An Assessment Method of Structure Strength Analysis on Full-Scale LNG Independent Type C Tank

Ge Liu¹, Zheng Xie¹, Qianglin An¹ and Fei Pei²

¹ System Engineering Research Institute, Beijing 100094, China
² School of Naval Architecture, Dalian University of Technology, Dalian 116024, China
E-mail: brant1987799@sina.com

Abstract. The sloshing induced by partial loaded in LNG (Liquified Natural Gas) independent type C tank will threat the structure of tank. The strength check of the tank plays an important role in the design of LNG tank, which can also improve the safety of the cargo containment system. Hence, an assessment method of the structure of LNG independent type C tank is presented, in which the method of one-way fluid-structure interaction is used. Sloshing load is considered with a numerical technique based on CFD theory, which can reduce large computational expense and remain a good accuracy. The dangerous conditions of sloshing pressure are determined by frequency domain analysis of the tank and ship. By computation of sloshing condition of 1000 m³ fuel bunker vessel, the feasibility of this method is explained and suggestions on structure design of tank is given.

1. Introduction
Sloshing problem always threaten the LNG tank. As the consumption of LNG in transportation, storage and bunkering, partial loaded appears. When the resonance occurs, the liquid will impact the bulkhead of tank, produce the huge external moment. Therefore, the simulation of sloshing, prediction of sloshing load and method of sloshing suppression has become the key of LNG tank design.

For computing sloshing load of independent type C tank, the “elliptic acceleration method” is employed in engineering [1] or structure analysis of tank [2-3]. However, in this method the sloshing load is replaced by the acceleration, which belongs to conservative evaluation.

The potential theory is also used to predict sloshing load [4-5], which could achieve rapidly result and have a good accuracy in some cases, nevertheless the numerical simulation may give a better result, when the excitation amplitude is large and sloshing becomes highly non-linear [7]. Usually, the solution of sloshing with numerical method is determined iteratively, which have a high time cost. The speed of assessing sloshing load is also important [6].

In this study, based on the numerical technique of sloshing and one-way FSI (Fluid-Structure interaction) method, an assessment method of the structure of LNG independent type C tank is presented. The method of dangerous sloshing conditions determination is also given. By computation of sloshing condition of 1000 m³ fuel bunker vessel, the feasibility of this method is explained and suggestions on structure design of tank is given.

2. Numerical Method and Mathematical Model
The process of assessment method of type C tank structure is divided into 3 steps:

- Determining the dangerous sloshing condition;
• Computing the sloshing load;
• Structure analysis with sloshing load.

2.1. Dangerous Sloshing Condition
The resonance will induce the violent sloshing. However, the violent sloshing can also occur under the excitation frequency close to the natural frequency, and the ending frequency of sloshing will decrease as filling level increasing \[8-9\]. Likewise, some of wave frequencies can induce large motion of the ship. This kind of frequency can be obtained through calculating the Response Amplitude Operator (RAO).

Therefore, refer to related criterion \[10-12\], the excitation frequency of dangerous sloshing condition is determined by table 1, which means the determined frequencies cannot only induce the violent sloshing, but also large amplitude of ship motion.

| Table 1. The frequency domain of dangerous sloshing condition. |
|---------------------------------------------------------------|
| Frequency determination method          | Specification                                      |
| \(|f_n - f_e|<0.2 f_n \) | \(f_n \) and \(f_e \) are natural frequency of media and wave encounter frequency, respectively. |
| RAO(\(\beta, \omega \)) > 0.7 max[RAO(\(\beta, \omega \))] | \(\beta \) is the wave angle; \(\omega \) is the wave frequency. |
| 0 \(\leq \beta \leq 30 \) | Considering longitudinal motion of ship |

The natural frequency of LNG in the tank is determined by modal analysis based on the finite element method. The governing equation is

\[
M\ddot{u} + C\dot{u} + Ku = -Md_ka_k(t)
\]  

(1)

where \(M\) is the mass matrix; \(C\) is the damping matrix; \(K\) is the stiffness matrix; \(d_k\) is direction vector; \(a_k\) is the external acceleration. \(u\) is the displacement of the whole tank relative to the ground. Assuming that the whole tank is affected continuously by gravity in analysis of natural frequency.

