Ocean Engineering 109 (2015) 226–242

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Nonlinear vibration modes of an offshore articulated tower

Elvidio Gavassoni [a], Paulo Batista Gonçalves [b,*], Deane de Mesquita Roehl [b]

[a] Department of Civil Construction, Paraná Federal University, DCC/TC, Bloco III-Caixa Postal 19011, 81531-990 Curitiba, PR, Brazil
[b] Department of Civil Engineering, Pontifical Catholic University, PUC-Rio, Rua Marquês de São Vicente, 225, 22451-900 Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Article history:
Received 19 March 2015
Accepted 20 August 2015

Keywords:
Compliant offshore structure
Nonlinear vibrations
Nonlinear normal modes
Dynamic instability
Parametric instability

ABSTRACT

Compliant structures, due to their low stiffness and hostile environmental loads, may present large displacements and rotations, leading to significant nonlinear effects. This work applies the theory of nonlinear normal modes to investigate the nonlinear vibrations of a discrete two-degree-of-freedom conceptual model of an offshore compliant articulated tower. The effects of buoyancy, added mass, ocean currents and waves are considered in the analysis. The elastic restoring forces are modeled, based on Augusti's model, using two orthogonal rotational springs. The invariant-manifold approach is then applied to the equations of motion, and the resulting equations are solved through an asymptotic expansion. The derived nonlinear normal modes are then used to reduce the problem to a single degree-of-freedom nonlinear oscillator in each mode. The stability of the solution is investigated through Floquet theory and Mathieu charts. Multiplicity of stable and unstable modes is detected using Poincaré sections. Similar and non-similar modes are also identified. The results of the reduced order model are compared to the numerical solutions of the original equations of motion. The favorable comparisons between both solutions confirm that nonlinear normal modes are a good alternative for the nonlinear analysis of an articulated tower and similar offshore structures.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Articulated towers are compliant structures suitable for numerous offshore applications (Kirk and Jain, 1978; Jain and Kirk, 1980; Nagamani and Ganapathy, 1996). Compliant platforms are economically feasible in the offshore industry due to their reduced weight compared to fixed or conventional platforms (Bar-Avi and Benaroya, 1997; Patel and Witz, 2013). The structure does not supply resistance to horizontal forces due to wind, ocean currents or waves. However, restoring forces are provided through buoyancy, ballast, guy wires, axial piles, tendons and other devices (Haslum and Faltinsen, 1990; Sellers and Niedzweck, 1992; Bar-Avi and Benaroya, 1997; Patel and Witz, 2013). As a result of this structural concept, the natural frequencies of compliant towers are usually lower than wave excitation frequencies (Islam et al., 2009).

Articulated towers have been used as advanced offshore production facilities (Choi and Lou, 1991) and mobile devices in large offshore oil storage and loading systems (Nagamani and Ganapathy, 1996). A typical articulated tower consists of a single leg articulated tower supporting a platform over its top and fixed at the bottom (Nagamani and Ganapathy, 2000). The support at the bottom can be a sole universal joint in the tower system; an articulated tower can also use intermediate universal joints in a multi-hinged articulated tower configuration (Nagamani and Ganapathy, 1996, 2000; Zhaheer and Islam, 2012), which is preferable in deep water systems. The tower can also be modeled as a flexible column with uniform or non-uniform cross-section (Taylor et al., 1983; Nagaya and Hai, 1985; Kuchnick and Benaroya, 2002; Wu and Chen, 2003).

Due to their reduced stiffness and hostile environmental loading conditions, compliant structures may present large displacements and rotations, which may lead to significant nonlinear effects (Tabeshpour et al., 2006). Nonlinear systems can exhibit extremely complex behaviors which linear systems cannot. These phenomena include jumps, bifurcations, saturation, subharmonic and superharmonic oscillations, internal resonances, limit cycles, modal interactions, quasi-periodic behavior and chaos (Thompson and Stewart, 1986; Nayfeh and Balachandran 2008; Patel and Witz, 2013). Among these nonlinear phenomena, parametric resonance is a rather common phenomenon in dynamical systems (Fossen and Nijmeijer, 2011). Specifically, offshore structures such as risers, mooring systems and spar platforms may be subjected to parametric resonance leading to large amplitude vibrations and even unstable motions. Relevant contributions in this field includes the works of Patel and Park (1991), Thampi and Niedzwecki (1992), Han and Benaroya (2000), Park and Jung (2002), Chatjigeorgiou (2004), Yang and Li (2009), Greco et al. (2015) and Yang and Xu (2015).

* Corresponding author.
E-mail address: paulo@puc-rio.br (Batista Gonçalves).

http://dx.doi.org/10.1016/j.oceaneng.2015.08.028
0029-8018/© 2015 Elsevier Ltd. All rights reserved.

Numerical discretization approaches such as the finite element method are typically used to analyze the nonlinear dynamic behavior of offshore structures (Agarwal and Jain, 2003; Yang et al., 2012). However, the computational effort necessary to address the large number of degrees-of-freedom and their couplings is very large (Pesheck et al., 2002; He et al., 2007; Li et al., 2011), precluding the use of finite element programs in parametric analyzes required in an initial design stage. Also, the use of finite elements in bifurcation and dynamic integrity analyzes are rather cumbersome, if not impossible.

