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Methodology for wave force monitoring of bottom-mounted cylinder using the measurement of the wave surface elevation around the body surface

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HIGHLIGHTS

- The relation of wave action and free surface elevation is formulated with a bottom-mounted cylinder.
- An experiment was performed to validate the efficiency of the estimated method.
- The error induced by the linear assumption is discussed.

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ABSTRACT

This paper presents a methodology to estimate the wave force on a bottom-mounted cylinder using the measured signals of wave surface elevation around the body surface of the cylinder. Based on the potential theory, the formulae are derived in a general manner for bottom-mounted cylinders of arbitrary cross section. Considering the difficulty of decomposing the signal of wave surface elevation measured by wave gauges, a linear estimation method is developed to achieve an approximate estimation of the wave loads on cylinders. A hydrodynamic experiment was conducted on a circular cylinder in a random wave field to validate the effectiveness of the proposed method. The horizontal wave forces and bending moments directly measured by force balance are employed for the validation of the proposed estimated results using the measurement of the wave surface elevation by wave gauges. Error analysis is also conducted in the frequency domain to investigate the effects of the linear approximation. The analysis results indicate that the proposed method can effectively estimate the wave loads acting on the cylinder. The linear approximation method slightly underestimates the wave loads of the difference-frequency component, while overestimating that in the sum-frequency region.

1. Introduction

A cylinder is a widely used structural component in coastal and offshore engineering, such as wind turbines, oil platforms and bridges. In a hostile marine environment, the water wave is a primary natural hazard that threatens the safety of the

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coastal structures. Understanding the wave–structure interaction mechanism and establishing an appropriate method for estimating the wave loads is fundamentally important for ensuring the safety of the structures.

For a small-scale cylinder, Morison et al. (1950) proposed a semi-empirical method, the so-called Morison equation, for calculating the inline wave force on structure in oscillatory flow. The Morison equation is composed of an inertial force in phase with the local flow acceleration and a drag force proportional to the square of the instantaneous flow velocity. When the diameter of cylinder becomes large, an obvious disturbance on the incident wave, which is generally called diffraction, becomes obvious. In such case, two dimensionless quantities, D/L and KC, are typically used to distinguish the flow regimes of diffraction (Isaacson, 1979), where D is the characteristic length of the cross-section, L is the wave length, and KC is the Keulegan–Carpenter number (Keulegan and Carpenter, 1956). It was found that the diffraction effect cannot be neglected when the ratio of D/L becomes larger than 0.2. In addition, the KC number should be less than the value of $0.44/(D/L)$ to prevent wave breaking. With these conditions, using potential theory, MacCamy and Fuchs (1954) formulated a linear solution for the diffraction problem of a regular wave around a large-scale bottom mounted cylinder.

Compared with a regular wave, a random wave more commonly appears in the ocean environment. When an offshore structure sustains the attack of random waves, the prediction of the wave load acting on the cylinders becomes more complex. Previous works attempted to extend the Morison equation from the condition of regular waves to random waves (Borthwick, 1989; Burrows et al., 1997; Li et al., 1997; Tung, 1996). Recently, Boccotti et al. (2012) conducted a comparison between the in-site measured wave force and the prediction results using the Morison equation acting on a vertical cylinder in a random wave field. In that study, the inertia and drag coefficients for the Morison equation were written as functions of the KC number and the Reynolds (Re) number to improve the accuracy of estimation. Lotfollahi-Yaghin et al. (2012) used an approach based on artificial neural network (ANN) to establish the predictive relationship between the hydrodynamic inline force and the wave surface elevation on a vertical cylinder. The advantage of the ANN method is that it is a model-free method. The results indicated that the predicted results of using ANN matched well with that of Morison equation.

With the application of a structural health monitoring technique in coastal engineering, such as an ocean wind turbine and an offshore platform (Hosseinlou and Mojtahedi, 2016; Jamalkia et al., 2016; Martinez-Luengo et al., 2016; Mojtahedi et al., 2011), the real-time estimation of the wind and wave loads becomes an important issue to assess the structural safety with the in-situ measured data. Although some theoretical methods have been developed for calculating the wave loads, those methods have some limitations for real-time estimation of the wave force, including: (1) because most of the theoretical methods were developed based on the regular wave action, in a random wave field, they are always not effective for computing the wave force; (2) the wave properties of the un-disturbed wave field, such as wave height and wave period, should be known. However, on the site of the structure, it is always difficult to measure the un-disturbed wave properties because of the influence of the structure, especially for multi-body cases, which contains the scattering wave and radiation wave from other bodies.

For large-scale structures, the previous studies (Chan et al., 1995; De Vos et al., 2007; Deng et al., 2016; Li et al., 2012, 2014; Niedzwecki and Duggal, 1992) found that there exists a correlation between the wave run-up and the wave force. Based on this conclusion, it is possible to determine a method to monitor the wave force acting on the cylindrical bodies through measurement of the wave surface elevation around the cylinders. Based on this philosophy, this paper presents a methodology to estimate the wave force of bottom-mounted cylinders by the measured data of wave gauges around the body surface. The main contents of this study are organized into three sections. First, the definition of the physical problem and the methodology for the wave load estimation are presented in §2. Next, a linear estimation method for the wave loads is introduced in §3 by using the recorded data of wave surface elevation around the cylinders. To validate the effectiveness of the proposed method, the results of a hydrodynamic experiment performed with a circular cylinder under random wave field is presented in §4. Finally, the main findings of the present work are summarized.

2. Methodology

Simulation of the wave–structure interaction, which is a very complicated physical phenomenon, is a difficult problem. To make the problem manageable, several assumptions were made to simplify the analysis (Sarpkaya, 2010), including:

(1) the fluid is inviscid and incompressible;

(2) the flow is unseparated around the solid structure;

(3) the effects of surface tension, dissolved gases, cavitation, density and temperature gradients of the water are negligible;

(4) the cylinder is rigid and bottom-mounted at the seabed with uniform shape.

Under the action of the gravity waves, the flow field can be represented by a scalar velocity potential. Without loss of generality, the rigid body is assumed to have an arbitrary cross-section with smooth surface. For the convenience of analysis, a rectangular and a polar coordinate are defined, as shown in Fig. 1. For the two coordinate systems, the $x-y$ or $r-\theta$ planes are all set at the still water level (SWL), and the origin is inside the cross-section of the cylinder. The z-axis is perpendicular to the SWL and positive upward.

The following derivation was formulated for the cylinder whose cross-section is arbitrary and can be represented by a Fourier series. The radius function, $r(\theta)$, of the cross-section in the polar coordinate was then written in the following form