Essentially, frequency analysis is the calculation of eigen values. The natural frequency and mode of vibration is calculated by the following equation.

\[
K\phi_i = \omega_i^2 M\phi_i
\]  

(2)

where, \(\phi_i\) is the form of \(i\)th mode, \(\omega_i\) is the angular velocity of \(i\)th mode. The eigen vector and mass matrix are orthogonal, which the following equation is satisfied.

\[
\phi_i^T M\phi_i = 1
\]  

(3)

The liquid in LNG tank is simulated by potential flow. Thus, the velocity potential \(\phi\) is satisfied with the Laplace’s equation.

\[
\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0
\]  

(4)

The analysis of frequency is the essential for general eigen value calculating. The eigen value of governing equation is obtained by the following equation.

\[
\begin{bmatrix}
-M & 0 & C_{fe} \\
0 & M_{fe} & 0 \\
-K_{fe} & 0 & K_{fe}
\end{bmatrix}
\begin{bmatrix}
U^{(i)} \\
F^{(i)}
\end{bmatrix}
= 0
\]  

(5)

where
The response frequency domain of ship is computed by hydrodynamic analysis. Firstly, the wave force is calculated by potential theory, the velocity potential \( \phi \) in flow field is also satisfied with the equation (2). The ship is considered as a rigid body, which has six degrees of freedom. Its motion response can be described as the following equation.

\[
M \ddot{X} = F
\]

(7)

where \( M \) is the mass matrix; \( \ddot{X} \) is the acceleration vector; \( F \) is the load vector, which includes waterplane restoring force, wave excitation etc. The wave force, restoring force and damping force are introduced to obtain the ship's response in frequency domain under linear wave excitation, the following equation can be achieved.

\[
\left[ M + M_a(\omega) \right] \ddot{X} + B(\omega) \dot{X} + KX = F_{\text{wave}}^{(1)}(\omega)
\]

(8)

where \( M_a \) is the additional mass matrix, \( B \) is the radiation damping matrix, \( K \) is the stiffness matrix for hydrostatic recovery. Using the linear method, the ship’s response function in frequency domain can be obtained as following equation.

\[
X^{(1)}(\omega) = H(\omega)F_{\text{wave}}^{(1)}(\omega)
\]

(9)

where \( X^{(1)} \) is the first order frequency response, \( H(\omega) \) is the transfer function for response, which can be described in following equation.

\[
H(\omega) = \frac{1}{-\omega^2(M + M_a) - i\omega B + K}
\]

(10)

Finally, the RAO is obtained in following equation.

\[
\text{RAO} = H(\omega)L(\omega)
\]

(11)

where the \( L(\omega) \) is the linear transfer function for wave load.

2.2. Computing the Sloshing Load

Due to the shape of LNG independent type C tank, it is sensitive to longitudinal excitation. Besides, in ship navigation, pitching motion appears at the highest frequency [13]. Hence, the model for sloshing simulation can be described in figure 1.

A CFD theory based numerical technique is used to compute the sloshing load. The VOF (Volume of Fluid) method is used for the free surface of the LNG. The RNG (Renormalized group) \( k-\varepsilon \) turbulence model is employed to handle more complex flow. The numerical method for computing is a non-iterative time advancement scheme. As the convergence of single equation is checked individually with inner iteration, it only needs an outer iteration per time step (see figure 2).

2.3. Structure Analysis

The Finite Element Method (FEM) is employed to analyse the structure of the tank. Based on the one-way Fluid Structure interaction, the sloshing load is transferred into the model for structure analysis. The data, which is achieved in fluid simulation, for example, the sloshing pressure, will be mapped from source node to the target location. However, there must be some target locations which cannot be matched to source node. The interpolation method will be used for them, which is based on the generated weights to project source data onto target locations. The mapping weights are applied in the following equation to evaluate \( \phi \), which is the target node, or iteration point face value.

\[
\phi = \sum_{i=1}^{n} w_i \phi_i
\]

(12)

where \( \phi \) is the value at the \( i \)th source node, and \( w_i \) is the associated weight.
3. Computational Case for Verification

3.1. Case Description
A 1000 m³ LNG fuel bunker vessel is selected to verify the feasibility of the structure assessment method of LNG tank. The principal dimension of the fuel bunker vessel and the dimension of full-scale tank are listed in tables 2-3, respectively.