In this scenario, the use of reduced order conceptual models becomes an attractive approach for performing nonlinear dynamic analyzes of complex offshore structures (Happawana et al., 1995; Matha et al., 2014; Chen et al., 2014). When analytically derived, the approximate reduced model and its solution can be used to understand the complex dynamic behavior of offshore structures subjected to large displacements (Thompson et al., 1984; Gottlieb and Yim, 1993; Jain, 1997; Falzarano et al., 2001; Zhou and Wu, 2015).

In recent years, analytical methods based on modal reduction using nonlinear normal modes (NNM) have been proposed as an efficient approach to describe the nonlinear motion of structures and machines (Rosenberg, 1961; Vakakis, 1991; Shaw and Pierre, 1991), including the nonlinear analysis of offshore structures (Mazzilli and Sanches, 2012). They provide a solid theoretical and mathematical tool for interpreting a wide class of nonlinear dynamical phenomena. Reduced order models obtained by the use of NNMs are able to capture the contribution of several modes (Gavassoni et al., 2014), thus allowing a smaller number of modes to generate a precise model compared to standard reduction approaches such as those using linear modes.

This work applies the theory of NNM to investigate the nonlinear dynamic behavior of a discrete two-degree-of-freedom conceptual model of an offshore compliant articulated tower. The effects of buoyancy, added mass, ocean currents and waves on the tower vibration are considered in the analysis. The elastic restoring forces are modeled using two orthogonal rotational springs. The nonlinear dynamic analysis of articulated towers has usually been conducted using single-degree-of-freedom systems (Choi and Lou, 1991; Pesheck et al., 2001; Han and Benaroya 2002). However, this SDOF model is unable to capture the nonlinear coupling between different vibration modes and out-of-plane motions of the structure, which may lead to complex dynamic phenomena.

This paper presents the derivation of the equations of motion of the compliant articulated tower under environmental loads using Augusti's model (Bazant and Cedolin, 2010; Pignataro et al., 2013; Orlando et al., 2013). The invariant-manifold approach proposed by Shaw and Pierre (1993) is then applied to the equations of motion, and the resulting equations are solved through an asymptotic expansion of the linear vibration modes of the linearized problem. These nonlinear normal modes are then used to reduce the problem to a single degree-of-freedom nonlinear oscillator in each nonlinear normal mode expansion. These reduced order models are used to thoroughly investigate the free vibration response of the tower, as well as the effects of the currents and symmetries on its dynamic behavior. In order to unveil the complex dynamics of the model and the inherent modal couplings due to symmetries, the wave effects in the reduced order model are investigated by considering a harmonically forced problem. The stability of the solution is investigated through the application of the Floquet theory and Mathieu stability charts. A multiplicity of modes is detected using Poincaré sections, where stable and unstable modes are obtained. Similar and non-similar modes are also identified. The results of the reduced order model obtained by the NNM approach are compared to the numerical solutions of the original equations of motion. The agreement between both solutions confirms that NNMs are a good alternative for the nonlinear analysis of an articulated tower and similar offshore structures. Finally, the results obtained from the harmonically forced reduced order models are compared to those obtained by numerical integration of the original equations of motion using Morison equation and Airy wave theory.

2. System model

The conceptual discrete model of the articulated tower is based on Augusti model (Bazant and Cedolin, 2010; Pignataro et al., 2013), which has been traditionally used to illustrate the phenomenon of nonlinear modal coupling in elastic stability theory. It consists, as illustrated in Fig. 1, of a stiffened inverted spatial pendulum composed of a slender rigid column of length l with an uniform hollow tubular cross-section with an outer diameter d_0 and inner diameter d_i (l»d_0), pinned at the base. The platform is modeled as a single lumped mass M located at the column's free end. The mooring system is represented by two rotational

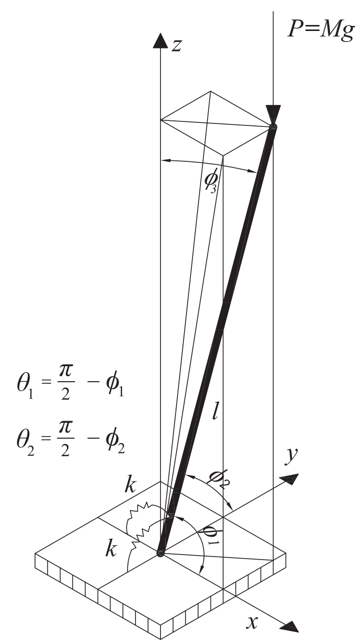

Fig. 1. Augusti's model. φ_i (i=1,2,3): the direction angles between the rod and, respectively, the x, y and z axes. θ_1 and θ_2:, the complements of the direction angles.

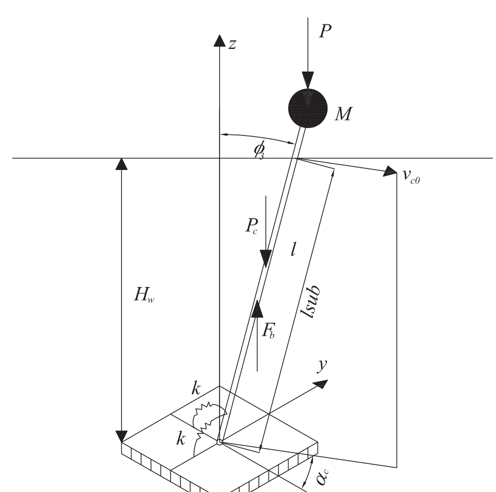

Fig. 2. Articulated tower model.

Download English Version:

https://daneshyari.com/en/article/8065183

Download Persian Version:

https://daneshyari.com/article/8065183

Daneshyari.com