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Experimental study on the dynamic responses of a freestanding bridge tower subjected to coupled actions of wind and wave loads

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A R T I C L E I N F O

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A B S T R A C T

This work presents an experimental investigation of the dynamic responses of a freestanding bridge tower model under coupled wave and wind actions. A test model with a geometric scaling of 1:100 was manufactured, and the test was performed in a wind tunnel and wave flume. The dynamic responses of the test model were measured under three cases of wind, wave and wind-wave coupled actions. The displacement, acceleration and bending moment were analyzed for the model with different wind speeds and wave exposures. The test results indicated that the coupled wind-wave effects are clear for lower wind speed with regular waves when the wave period is in the resonant region of the structures. When the wave period is far from the resonant frequency of the structure or the wind speed is much higher, the coupled wind-wave action does not significantly affect the dynamic responses of the bridge tower.

1. Introduction

Coastal engineering, which includes cross-strait bridges, offshore platforms and wind turbines, is an important civil infrastructure for the transportation or exploration of ocean energy. In the marine environment, these kind of structures sustain more serious environment loads, such as wind, waves and currents. Furthermore, a current trend in offshore engineering is the quest to exploit deeper waters. Deeper waters and severe environments make the structures more vulnerable to the marine environment forces.

Offshore platforms, such as conventional fixed leg platforms, tension leg platforms, guyed and articulated tower platforms, are a type of flexible structure that are extremely susceptible to wind- and wave-induced oscillations. The study of Vickery (1995) indicated that the strong interdependence between the wind and wave responses of tension leg platforms means that winds and waves must be treated simultaneously when predicting the responses of offshore platforms. Bisht et al. (1998) used an iterative frequency domain method to analyze the dynamic responses of a guyed tower platform under the actions of wind, wave and current loads. The analysis results showed that the wind force significantly influences the displacement response of the first mode, whereas the effects on the bending moment and shear force were small.

Offshore wind turbines are another type of coastal structure, which is susceptible to wind and wave actions. With the development and strong requirement of green energy, offshore wind turbines have become the device with the most potential to harvest energy. In recent years, numerical tools, such as FAST, bladed and HAWC/HAWC2, have been adopted for numerical simulations of turbines that consider aerodynamics and hydrodynamics simultaneously (Iijima et al., 2010; Karimirad, 2013; Li et al., 2014; Philippe et al., 2013; Stewart and Lackner, 2014). Ren et al. (2012) conducted a laboratory test on a floating wind turbine with a tension-leg platform under wind and regular wave actions. The comparison in his study between numerical and experimental results indicated that the numerical method is not perfect in some respects.

Large-span bridges, such as cable-stayed bridges and suspension bridges, in the coastal area are also a type of flexible structure vulnerable to wind forces. Wind-induced vibrations, which include flutter, buffeting, vortex-induced vibrations, etc., of cables, bridge decks and completed bridges have been widely investigated by researchers (Davenport, 1962; Larsen and Walther, 1997; Scanlan and Tomko, 1971). As the crucially important the bridge tower is, Larose et al. (1998) and Siringoringo and Fujino (2012) measured the vibrations of a large-span suspension bridge with a health monitoring system installed on the bridge tower. The aerodynamic and aeroelastic

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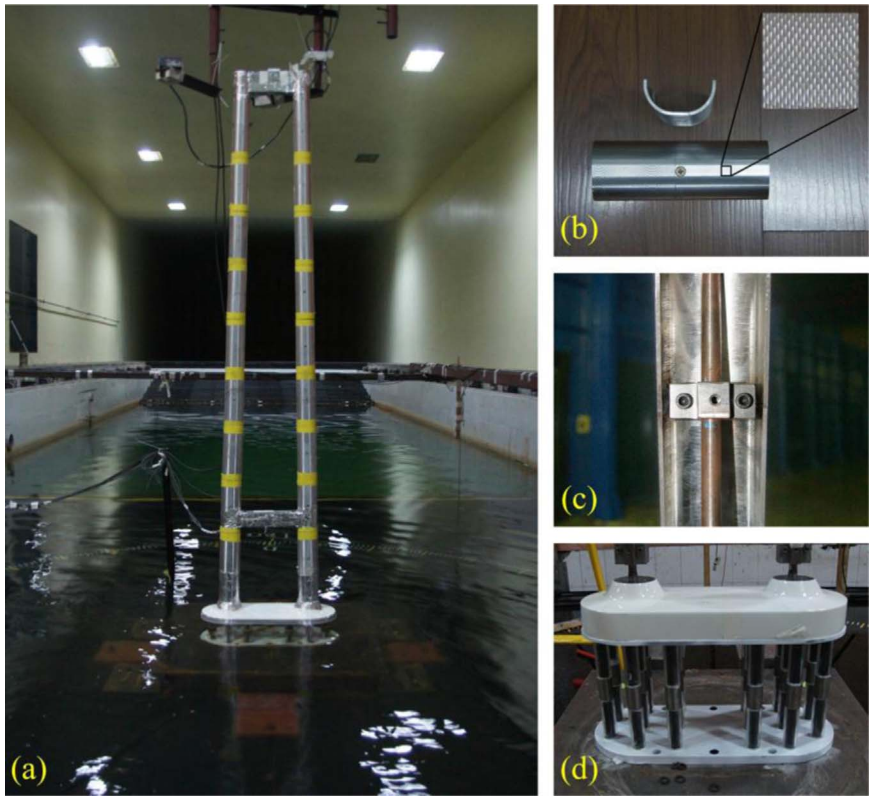

