Vibration Frequencies of non-isolation and isolation structures.

| Modulus order | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Non-isolated  | 0.552 | 0.568 | 0.655 | 1.663 | 1.703 | 1.962 | 2.885 | 2.900 | 3.271 |
| Vibration isolation | 0.218 | 0.221 | 0.257 | 1.024 | 1.134 | 1.397 | 2.413 | 2.432 | 2.747 |

Figure 4. X-direction acceleration time history curve of the first floor.

Figure 5. X-direction acceleration time history curve of the tenth floor.
4.2. Floor accelerations

Figure 4 to figure 7 are acceleration time history curves of vibration isolation structure and non-vibration isolation structure under the excitation of floating structure. Generally speaking, the amplitude of acceleration in the vertical direction (Z direction) decreases and the period increases. However, the magnitude of acceleration in the long axis direction (X direction) increases.

4.3. Interlayer displacement

As can be seen from figure 8 and figure 9, displacement will occur at the bottom of the isolation structure because 1.6m isolation floor is set below the bottom floor. But in general, the displacement of each layer will increase, the displacement in the X-axis direction will generally increase by about 35 mm, and the Z-axis direction will increase slightly.

Table 2. Interlaminar shear force comparison between non-vibration and vibration isolation structures.

| Floor Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Non-vibration isolation F1/kN | 194.9 | 179.0 | 160.9 | 140.8 | 121.4 | 102.3 | 82.8 | 62.4 | 41.2 | 20.4 |
| Vibration isolation F2/kN | 190.4 | 159.1 | 147.2 | 129.2 | 111.3 | 93.1  | 74.8 | 56.3 | 37.7 | 18.9 |
| F1/F2        | 0.98 | 0.89 | 0.91 | 0.92 | 0.92 | 0.91  | 0.90 | 0.90 | 0.91 | 0.93 |

4.4. Interlaminar shear

It can be seen from table 2 that the interlaminar shear force of the vibration isolation structure is reduced, but the interlayer shear ratio of the intermediate floor is stabilized at 90%. Setting the vibration isolation only reduces the interlaminar shear force to a small extent, but it is quite different from the shear ratio of 20% to 30% of the normal ground vibration isolation building.
5. Conclusion
The hydrodynamic analysis of the super large floating body and the vibration isolation analysis of the multi-storey steel frame show that:

• Under the wave excitation of typical South China Sea conditions, the motion responses of super-large floating structures are mainly surge and heave. The acceleration amplitudes in these two directions are larger, but the periodicity of acceleration is stronger.
• The dynamic time history analysis of the steel frame structure after vibration isolation has significantly increased the structural vibration period. The vertical acceleration and inter-layer shear force are slightly reduced, but the acceleration and displacement in the long-axis direction increase greatly.
• Vibration isolation can extend the natural vibration period of the steel frame structure and reduce the frequency. The acceleration frequency generated by the movement of the super large floating body structure is much smaller than the natural vibration frequency of the structure, the frequency after the structural vibration isolation is reduced, which will aggravate the structural response.

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