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Dynamic response of articulated towers under correlated wind and waves

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ABSTRACT

This paper deals with the dynamic behavior of a double-hinged articulated tower to wave alone, and correlated wind and waves. The analysis includes the nonlinearities due to nonlinear drag force, fluctuating buoyancy, variable added mass and instantaneous tower orientation. The fluctuating wind load is modeled by Ochi and Shin spectrum, while the wave load is characterized by Pierson–Moskowitz (P–M) spectrum. The nonlinear dynamic equation of motion is derived by Hamilton's principle. The equations of motion are solved in time domain by using Wilson-θ method. Power spectral density function (PSDF) of surge, tilting motion, hinge shear and bending moment are presented under high, moderate and low sea states. Studies of correlated wind and waves are found to be imperative for double hinged articulated towers to serve and survive in the extreme ocean environment. The response PSDF highlights the wind induced dynamic responses of the tower.

1. Introduction

Although wave loading on offshore platforms is generally assumed to be more significant than wind loading, exceptions can be found. Low frequency articulated tower platforms reduce the response to high frequency wave forces. However, the structure vibrates within the range of the most energetic low frequencies of wind excitation as shown in Fig. 1. This indicates the crucial impact of wind action on the behavior of articulated tower platforms.

The wind induced vibration of articulated towers is a complicated phenomenon due to fluid structure interaction effects. As such, there is lack of a comprehensive study conducted to investigate the wind induced vibration of articulated tower platforms. Some studies related to these vibrations are available on other compliant platforms such as TLPs and Guyed towers (Kareem, 1985; Kareem et al., 1987; Bisht and Jain, 1998; Vickery, 1995; Ormberg et al., 2003; Jain and Chandrasekaran, 2004; Zeng et al., 2006; Kwon et al., 2012). Chandrasekaran and Madhuri (2015) carried out experimental and numerical investigations on offshore triceratops (a new generation offshore compliant platforms), which showed response reduction of the deck under lateral loads. While most of the researchers analyzed the response of compliant towers under wave alone, only few works (Bisht and Jain, 1998 and Jain and Chandrasekaran, 2004) were reported under correlated wind and waves which has important practical applications.

Few earlier researches were focused the dynamic analysis of single hinged articulated towers (Datta and Jain, 1990; Bar-Avi and Benaroya, 1996a, 1996b, 1997). Nagamani and Ganapathy (2000) presented an analytical treatment as well as experimental program for a three-leg articulated tower. In a similar study, Chandrasekaran et al. (2010) analyzed the response of a three leg articulated tower with and without Tuned Mass Damper (TMD). Recently, Gavassoni et al. (2015) applied the theory of nonlinear normal modes to investigate the nonlinear vibrations of a discrete two-degree-of-freedom model of an articulated tower. The study showed that nonlinear normal modes are a good alternative for the nonlinear analysis of an articulated tower and similar offshore structures.

However, there has been growing interest on multi-hinged articulated towers in the recent past. For instance, the concept of multi-hinged articulated towers was introduced by Jain and Kirk (1981) and McNamara and Lane (1984). Subsequently, a new concept namely Tension Restrained Articulated Platform (TRAP) was proposed by Hanna et al. (1988) who concluded that multi articulation concept is an attractive option for deep water applications. Helvacioglu and Incecik (1990) performed an analysis and model test of single and double hinged articulated towers. Sellers and Niedzwecki (1992) presented a mathematical model of multi-hinged articulated tower and identified the role of salient parameters in characterizing the natural periods, while Islam compared the response of single and double hinged articulated towers under various ocean environments.

In one of the authors' previous studies (Zaheer and Islam, 2012), the response of an articulated loading platform (ALP) to wave alone, wind alone, and correlated wind and waves under various wind spectra, was analyzed. However, this study was limited to tower response under

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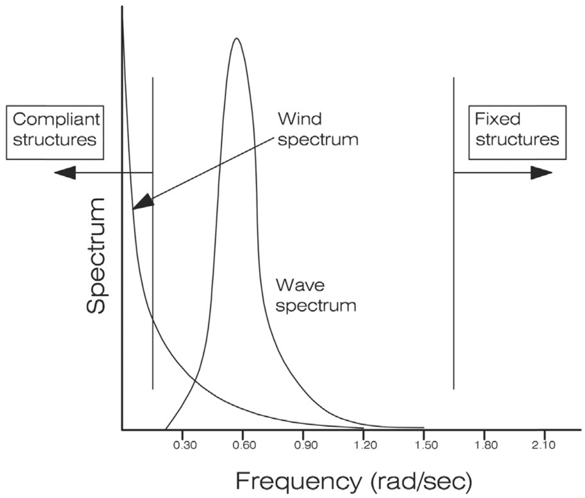

Fig. 1. Excitation and frequency ranges of offshore platforms.

single sea state. Recently, the authors (Zaheer and Islam, 2015), conducted a parametric study on the dynamics of bi-articulated tower. It was observed that variations in the diameter and the depth of buoyancy chamber from sea water level (SWL) had a significant effect on the natural frequencies of the tower.

