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Experimental study on motion responses of a moored rectangular cylinder under freak waves (I: Time-domain study)

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ABSTRACT

Extensive experiments on the motion responses of a rectangular cylinder under random and freak waves have been conducted in the present study. The effects of the relative wave height, relative period and freak wave parameters on the motion responses were investigated. Analysis in time-domain revealed that the freak wave parameter α_1 has significant effect on the motion responses of the cylinder, especially for surge and heave. However, α_2, α_3, α_4 have not such significant effect on the motion components. With $\alpha_1 = 2$–2.8, the maximum surge and heave under freak waves were 2.5 and 1.5 times, respectively, larger than those under irregular waves. In addition, the maximum pitch under freak waves was approximately 1.3 times of that under irregular waves. The difference in motion response under freak waves and irregular waves decreased with the increasing relative wave heights. With $Hs/d = 0.03$–0.1 and $\alpha_1 = 2$–2.2, the maximum surge and heave under freak waves were approximately 30–60% and 20–40%, respectively, larger than those under irregular waves. For the effect of the relative period, the critical surge, heave and pitch occur at period around T_p/T_{0heave}~1.0, 1.5, 2.0 and T_p/T_{0pitch}~1, respectively. With the natural periods and $\alpha_1 = 2$–2.2, surge, heave and pitch under freak waves were approximately 44%, 40% and 30%, respectively, larger than those under irregular waves.

1. Introduction

During offshore structures design, the extreme wave conditions are commonly adopted to determine the design wave loads according to most of design codes, which ignore freak waves. Generally, the distribution of the freak wave height does not follow the classic distribution for sea waves, i.e. Rayleigh distribution in deepwater and Глуховский distribution in shallow water (Yu, 2000). Although it is hard to forecast, the existence of freak waves still imposes serious potential risks on marine structures and vessels.

Random waves can be described as irregular wave sequence in time-domain and wave spectrum in frequency-domain. With the same wave spectrum, there are various wave sequences, in which freak waves could occur. It is therefore important to clarify if the occurence of freak waves leads to significant difference on the dynamic response of the offshore structures. In this study, the wave sequence with and without freak wave are referred to "freak wave sequence" and "conventional irregular wave sequence", or "freak wave" and "irregular wave", respectively.

The existing study of freak waves foucses on revealing the formation mechanism, the probability of occurrence and numerical simulation, etc. Few researches concerned the interaction between freak waves and marine structures.

For the generation mechanism of freak waves, Tromans et al. (1991) proposed NewWave methodology as an efficient approach to simulate extreme wave. Osborne (2001) and Slunyaev et al. (2002) used nonlinear Schrodinger (NLS) equation to simulate freak waves numerically. Pei et al. (2007) superposed a random wave train with two transient wave trains to generate freak waves in a short wave train. Cui et al. (2012) applied the constrained NewWave theory in the simulation of freak waves and studied the bottom influence on the propagation of the freak waves.

As to the probability of occurrence, numerical and experimental studies have demonstrated that waves with freak wave features can be generated frequently in a two-dimensional wave flume without current, refraction or diffraction (Stansberg, 1990; Mori et al., 1992). Chien et al., (2002) analyzed the probability of nearshore freak waves and pointed out that the probability of freak wave occurrences increases significantly after a typhoon.

On the aspect of interaction between freak waves and structures, Clauss et al. (2003) analyzed the motions behavior and resulting splitting forces of a semisubmersible under freak wave with both the

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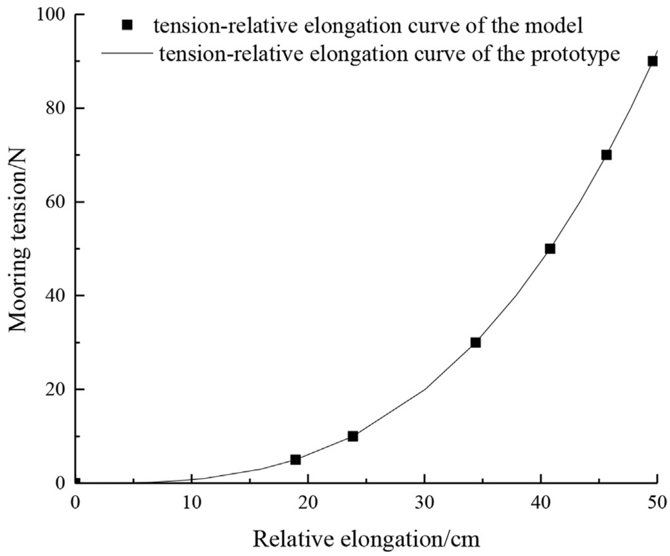

