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Analysis of nonlinear dynamics of fully submerged payload hanging from offshore crane vessel

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ABSTRACT

The nonlinear dynamic responses of a fully submerged payload hanging from a fixed crane vessel are investigated numerically. A three dimensional fully nonlinear time domain model based on the boundary element method is implemented to perform the analysis. Both the payload and fixed crane vessel are considered to be periodically excited by regular waves inside the numerical tank. The motion of the payload is found to exhibit various nonlinear phenomena (for example, sub-harmonic motion, period doubling behavior) due to the presence of fixed crane vessel. Analysis tools such as the phase trajectory, bifurcation diagram and Poincaré map are used to investigate the motion characteristics of this submerged payload which is undergoing constrained pendulum motions in various scenarios. Parametric studies are also performed by varying several design parameters in order to evaluate the sensitivity of the nonlinear phenomena. Different orientations of the crane vessel and submerged payload are also considered and the results obtained reveal several important conclusions concerning the dynamic behavior of the submerged payload of offshore crane vessel during operations. It is found that change of wave motion frequency coupled with various orientations of the floating barge and submerged payload significantly alters the payload motion behavior and introduces various nonlinear phenomena. The present study can be further extended to identify the limits of the operating conditions of floating cranes and to devise techniques to control or damp the unexpected motions of the submerged payload.

1. Introduction

Floating cranes are applied for a variety of tasks in offshore areas including transportation, assembling of costly structures and salvage operations. Efficient and safe operations of crane vessels at offshore are thus becoming increasingly important due to the increase in offshore activities particularly in deep water region and with a demand for higher lift capacity. Practical problems arise during crane vessel operations due to the difficulties in positioning accurately the payload being handled, which could result in collisions. Even small disturbances in the state of the system, for example caused by waves of a ship passing by, can entail the danger of collisions of the load with the ship or other objects. Besides, the amplitude of the motion of the hull has to stay small as well, in order to achieve the required positioning accuracy.

There exists considerable amount of literature devoted to the analysis and control of undesired motions of the crane payload hanging in air for example, Patel et al. (1987), McCormick and Witz (1993),Witz (1995), Balachandran et al. (1999), Cha et al. (2010). Linearized mathematical models to describe the dynamics of crane vessel in a wide range of operations are also reported in several papers such as Clauss and Riekert (1989, 1990 and, 1992), Clauss and Vannahme (1999). Among these, Clauss and Vannahme (1999) showed that the coupled system of floating crane and swinging load in air shows distinctly nonlinear phenomena and parametric oscillations can occur. They also concluded that under such conditions linear methods can not predict a heavy lift operation as those methods underestimate the occurring loads and motions. Another study performed by Liaw et al. (1992) found that one of the frequently encountered nonlinear behavior, namely sub-harmonic oscillations of many offshore structures can be attributed to the wave force-structure interaction. This fact was investigated by them both analytically and experimentally using an articulated tower model.

Ellermann and Kreuzer (1999, 2003) and Ellermann et al. (2002) on the other hand, studied the nonlinear dynamics of floating cranes from more practical point of view. They applied the potential theory to evaluate the dynamic responses of moored crane vessels in regular waves and compared the results with physical experiments. In the

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experimental part of their work, moored models of two different crane vessels were excited by regular waves in a wave tank (Ellermann et al., 2002). The hydrodynamic properties (added mass and radiation damping matrices) as well as hydrodynamic exciting forces on both vessels were computed using the software package WAMIT. The theoretical part of the work concerned a multi-degree-of-freedom mathematical modeling of the floating crane vessel where the hull and the payload were represented by rigid bodies. The mathematical description of the moored crane vessel was mainly based on the work of Jiang (1991) which involved the transformation of the frequency-dependent hydrodynamic radiation forces into the time domain by introducing additional state variables. In addition, in this model both the wave-vessel interaction and the hydrodynamic fluid loading on the hull were assumed to be linear so that superposition was applied.

Different mathematical tools have also been used in literature to investigate resonances and sub-harmonic motions, for example in Liaw (1988), Raghthama and Narayanan (2000), Ellermann (2005). The multiple-scale method is used for the analysis in frequency domain and the path following algorithms are applied for a numerical bifurcation analysis (Jiang, 1991). In general, periodically forced systems are found to exhibit different nonlinear phenomena ranging from periodic, sub-harmonic or quasi-periodic motion to chaotic behavior. Qualitative changes in the dynamics of the system also arise as parameters are varied. Some of these changes can be considered as critical with respect to the vessel safety and operating limits. Even if not all of these phenomena exist for a specific technical system, they can often be observed for some sets of parameters. With mathematical models of crane vessels including nonlinearities, it is possible to show that period doubling and chaotic behavior occur in the motion of the investigated systems.