3.2. Dangerous Sloshing Condition

3.2.1. Natural Frequency Analysis. The full-scale tank is used to frequency analysis. The bulkhead of tank is meshed with triangular face mesh with four nodes, while the liquid in tank is meshed into tetrahedral body mesh with four nodes (shown as figure 3). The material properties of LNG are assigned to liquid in tank. The potential is selected to simulate the LNG. Determinate search is used to compute eigen values.

| Length of tank \((L_T)/m\) | Diameter of inner tank \((D_i)/m\) | Shape of head | Thickness of bulkhead \((t_b)/mm\) |
|----------------------------|----------------------------------|--------------|-------------------------------|
| 35.2                       | 6.4                              | Spherical    | 12.5                          |

| Length overall/m | Length between perpendiculars/m | Moulded breadth/m | Moulded depth/m | Design draft/m | Design speed/kn |
|------------------|---------------------------------|-------------------|-----------------|---------------|-----------------|
| 62.8             | 59.5                            | 12.8              | 6.5             | 4.5           | 12              |
Refer to related criterion and research, the liquid which is half loaded in tank is the most dangerous filling condition, especially in the range of 60%-80% diameter of tank. In this article, the filling range from $0.6D_i$ to $0.8D_i$ is selected as the dangerous filling condition. And the computational step of natural frequency analysis is $0.5D_i$. The natural frequencies of each filling condition are listed in Table 4. Thus, the excitation frequencies induced violent sloshing are determined.

### Table 4. The range of dangerous excitation frequency induced sloshing.

| Filling condition | Natural frequency ($f_n$/Hz) | Excitation frequencies induced sloshing |
|-------------------|-----------------------------|----------------------------------------|
| $0.60D_i$         | 0.082                       | 0.066 0.098                            |
| $0.65D_i$         | 0.087                       | 0.070 0.104                            |
| $0.70D_i$         | 0.093                       | 0.074 0.112                            |
| $0.75D_i$         | 0.099                       | 0.079 0.119                            |
| $0.80D_i$         | 0.107                       | 0.086 0.129                            |

3.2.2. Analysis of Ship Frequency Domain Response. According to the table 1, the head sea at the range of 0-30 is selected as the wave direction. The analysis of pitching motion frequency response is computed in figure 4.

3.3. Sloshing Simulation

The half model for sloshing simulation is built with the dimension of full-scale tank (listed in table 2) and meshed by structured grid (shown as figure 5). The quantity of the grid is 163 thousand. The unsteady term is discretized using first order Euler implicit scheme. Second order upwind scheme for momentum, turbulent kinetic energy and turbulent dissipation rate are selected to reduce numerical diffusion. The commercial software FLUENT is employed to obtained the sloshing pressure.

![Figure 3. Numerical model for analysis of natural frequency.](image)

**Figure 3.** Numerical model for analysis of natural frequency.

**Table 4.** The range of dangerous excitation frequency induced sloshing.

![Figure 4. The analysis of pitching motion frequency response.](image)

**Figure 4.** The analysis of pitching motion frequency response.

![Figure 5. The grid of full-scale tank for sloshing pressure computation.](image)

**Figure 5.** The grid of full-scale tank for sloshing pressure computation.
Table 5. The dangerous sloshing conditions.

| Number of conditions | Filling condition | Excitation frequency ($f_n$/Hz) | Excitation amplitude/deg. |
|----------------------|-------------------|----------------------------------|---------------------------|
| 1                    | $0.60D_i$         | 0.087                            | 2.92                      |
| 2                    | $0.65D_i$         | 0.087                            | 2.92                      |
| 3                    | $0.70D_i$         | 0.087                            | 2.92                      |
| 4                    | $0.75D_i$         | 0.087                            | 2.92                      |
| 5                    | $0.80D_i$         | 0.087                            | 2.92                      |
| 6                    | $0.80D_i$         | 0.124                            | 4.17                      |

