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Dynamic pressure distributions of semi-submersible

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ABSTRACT

In the hydrodynamic study of Semi-submersibles, the wave pressure distribution on the wetted surface is critical input for structure analysis. Based on wave radiation and diffraction theory, a higher-order boundary element method (HOBEM) was applied to calculate the wave pressure distribution for a semi-submersible under specified wave direction and frequency. An integral system containing the FEM modeling of the semi-submersible, numerical calculation of hydrodynamic motion coefficients and data extraction and export for BEM analysis was established in the current study. A newly developed multiple and double nodes relocation method coupled with FEM-BEM model transformation is applied to remove the singularities along the sharp edges and corners of the semi-submersible. The numerical results confirm that the above algorithm significantly improves the numerical accuracy of wave pressure analysis for the semi-submersible.

1. Introduction

Semi-submersible and FPSO system (Floating Production, Storage and Offloading system) are important equipment for oil exploration for water depth over 3000 m. A FPSO system combines oil and gas production, storage and offloading, but it is very expensive and technically complicated. However, Semi-submersibles can extract and store oil at the same time and its underwater part is composed of pontoons and a number of vertical columns. A topside is installed on top of the vertical columns. The pontoon has a deep draft and is subject to smaller wave force compared with the conventional ships. The vertical columns have small wave diffraction and wave run-up and overtopping can be avoided. The structure designing of semi-submersible must ensure absolute safety during the entire operation period [1,2]. The above mentioned requirement makes it necessary to consider the following three aspects in the process of designing: accurate three-dimensional real body modeling method; efficient hydrodynamic analysis of wave loads; direct structure analysis based on wave loads of real model.

The commonly used software for example GAMBIT, MSC Pastran and ANASYS can set up very accurate three dimensional real body finite element models. These kind models can be used for fluid and structural analysis. The analysis of hydrodynamic response and wave loads of semi-submersible on the basis of real finite element model is vital for designing. Traditionally Morison equation is employed to study vertical or horizontal cylindrical structures like columns and pontoon-type buoys of semi-submersibles if their diameters are considerably smaller than the wave length. However Morison theory neglects the wave diffraction effect and the hydrodynamic interaction between different parts of a structure, although it can consider the effect of fluid viscosity [3]. Currently Green function method based on the wave radiation and diffraction theory is widely used in the hydrodynamic study of ocean engineering which can consider the wave interaction between pontoons and vertical columns of a semi-submersible [4,5].

Finite element method is an efficient method in structural design and analysis of semi-submersibles [6–8]. This method combines marine hydrodynamics, structural mechanics, finite element analysis and mathematical algorithm together. The first step of finite element structural analysis of semi-submersible is to correctly predict the fluid pressure distributed on the wetted surface of the floating body, including hydrostatic pressure and wave pressure caused by motion response and wave excitation. The fluid pressure on wetted surface needs to be transferred to the finite element model for structural analysis. Normally the numbers of nodes and elements for fluid pressure calculation and structural analysis are different. The fluid calculation only needs the boundary information on the wetted hull surface of the structure and the number of nodes and elements are small especially when high order boundary element method is used. However, structural analysis should utilize wave pressure on the so-

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called neutral layer of the body boundary and wave pressure transferred between BEM and FEM should be investigated. Moreover, in order to ensure enough numerical accuracy, large number of finite elements is needed for structural analysis.

Theories about the interaction between wave and offshore structures have existed for a long time [9–14]. So far, the most effective and widely used method is wave radiation and diffraction theory based on potential flow assumption. This Green function method can predict the hydrodynamic response and wave pressures of complicated offshore structures with reasonable accuracy [15]. And the inertia relief method can be applied to finite element analysis of a whole ship like structure which is an efficient static force analysis method for unconstrained structures with rigid body displacement. In this method, the equilibrium status is set up by inertia force and original loads, the real deformation and stress state of the structure can be obtained correctly by adding virtual constraints. Zhang Shaoxiong [16] applied inertia relief method in the structural analysis of ship like submarines.

Semi-submersible, as a large spatial structure, has six rigid body motions. The calculation of wave pressure distribution should take into account the combination of radiation and diffraction problems, which is an extremely complicated numerical analysis system [17]. At present, boundary element method [18] based on the wave radiation and diffraction theory is widely adopted in solving problem concerning the interaction between wave and offshore structures. In order to obtain stable numerical solution of wave pressure distribution for semi-submersibles under given wave directions and frequencies, higher order boundary element method [19] is employed in current research and geometrical symmetry is also considered. An integral system containing FEM modeler of semi-Submersible, calculation of hydrodynamic motion coefficients and data transfer for BEM analysis is firstly investigated in the study. A newly developed multiple and double nodes relocation method coupled with FEM and BEM data transformation is applied along complicated sharp edges and corners of semi-submersibles. The nodes along these edges or corners normally have geometrical or physical singularities. By use of nodes relocation method, nodes at these places have different normal derivatives and belong to different elements, but they share the same coordinates and velocity potentials. Numerical testing proves that the above-mentioned method is a crucial to ensure the high precision of the computation results of wave pressure distribution on semi-submersible hulls [20].

