Numerical simulation of solitary wave interacting with gasbag-type floating bridge using the ALE method

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Abstract. The dynamic numerical modeling theory and wave impact calculation method of gasbag type floating bridge (GTFB) were studied by using the multi-material Arbitrary Lagrangian-Eulerian (ALE) method and penalty function method. The air and seawater were described by the ALE method, the structure of floating bridge was described by the Lagrangian method and the coupling force between floating bridge and flow field was calculated by penalty function method. The floating bridge-fluid coupling models were established by HyperMesh software. Then, the models and calculation parameters were validated. The structural responses of the GTFB under solitary wave impacting were analyzed. The results show that the maximum contact force of hinge and maximum stress of gasbag appeared at the ends of the floating bridge, and the maximum bending moment of hinge appeared in the middle section.

1. Introduction
Floating bridges are important transport structures for military and civil fields. In the last more than 10 years, the gasbag-type floating bridge (GTFB) is a novel kind of international emerged floating bridge structure, which could be widely used in the national defense and disaster relief. They are vulnerable to moving load and violent waves. Thus, the fluid-structure interaction dynamics analysis of the GTFB should be discussed.

The responses of different floating bridges have been proposed by Pratt et al.[1] based on physical model tests. The model is able to calculate displacement for different materials. Giannin et al.[2] experimentally studied on dynamic characteristics of floating bridge under vehicle load. Rahman et al.[3] established the model of floating bridge by using finite element method, and analyzed the dynamic response of floating bridge under regular wave impact. In recent years, the Arbitrary Lagrangian Eulerian (ALE) method has been widely used in fluid-elastic structure coupling problems. It can be used to calculate the dynamic response of structures under fluid impact [4]. Based on ALE method, the mode shapes, natural frequencies and the moving load response of floating bridge were studied by Wang et al. [5]. Lou et al. [6] carried out the wave-breakwater coupling model, and the interaction of wave and elastic structure was investigated. In addition, the interaction between wave and objects drifted was analyzed by Lou et al. [7]. Compared with structural dynamics analysis, there are a lot of
non-linear computations for fluid-solid coupling analysis. Especially for large-scale engineering structure design, the amount of calculation will exceed the computing power of personal computers. So supercomputers are used for calculation.

In this paper, the numerical modeling theory of air-sea water-floating bridge dynamic coupling and the dynamic calculation method of wave impact floating bridge are studied. Firstly, the three-dimensional numerical model of air-sea-floating bridge is established. Secondly, the model is validated by experiment and theoretical solution. Finally, the dynamic response of floating bridge under wave impact is analyzed on supercomputer in Shanghai Supercomputer Center.

2. Numerical Method and Model

2.1 ALE kinematics

Based on the multi-material ALE modeling method and the penalty function coupling method, the numerical simulation of floating bridge under wave impact is carried out.

The ALE method includes single-material ALE and multi-material ALE. The ALE approach differs from the pure Lagrangian or Eulerian approach in that it introduces a referential configuration where reference coordinate is introduced to identify the mesh. In the ALE approach, mesh can move arbitrarily, and it does not necessarily follow the material. Therefore, it is easier to trace the free surfaces and moving boundaries accurately while conserving the regularity of the computational mesh.

The momentum equation and mass equation in ALE approach are iterated in the following equations:

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \mathbf{f} + \rho \mathbf{c} \frac{\partial \mathbf{v}}{\partial t} \tag{1}
\]

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{2}
\]

where \( b_i \) represents the body force. \( \mathbf{v} = v_i(x, t) \) are the material velocity field in space coordinate system \( x \), \( X \) denotes the ALE coordinate system; \( \rho \) is the density. \( \mathbf{c} \) is the ALE convective velocity.

The state equation and material model are used in the definition of fluid model. In this paper, the polynomial equation and the Gruneisen equation are used as state equations of air and sea water, respectively. The empty materials are used for both air and sea water.

2.2 Fluid structure interaction

In order to analyze the dynamic response of floating bridge structure under wave impact. The linear elastic material is used for gasbag of floating bridge.

The constitutive equation of gasbag elastic body is iterated in the following equation:

\[
\rho_i \frac{\partial^2 u}{\partial t^2} = -\frac{\partial \sigma}{\partial x_i} + f_i \tag{3}
\]

where \( X \) denotes the Lagrangian coordinate, \( \rho_i \) is the density of the structure, \( f_i \) is the body force, \( u \) is the displacement of the structure.

The penalty function method which can ensure the energy conservation in the coupling process calculates the penetration by calculating the penetration velocity and time. The coupling force is calculated by the penetration \[8\].

Figure 1 illustrates the penalty function method for fluid-structure interaction. There are different number of coupling points in fluid and structure respectively. When there is relative displacement between fluid and structure, a spring damping system is established between fluid and structure by coupling points. The coupling force is calculated by relative displacement of coupling point and coupling stiffness, and high frequency vibration is eliminated by coupling damping coefficient, as shown in equation (4).
Figure 1. The penalty function method.

Usually, the number of coupling points can be used to change the coupling effect. For example, when the coupling effect is weak and the fluid leakage occurs, the number of coupling points should be increased. In addition, the coupling volume can also change the coupling effect. In the setting of master-slave relationship of fluid-structure coupling, the fluid is often regarded as the master and the structure is regarded as the slave.

\[
F = \frac{d^2Z}{dt^2} + \xi \frac{dZ}{dt} + \omega^2 Z
\]

(4)

where \(F\) is the couple force, \(\xi\) is the damp coefficient, \(\omega = \sqrt{k(m_s + m_f)/(m_s - m_f)}\), \(k\) is the contact rigidity, \(Z\) represents the penetration, which is iterated in the following equation

\[
Z_{n+1} = Z_n + (V^c_{n+1/2} - V^r_{n+1/2}) \cdot \Delta t_{n+1/2}
\]

(5)

where \(V^c_{n+1/2}\) and \(V^r_{n+1/2}\) are the velocities of the coupling points in the ALE and Lagrangian body, respectively.