Fig. 1. Photograph of the tested bridge tower model. (a) bridge tower; (b) cover; (c) spine and additional mass; (d) foundation.

responses of the slender bridge tower have also been widely investigated in laboratories to ensure the safety of the structure under wind-structure interaction. Larose et al. (1995) conducted 3-D aeroelastic tower model tests in a wind tunnel. The vibration characteristics of the structure with the effect of vortex shedding and wind exposure were discussed. Belloli et al. (2011) experimentally investigated the aerodynamic characteristics of a cable-stayed bridge tower in a stand-alone configuration using a 1:100 scaled aeroelastic model and a 1:30 scaled section model. The vortex shedding responses were analyzed, and the effects of the model scaling were also discussed. These studies have produced valuable information regarding the fluid-structure interactions of bridge towers. As to the hydrodynamic problem for the cross-strait bridges in deep water, several studies have focused on the wave action of pile foundation (Bittner et al., 2007; Liu et al., 2007). However, due to the complexity of the experiment, a model test of such types of structures is still a challenge if both aerodynamic and hydrodynamic characteristics are considered.

With more and more offshore bridges being constructed for transportation in the strait and gulf areas, the oscillations of navigable bridges with long spans in deep water under wind and wave actions have also attracted great attentions of researchers. This paper presents an experimental investigation of the dynamic responses of an offshore bridge tower in a stand-alone configuration when subjected to wind and wave coupled actions. The objectives of this study are to investigate the dynamic responses of the structure and explore a laboratory technique for a flexible structure under wind and wave actions. To achieve this purpose, an aeroelastic model with a geometrical scaling of 1:100 was manufactured, and the tests were performed in a wind tunnel and wave flume. In this paper, the details of the test model, test facility and measurement instruments are first introduced. To correct the wind and wave fields, several trials were performed in a vacant wind tunnel and wave flume, and the flow field test results were analyzed. Afterwards, the dynamic responses of the test model were measured for the structure under wind, wave and wind-wave coupled action with varying wind speeds, wind exposures and wave properties. The analysis results indicated that the coupled effects of wind and waves are clear for lower wind speed with regular waves when the wave period is in the resonant region of the structures. On the other hand, when the wave period is far from the resonant frequency of the structure or the wind speed is much higher, the coupled action of wind and waves does not significantly affect the dynamic responses of the test model.

2. Experimental setup

2.1. Description of the bridge tower model

The prototype structure investigated in this study is a main component of a cross-strait bridge planned for construction. The freestanding bridge tower has a height of 233.9 m measured from the seabed to the tower top. The superstructure of the tower is composed of two tapered-shaped legs that vary linearly along the height with an approximate elliptical cross-section (chamfered square). Two cross-beams connect the legs at the upper end and the bottom. The bridge tower is located at a site with a water depth of 28.5 m. The foundation consists of 16 piles with a radius of 3.0 m and a length of 23.0 m in the water. A concrete mass pile cap with a height of 7.0 m connects those piles as a unit and supports the superstructure.

The aeroelastic test model was designed with a geometric scaling of 1:100. Theoretically, the Froude and Reynolds similitude criterion, which related to the viscous force and gravity respectively, should be simultaneously matched for the model design of the structures under wind and wave actions. In this study, the Reynolds number of the test model and the prototype structure were calculated to be within the scope of 10^3–10^5 and 10^6–10^8, respectively. It was recognized that it is impossible to reproduce the same Reynolds number for the test model of bridges in wind tunnel experiments. Therefore, the effects of Reynolds number were neglected in the present study and the Froude similitude law was adopted for the test model design. Previous studies on Reynolds number effects usually focused on flow