Fig. 1. Relationship of tension (T_m) versus deformation (Δs).

time-domain simulation and model tests. Schmittner. (2005) investigated the motions and bending moments of an FPSO and a heavy lift vessel as well as the motions and splitting forces of a semisubmersible due to Rogue Waves. The results show that the vertical bending moments, heave and pitch motions of an FPSO and a heavy lift vessel as well as the airgap and splitting forces of a semisubmersible under Rogue Waves are larger than the maximum values predicted by the classification rules and frequency-domain analysis. Bunnik et al. (2008) used a VOF-based model to predict the extreme wave loads on fixed offshore structures due to focused wave groups. Shen and Yang, (2013) investigated the stress, wave climbing and wave slamming force on the column and semi-submersible platform by freak wave through numerical simulations. The results showed that the crest of a freak wave is the main parameter affecting the platform motion. Rudman and Cleary (2013) adopted the Smoothed Particle Hydrodynamics (SPH) method to simulate the fully non-linear interactions between a TLP and freak waves. They considered the effect of wave impact angle and mooring line pre-tension on the subsequent motions of the platform. Gu et al. (2013) studied the hydrodynamic of a TLP under freak waves. Zhao et al. (2014) developed an advanced tool to model freak waves impact on a floating body under large amplitude motions. The model is solved by a Constrained Interpolation Profile(CIP)-based high order finite-difference method on a fixed Cartesian grid system. The comparison of the numerical results and measured data reveals that the proposed model is applicable in predicting the nonlinear dynamics of the floating body. Deng et al. (2014, 2015) investigated the effects of wave group characteristics on a semi-submersible under freak wave condition and found that the surge response increased significantly. Gao et al. (2015) studied numerical simulation of deterministic freak wave series and wave-structure interaction. Freak wave interactions with fixed cylinders submerged in different depths are investigated. The results suggest that the most critical vertical loads appear at the process of the freak wave approaching which may cause severe vertical responses on offshore structures.

The present investigation compares the motion response of a floating rectangular cylinder under freak and irregular waves and quantifies the difference through experimental measurements. This provides a basis for understanding the mechanism of interaction between freak waves and structures.

2. Experiments

2.1. Experimental setup

The tests were carried out in a wave flume at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The flume is 60 m long, 4.0 m wide and 2.5 m deep. The wave generation system is Hydro-servo irregular wave maker system, and it generates waves with a wave period ranging from 0.5s to 5.0s. At the other end of the flume, an absorbing beach is installed for wave dissipation.

The motion responses were measured by a non-touched 6DOF (degree of freedom) measurement system, consisting of dual-CCD cameras and a data acquisition system. Three light markers were arranged in a plane and fixed on the top of the cylinder to track the motion behaviors by the dual-CCD cameras. The images of the markers were continuously acquired by the two cameras at 30 frames per second, and the signals were processed to recover the instantaneous position of each marker in a calibrated coordinate system. The mooring tension was measured by a tension sensor with an accuracy of 0.1 N. The wave heights were measured by DS30 waves measuring system, which controlled 64 wave gauges synchronously. The wave gauges were calibrated before tests with an accuracy is 0.1 mm.

2.2. Model design and experimental parameters

The floater is an airtight rectangular cylinder made of acrylic (Fig. 1). The cylinder is a rectangular solid with a height of h = 62 cm, and a square base with a side length of D = 50 cm. The sharp corners of the cylinder were grinded to smooth arcs with a radius of R = 6.6 cm. The

Table 1
Summary of hydrodynamic parameters of the floating cylinder model.

Parameters	unit	magnitude
Moulded height	cm	62
Draft	cm	34
Weight	kg	73
Center of gravity measured from bottom	cm	20
Center of buoyancy measured from bottom	cm	17
Transverse metacentric radius	cm	6.13
Longitudinal metacentric radius	cm	6.13
Transverse metacentric height	cm	5.13
Longitudinal metacentric height	cm	5.13
Transverse moment of inertia	cm^4	5.2×10^5
Longitudinal moment of inertia	cm^4	5.2×10^5
Natural surge period	s	10.0
Natural heave period	s	1.4
Natural pitch period	s	2.0