As can be seen, all these previous studies so far only considered the behavior of the payload suspended in air. Most of these studies mainly focused on the analysis of crane vessels and ignored the motion of submerged payload in waves, as well as the influence of crane vessel on submerged payload motions. However, understanding of the dynamics of the fully submerged payload under nonlinear wave-structure interactions is quite important in order to ensure safe installation, especially when the payload is quite heavy compared to the vessel displacement. Furthermore, the installation process is a time varying problem and involves the wave interaction with a constantly moving payload. The use of traditional frequency domain analysis to solve this problem, therefore, might not be appropriate to obtain accurate results, because the Taylor series expansion adopted in the frequency domain analysis that expresses the boundary condition on the mean body surface is not applicable.

Therefore, a fully nonlinear time-domain numerical model was adopted in Hannan and Bai (2015) to simulate a submerged moving payload of a crane barge in water waves. The present study is a continuation to the same authors' previous work, but attempts to shed further light on the nonlinear dynamics of the payload. In Hannan and Bai (2015), the general hydrodynamic information, including forces and motions of the submerged payload were reported for different arrangements and scenarios. Whereas, in this work emphasis is given towards the insightful analysis of the nonlinear dynamics of payload motion behavior. Dynamic analysis tools such as the phase trajectory and the Poincaré map are used here to identify the motion characteristics of the suspended heavy submerged payload as it moves laterally or down towards the sea bed while influenced by the nonlinear waves and a fixed crane barge near to it, which is not available in literature till date.

Generally, the phase trajectory and the Poincaré map are widely used to explain the nonlinearity of various engineering systems. Applications of these tools in offshore engineering problems can also be found in literature. For example, Witz et al. (1989) used the Poincaré mapping to identify the region of chaotic motions in response of a semisubmersible to harmonic excitations. Yim and Lin (1991) investigated the rocking behavior and overturning stability of free standing offshore equipment due to support excitations using these techniques, while Lin and Yim (1995) studied the chaotic roll motion and capsize of ships under periodic excitations including random noises. Among more recent studies, Chen et al. (2014) applied the techniques of impact maps, Poincaré maps and phase portraits to explain the motion characteristics of the barge-deck system undergoing vertical impacts with the substructure. Their emphasis was on the modeling of float over installations of offshore structures. Gavassoni et al. (2015) on the other hand, studied nonlinear vibration modes of offshore articulated tower and applied the Poincaré mapping to detect the multiplicity of corresponding stable and unstable modes.

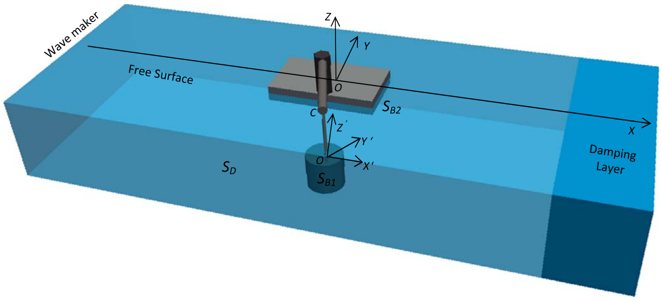

Fig. 1. Sketch of definition for the numerical model.

2. Mathematical formulation

A numerical wave tank defined in Fig. 1 is considered to simulate the above mentioned wave structure interaction problem. This numerical wave tank involves a wave maker (paddle to generate the wave) at the left end and a damping layer placed on the water surface to avoid the wave reflection from the far right end of the wave tank. The floating barge and its fully submerged cylindrical payload are placed near the middle of the tank. The cylindrical payload, hanging from the crane here is attached to a cable from the top to have constrained motions and subjected to the following nonlinear equation of motion (Bai et al., 2014):

$$-(f_x \cos \xi_5 - f_z \sin \xi_5)L = mL^2 \frac{d^2\xi_5}{dt^2}. \tag{1}$$

Here, m is the mass of the cylindrical body concentrated at its center of mass, and L is the distance between the rigid cable origin and the center of mass of the cylindrical payload. ξ_5 is the angular displacement of the vertical cylinder at the cable origin with respect to the vertical plane, f_x and f_z are the horizontal and vertical dynamic forces on the submerged cylinder respectively.

Two right handed Cartesian coordinate systems are defined. One is a space fixed coordinate system Oxyz having the Oxy plane on the mean free surface and the origin O usually at the center of the crane barge on the Oxy plane. In this case the z axis is positive upwards. The other is a body fixed coordinate system O$'x'y'z'$ with its origin O$'$ placed at the center of mass of the submerged moving body. When the body is in an upright position, these two sets of coordinate systems are parallel and the center of mass of the submerged body is located at $\mathbf{X}_g=(x_g, y_g, z_g)$ in the space fixed coordinate system.

Based on the assumption that the fluid is incompressible and inviscid, and the flow is irrotational within the fluid domain, potential flow theory can be used to describe this wave–body interaction problem, where a velocity potential $\phi(x, y, z, t)$ satisfies Laplace's equation within the fluid domain Ω,

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0, \tag{2}$$

and is subject to various boundary conditions on all surfaces of the fluid domain.

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