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Numerical analysis on the secondary load cycle on a vertical cylinder in steep regular waves

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ABSTRACT

The secondary load cycle induced by regular waves of large amplitude has an important influence on the ringing response of offshore structures. To understand the mechanism of the effect of local violent water deformation of the free surface around a vertical cylinder on the wave loads, the numerical simulations are carried out for the cases of the steep regular waves. The numerical wave tank is established by solving the two-phase incompressible Navier–Stokes equations. The VOF method is applied to capture the violent flow with the free surface near the cylinder. The numerical model is validated by experimental measurement and theoretical result. New characteristic parameters of the secondary load cycle are defined in terms of the amplitude, duration and phase. The effects of wave steepness, relative diameter and relative depth on these characteristic parameters are presented and discussed. The results show that the characteristic parameters depend mainly on relative wave height and relative diameter of cylinder while the dependence on relative depth is weak. Using the fitting method, the empirical formulas are proposed to calculate the characteristic parameters of the secondary load cycle in terms of different wave steepness and relative diameter.

1. Introduction

With the utilization of marine energy and resources, the offshore activity is moving towards deep oceans. Compared to the fixed foundation on the seabed, the floating foundation is the superior construction in deep oceans. The tension-leg platform (TLP) is one kind of the popular floating structures which is widely used in the oil and gas production engineering and the foundations of the offshore wind turbine. In general, the natural frequency of TLP is far away from the frequency corresponding to the peak of the wave spectrum of the local seas. However, TLP may experience responses of large magnitude in terrible ocean environment which is very suddenly generated at the resonance period. This is a concern with respect to very high stress levels within a burst of only a few oscillations (Chaplin et al., 1997) and this phenomenon is named as “ringing”. The ringing phenomenon of TLP structure was firstly recorded in the model tests of two oil production platforms Heidrun and Troll (Natvig and Teigen, 1993).

Once happened, the ringing performance will badly influence the safety of the offshore structure. For this reason, it has attracted wide attention in the world. On the theoretical side, Faltinsen et al. (1995) proposed a third-order harmonic perturbation solution in the long-wave region which refers as FNV formula. Malenica and Molin (1995) extended this solution to the cases of the finite depth water region. For the irregular wave, the theories were developed by Newman (1996), Krokstad et al. (1996), and Johannessen (2012). Addition to the theoretical work, many investigations have been done experimentally. Based on the model tests and full-scale measurements, Jeffreys and Rainey (1994) discussed the ringing performance in detail and presented a slender-body wave model which was validated by the measurements. Welch et al. (1999) did an experimental study of the ringing response of a vertical cylinder in breaking wave groups, and spectral analysis was undertaken to explain the physical mechanism driving the response of the structure. Some numerical results about the ringing performance are also available. Liu et al. (2001) applied the Euler–Lagrange boundary element method to simulate the third order harmonic wave force which agrees with the theoretical results of Faltinsen et al. (1995) and Malenica and Molin (1995). Bai and Eatock-Taylor (2007) used the boundary element method to solve the fully nonlinear potential flow problem and the results coincide with the measurements.

It is worth considering that there is an additional loading of short in the direction of wave propagation shortly near the negative peak value

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in time history in some conditions. It is called the secondary load cycle. Chaplin et al. (1997) did an investigation on the interaction between the cylinder and the non-breaking phase focused wave. The results showed that the secondary load cycle may have an important effect on ringing response. Besides, a strong correlation was found between the magnitude of secondary load cycle and the wave steepness. Grue and Huseby (2002) also observed that the happening of ringing performance is related with the secondary load cycle. They suggested that the Froude number is a governing parameter for this small-scale load. Here, the Froude number is defined as $Fr = \omega\eta_m/\sqrt{gD}$, where ω is the angle frequency of the incident regular waves, η_m is the maximum value of elevation, g is the gravitational acceleration and D is the diameter of a cylinder. In addition, they found that the secondary load cycle contributes locally to a higher harmonic wave force. The timing of the load cycle is about one quarter wave period later than the main peak of the force. In the small-scale experiments it occurs when the wave slope exceeds a certain value, that is for $k\eta_m > 0.3$ and for the range $kD < 0.66$, where k is the wavenumber. For moderate scale, the secondary load cycle occurs for a smaller wave slope than observed in the small-scale experiments. Paulsen et al. (2014) presented the physics of the secondary load cycle. They pointed out that the secondary load cycle is clearly associated with the return flow of the diffracted waves, which through interaction with the positive flow velocity of the outer wave motion and drives a downstream vortex. They also found that the secondary load cycle is higher than the sixth order. The magnitude and temporal development of the secondary load cycle are shown to depend mainly on wave steepness while the dependence on relative depth was weak. The magnitude of the secondary load cycles was further shown to increase in the long-wave regime.