Table 6. The maximum load of the whole tank on each condition.

| Number of conditions | Maximum force on the bulkhead/kN | Number of conditions | Maximum force on the bulkhead/kN |
|----------------------|----------------------------------|----------------------|----------------------------------|
| No.1                 | $4.97 \times 10^4$               | No.4                 | $4.90 \times 10^4$               |
| No.2                 | $47.5 \times 10^4$               | No.5                 | $4.71 \times 10^4$               |
| No.3                 | $4.71 \times 10^4$               | No.6                 | $4.92 \times 10^4$               |

Based on the significant wave height in the sea condition, in which the ship sails, the excitation amplitudes are calculated. Finally, the dangerous conditions for sloshing computation is listed in table 5.

The maximum forces on the whole bulkhead of tank are extracted from the simulation result, which are listed in table 6. It can be seen that the No.1 condition will have great effect on the structure of tank. In this condition, the shape of free-surface and velocity of free-surface fluid is shown in figure 6. Correspondingly, the position of tank is plotted in figure 7.

3.4. Structure Analysis of the Tank
The model for structure analysis is built in accordance with the real tank, which includes 6 vacuums stiffeners and two support stiffeners. The saddle support which hold the tank are attached with support stiffener with its top surface. However, the structure of tank bulkhead is mainly concerned in this article. So, the saddle support is simplified with three portions according with the size of the tank grid and welded with the support stiffeners (shown as figure 8). The model is meshed with structured grid (shown as figure 9). The size of grid is in accordance with the grid for sloshing simulation. For corresponding to the model for sloshing simulation, the model for structure analysis is rotated, so that two model’s position are the same.

Figure 6. Velocity and shape of free-surface.

Figure 7. Position of the tank motion.
Except for sloshing load, the ground acceleration, rotational velocity of the tank and internal steam pressure of LNG are also loaded on the model. For relieving tank deformation caused by low temperature of LNG, the saddle support is designed to be slidable. Therefore, the left saddle support in figure 8 is set to have the X-direction displacement freedom, while the right saddle support is fixed. The commercial software ANSYS Mechanical is employed to analyze the structure of the tank. The stress and deformation are obtained, which is listed in table 7, and the contours of them are shown in figures 10-11.

| Component of tank | Max equivalent stress/MPa | Max deformation/mm |
|-------------------|---------------------------|--------------------|
| Bulkhead          | 170                       | 5.5                |
| Support stiffener | 114                       | 3.7                |

It can be seen in the contours of deformation and stress. The maximum stress of bulkhead is located in the bottom and near the sliding saddle support. Combined with the contour of fluid flow (shown as figure 6), the fluid is impacting on one side of tank top, which will apply downward force at the head of tank. The support stiffener connected to the sliding saddle support, is also affected by the fluid impacting. Due to the hold of saddle support, the joint of saddle and stiffener will be extruded, where the maximum stress of stiffener is located.
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Figure 11. Contour of deformation.

4. Conclusion

(1) With combination analysis of natural frequency, hydrodynamic of ship, sloshing load and structure of tank, an assessment method of structure under the sloshing effect is presented.

(2) Consider with criterion and research, the dangerous sloshing condition is achieved, which can reduce the quantity of sloshing simulation. Besides, with the employment of the numerical technique of sloshing, the cost of sloshing simulation is further reduced. Thus, the assessment method can be used for rapidly evaluating the structure strength of LNG independent type C tank.

(3) It can be achieved that the half loaded is also the dangerous filling condition in the full-scale tank. The impact of fluid will produce a downward force to the head of tank. Hence, the position of saddle support should be set properly, to prevent from the large distance between saddle support and head of tank.

(4) It can be concluded that concentrated stress can be produced on support stiffeners, which is caused by saddle support extruding. The reason is that, the support stiffener limits the deformation of the whole tank, and join to the saddle support at the same time. Thus, the dimension of support stiffener is the key point in design of LNG independent type C tank.

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