The literature review reveals that many researchers were interested on analyzing the response of the tower under wave force only. The correlated wind and wave approach has a crucial impact on the prediction and accuracy of multi-hinged articulated towers. However, this issue has not been addressed so far. Moreover, the tower response under different sea states is also lacking. Accordingly, the present study investigates the dynamic behavior of double hinged articulated towers under correlated wind and waves for various sea states, covering the realistic ocean environments.

2. Methodology

2.1. The physical model

In the present study, a double hinged articulated tower is modeled as an inverted double pendulum enacted by two articulation points. As shown in Fig. 2, the articulated tower consists of a ballast chamber attached to the lower shaft/column of length L_1 near the bottom. The lower column is attached to the seabed through a universal joint at the base. The upper part of the structure consists of a buoyancy chamber attached to another column of length L_2 near the sea water level (SWL). The upper column is connected to the lower one through an intermediate articulated joint. The upper part of the buoyancy chamber has a surface piercing cylinder of the same diameter as that of the upper shaft. The deck and other attachments are provided on the top of the surface piercing cylinder above SWL. The in plane rotations at the two articulation points constitute the dynamic degree-of-freedom of the system. Thus, there are two generalized coordinates; rotations θ_1 and θ_2 about the vertical axis. All forces/moments are derived in the fixed coordinate system attached to the earth, which means that the tower rectilinear velocity is resolved into x, y coordinates.

2.2. Mathematical modeling and analysis

2.2.1. Model description

The present nonlinear model for the dynamic analysis involves formulation of matrices such as a nonlinear stiffness matrix comprising fluctuating buoyancy, a mass matrix representing structural mass and added mass due to the tower motion, and a damping matrix. The tower structure is idealized by replacing its mass distribution with discrete masses located at the centroids of a series of small elements of length L_i

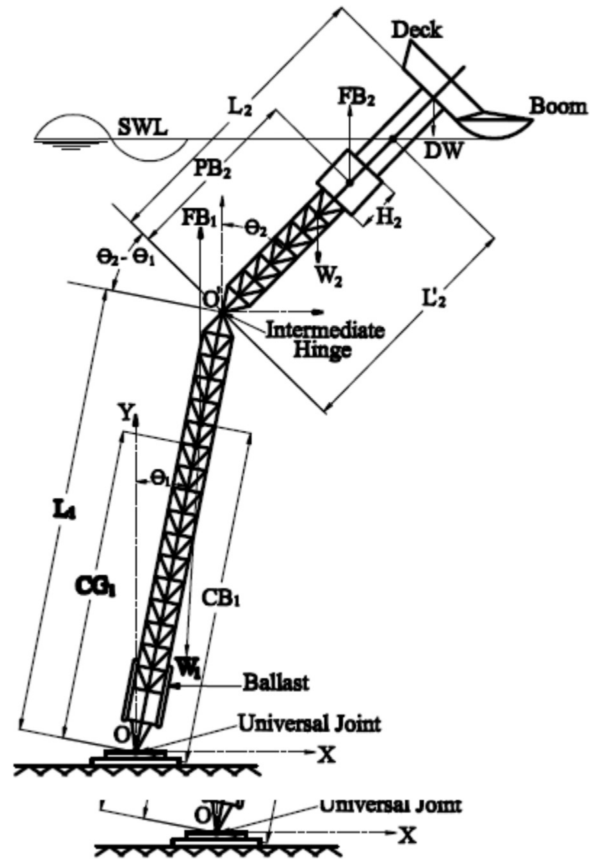

Fig. 2. Mathematical model of double hinged articulated tower.

and diameter D_i. All forces are assumed to act at these centroids and include weight, inertia forces, buoyancy, fluid forces on the submerged parts and wind forces on the structure above water surface. The model also involves the selection of wave theory that reasonably represents the water particle kinematics. In the numerical analysis, the equations describing motions and loads of the articulated loading platform are based on Morison's equation applied to a moving system. In order to incorporate high degree of nonlinearities associated with the system, a time domain numerical integration scheme is required to solve the equations of motion. The following assumptions have been made while developing the present model:

1. The aerodynamic force coefficient of the superstructure is derived using a projected area approach.
2. The wind does not modify the wave at mean sea level and the Airy's linear wave theory is considered valid. The wave diffraction effects have been neglected.
3. The total wind force is concentrated at the aerodynamic center, while the total mass is acting at its center of gravity of the platform.

2.2.2. Governing equations

The equations of motion are obtained by using the Lagrangian approach. This approach provides several advantages over the Newtonian method, such as eliminating of free body diagrams with interaction forces between the members (Craig, 1983).

Lagrange's equation can be derived from the principle of virtual displacements or from Hamilton's principle. The latter approach is employed in this study; this principle reduces the formulation of a dynamic problem to the variation of two scalar quantities: the work function and the kinetic energy, and also it is invariant under coordinate transformation (Humar, 2012).

The first nonlinear equations of motion of double hinged articulated