Diffraction theory, which is based on the potential theory, is widely applied to simulate the wave loading on large objects. Because it is timesaving and can satisfy the engineering demand in its scope of application. The FNV formula (Faltinsen et al., 1995) is widely applied in calculating the nonlinear wave load on a slender vertical cylinder. The boundary integral equation method and the high-order spectral method for solving the Laplace equation have been developed to simulate the propagation of nonbreaking waves in the framework of the potential flow theory (Liu et al., 1992; Dommermuth and Yue, 1987; Qi et al., 2018). However, the potential-flow based solvers are limited to a smooth and single-valued free surface which means the simulation of the complicated flow such as over-turning and wave breaking in the steep wave condition is beyond their applicabilities. The numerical model, based on the Navier-Stokes equations and the VOF method, can be used to simulate the violent flows with large deformation of the free surface around a cylinder and to compute the secondary load cycle on the cylinder in steep waves (Paulsen et al., 2014). In order to extend the FNV formula to simulate the wave loads induced by the steep regular waves, the present paper focuses on calculating characteristic parameters of the secondary load cycle through a series of numerical experiments. The effect of wave steepness, relative water depth and relative diameter on the characteristic parameters of the secondary load cycle will be studied. The empirical formulas are proposed to calculate the characteristic parameters of the secondary load cycle on a cylinder in regular waves which could be used to reconstruct the time series of the secondary load cycle.

2. Methodology

The numerical model is based on the solution of the incompressible Navier-Stokes equations using the open-source CFD toolbox OpenFOAM®. The volume of fluid (VOF) scheme is used to capture the free surface. The finite of volume method (FVM) and implicit Eulerian method are applied for the spatial discretisation and the time integration of the governing equations. The PISO-SIMPLE (PIMPLE) algorithm is used for the solution of the pressure-velocity coupling (The OpenFOAM® Foundation, 2011a, 2011b).

2.1. Governing equations

The Navier-Stokes equations are applied to describe the viscous fluid flow. Considering an incompressible fluid, the governing equations include the continuity equation and the momentum conservation equations. In a Eulerian frame, the governing equations can be formulated as following:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial (U_i)}{\partial x_i} + \frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + f_i \tag{2}$$

where U_i is the velocity, ρ the density of water, ν the molecular viscosity, f_i the volume force, and P the pressure.

2.2. VOF method

During the interaction between the steep waves and the cylinder, the flow near the cylinder shows large deformation and breaking of the free surface (Chaplin et al., 1997; Wienke and Oumeraci, 2005; Deng et al., 2016). Since the violent flow with the free surface has been proved to be very important for the secondary load cycle (Paulsen et al., 2014), the modelling of this flow is beyond the applicability of the traditional potential flow solvers. In the present study, the VOF method is applied to capture the strong nonlinear free surface motion. The VOF method was presented by Hirt and Nichols (1981) and is based on the Marker and Cell (MAC) method. The coefficient α, which is defined as the volume fraction coefficient of the fluid, is introduced into the VOF and evaluated as:

$$\alpha = \begin{cases} \alpha = 1 & \textit{water} \\ 0 < \alpha < 1 & \textit{interface} \\ \alpha = 0 & \textit{air} \end{cases} \tag{3}$$

The two-phase flow is considered as a mixed fluid. The density and dynamic viscosity can be presented as:

$$\begin{cases} \rho = \alpha\rho_w + (1-\alpha)\rho_a \\ \nu = \alpha\nu_w + (1-\alpha)\nu_a \end{cases} \tag{4}$$

where ρ_w and ρ_a denote the density of water and air, respectively; ν_w and ν_a denote the viscosity coefficient of water and air, respectively.

The above variant α satisfies the following governing equations:

$$\frac{\partial \alpha}{\partial t} + \frac{\partial (U_i\alpha)}{\partial x_i} - \frac{\partial [U_{ir}\alpha(1-\alpha)]}{\partial x_i} = 0 \tag{5}$$

in which, the compression term takes effect only on the interface due to the existence of $\alpha(1-\alpha)$, U_{ir} is the relative velocity between the water and air used to compress the interface (Weller et al., 1998).

2.3. Numerical wave tank

The present numerical wave tank is established using the open source package waves2Foam which is a two-phase flow package developed from the default solver interFoam in OpenFOAM®. The numerical wave tank is composed by the wave generating zone, the working zone and the damping zone, which is sketched in Fig. 1.

For the generation of the incident waves, the time series of velocity and free surface elevation obtained from the fifth order Stokes wave theory are specified at the inlet boundary. In order to absorb the reflected waves from the structures, a finite generating zone is developed to damp the reflected waves, which is similar with the function of the damping zone approaching the tank end, but the incident waves can successfully propagate through the generating zone into the working zone.

In the present model, the relaxation method is applied to update the