Section 2 introduces basic theory and mathematical formulations for computing wave pressure. The results of the wetted surface pressure of an ISSC type semi-submersible are analyzed in Section 3. Section 4 discusses the results and advantages and necessity of higher order boundary element method and nodes relocation in computing wave pressures. Conclusion and remarks are given in Section 5.

2. Boundary value problem

2.1. Basic theory

The Cartesian coordinate system defined in Fig. 1 is stationary relative to the undisturbed position of free surface and body. The origin is located on the free surface with z axis positive upward. Supposing that the fluid is non-viscous and incompressible and its motion is irrotational, the fluid velocity can then be expressed by the gradient of the velocity potential Φ. The motion of the semi-submersible in waves can be assumed to be in the form of harmonic oscillation. The velocity potential of fluid caused by the move of semi-submersible can be expressed as $\Phi = \mathrm{Re}\{\phi e^{-i\omega t}\}$, where Re denotes the real part, ω is the frequency of the incident wave in radians per second, t represents time and ϕ is spatial complex velocity potential irrelevant to time. In this way, all boundary value problems can be expressed with complex velocity potential ϕ and the final result is the product of complex variable and time factor $e^{-i\omega t}$. The velocity potential ϕ satisfies Laplace's equation in the whole fluid domain.

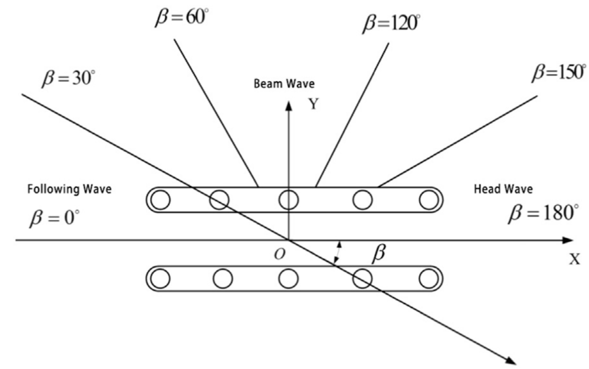

Fig. 1. Calculation sketch of Semi-submersible.

$$\nabla^2\phi = 0 \tag{1}$$

The linearized form of the free-surface condition is

$$\phi_Z - K\phi = 0,\ z = 0 \tag{2}$$

where: $K = \omega^2/g$ is deep water wave number and g is gravitational acceleration. The velocity potential of the incident wave is defined by

$$\phi_0 = \frac{igA}{\omega}\frac{\cosh[k_0(z+H)]}{\cosh k_0 H}e^{-ik_0(x\cos\beta + y\sin\beta)} \tag{3}$$

where : A is the amplitude of incident wave, H is water depth and β is the angle between the direction of propagation of the incident wave and the positive x axis. The wave number k_0 is the real root of the dispersion relation $\frac{\omega^2}{g} = k_0 \tanh k_0 H$. According to the linear assumption of wave motions, the total velocity potential of fluid ϕ can be decomposed into two components: the radiation potential ϕ_R and the diffraction potential ϕ_D, which can be respectively expressed as follows:

$$\begin{cases} \phi = \phi_R + \phi_D \\ \phi_R = -i\omega\sum_{j=1}^{6}\xi_j\phi_j \\ \phi_D = \phi_0 + \phi_7 \end{cases} \tag{4}$$

where the diffraction potential ϕ_D includes incident potential ϕ_0 and scattering potential ϕ_7, ξ_j denotes the complex amplitude of the body rigid motion with six degrees of freedom, ϕ_j is the corresponding unit amplitude radiation potential and ϕ_7 represents the scattering potential produced by the incident potential on the body fixed at its undisturbed position. The radiation potential and diffraction potential are subject to the following boundary conditions:

$$\begin{cases} \phi_{jn} = n_j \\ \phi_{Dn} = 0 \end{cases} \tag{5}$$

where: $(n_1, n_2, n_3) = \mathbf{n}$, $(n_4, n_5, n_6) = r \times \mathbf{n}$, $r = r(x, y, z)$, the unit vector $\mathbf{n}$ points positive into the body surface and $\mathbf{x}$ denotes the coordinates of body surface. The radiation potential ϕ_j, $j = 1,\ldots,6$ and scattering potential ϕ_7 satisfy the following conditions in far field:

$$\begin{aligned} &\lim_{R\to\infty}\sqrt{R'}\left(\frac{\partial\phi_j}{\partial R'} - ik_0\phi_j\right) = 0 \\ &\lim_{R\to\infty}\sqrt{R'}\left(\frac{\partial\phi_7}{\partial R'} - ik_0\phi_7\right) = 0 \end{aligned} \tag{6}$$

where $R' = \sqrt{x^2 + y^2}$.

The total wave pressure $\bar{P}$ is defined as

$$\begin{aligned} \bar{P} &= -\rho g z - \rho\frac{\partial(\phi e^{-i\omega t})}{\partial t} \\ &= -\rho g z + i\rho\omega\phi e^{-i\omega t} \\ &= P_0 + P e^{-i\omega t} \\ &= P_0 + (P_D + P_R)e^{-i\omega t} \end{aligned} \tag{7}$$

where P_0 is static pressure and P is dynamic pressure. The diffraction