2.3 Numerical simulation model

The floating bridge module is composed of plate, connecting band, hinge and gasbag. Their detailed geometric dimensions are shown in Figure 2(a) and Figure 2(b).

The whole model of floating bridge consists of 20 floating bridge modules. The floating bridge
modules are joined together by hinges, and the gap between the floating bridge modules is 2 mm. Finally, the length of the whole floating bridge is about 60m, and the total weight is 58 ton. In order to analyze the fluid-structure interaction, the fluid domain is added to the model of floating bridge, as shown in Figure 3. After initialization, the whole model consists of five parts: the internal air, the external air, the floating bridge, the water and the wave maker. The material parameters of the whole model are listed in Table 1.

| Part           | Density \(\text{kg/m}^3\) | Elastic Modulus \(\text{Pa}\) | Poisson Ratio |
|----------------|-----------------------------|-----------------------------|--------------|
| Gasbag         | \(1.15\times10^3\)         | \(2.00\times10^8\)         | 0.34         |
| Connecting band| \(1.15\times10^3\)         | \(2.00\times10^8\)         | 0.34         |
| Plate          | \(2.65\times10^3\)         | \(7.10\times10^{10}\)      | 0.30         |

| Initial destiny | Coefficient of kinematic viscosity | Sound speed in water |
|-----------------|-----------------------------------|----------------------|
| Water           | \(1.00\times10^3\) \(\text{kg/m}^3\) | \(8.68\times10^{-4}\) \(\text{Pa}\cdot\text{S}\) | \(1.48\times10^3\) \(\text{m/s}\) |

3. Results and discussion

3.1 Experimental and simulation results comparison

In the static loading test of pontoon bridge [1], the experimental floating bridge consists of 12 modules. Compared with the actual model, the experimental model has a scale of 1:3. The parameters of static load test are listed in Table 2.

| Parameter                              | Full scale | 1/3 scale | Test model |
|----------------------------------------|------------|-----------|------------|
| Plate, \(L\times W\times H\) (m)       | 3.05×6.10×0.45 | 1.017×2.033×0.15 | 1.017×2.033×0.15 |
| Gasbag, Diameter (m)                   | 1.525      | 0.508     | 0.508      |
| Weight (Kg)                            | 2721.6     | 100.8     | 100.8      |

According to the static loading test model, the numerical test model is established by 12 modules, and the geometric size is reduced by 1:3 scale, as shown in Figure 4(a). The location and value of the load in the numerical model are also consistent with the test. As can be seen in Figure 4(a), the fluid-structure coupling effect between floating bridge and fluid field is good. Under the action of gravity and external load and coupling force, the bridge floats at the surface of the water.

Figure 4(b) shows the vertical displacement of the different modules. Under static load, the vertical displacement reaches the maximum value of -0.23m in the middle of the floating bridge. On the contrary, there is slight floating range at both ends of the floating bridge. By comparing different methods, it can be seen that the ALE method adopted in this paper is closest to the experimental value.
3.2 Wave impacting Analysis

Base on the whole model of floating bridge, the dynamic response of floating bridge are studied.

3.2.1 Transverse wave impacting The direction of transverse wave is perpendicular to the axis of floating bridge. Figure 6 shows the joint force, moment and stress of gasbag versus time under transverse wave impacting (wave height=2m). It can be seen that the maximum contact force of hinge and maximum stress of gasbag appeared at the ends of the floating bridge, and the maximum bending moment of hinge appeared in the middle section. The maximum stress value of gasbag is 7.26MPa. Figure 7 gives representative views of the displacement and stress of floating bridge. Due to the restraint of cable, the stress of gasbag is concentrated in the ends of bridge.
3.2.2 Longitudinal wave impacting The direction of longitudinal wave is along the axis of floating bridge. Figure 8 shows the joint force, moment and stress of gasbag versus time under longitudinal wave impacting (wave height=2m). As shown in Figure 8, the maximum contact force of hinge and maximum stress of gasbag appeared at the T1 module, and the maximum bending moment of hinge appeared in the middle section. The maximum stress value of gasbag is 9.83MPa. Figure 9 gives representative views of the displacement and stress of floating bridge. Due to the restraint of cable, the stress of gasbag is concentrated in the T1 module.

4. Conclusions

Complex fluid-structure interaction exists in the gasbag type floating bridge, which makes it difficult to simulate numerically. In this paper, the Arbitrary Lagrangian-Eulerian method and the penalty function method are used to study the dynamic numerical modeling theory and the wave impact calculation method of floating bridge.

Some concluding remarks are given as follows.

The dynamic numerical modeling theory and wave impact calculation method of gasbag type floating bridge presented in this paper have high accuracy and can be applied to engineering examples. Technical support will be provided to spread the scope of the GTFB application in military and civil fields.
Under solitary wave impact, the maximum contact force of hinge and maximum stress of gasbag appeared at the ends of the floating bridge, and the maximum bending moment of hinge appeared in the middle section.

Acknowledgement
This work is based on the Key Scientific and Technological Project (2016YFB0201800) and the National Natural Science Foundation (11772192) supported by the State Key Laboratory Mechanical System and Vibration (Shanghai Jiao Tong University) and the Shanghai Supercomputer Center.

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