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Nonlinear dynamics of heave motion of the sandglass-type floating body with piecewise-nonlinear, time-varying stiffness

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ABSTRACT

In this paper, the dynamic behaviors and stability of the nonlinear heave response of the sandglass-type Floating Production, Storage, and Offloading unit (FPSO) under harmonic wave excitation force are studied. With consideration of the special shape characteristics, the heave restoring stiffness is modeled as a piecewise-nonlinear, time-varying (PNTV) function. The incremental harmonic balance (IHB) method in conjunction with the incremental arc-length method are employed to perform an elaborate investigation on its dynamic behaviors. Floquet theory is applied to determine the stability of the periodic solutions. The accuracy of the approach is verified through a comparison with the results of direct numerical integration using 4th-order Runge-Kutta method. Then, hardening-type nonlinearity of the heave motion is proved by parametric studies concerning the effects of damping ratio, wave excitation force, wave elevation and its phase difference with the wave excitation force on the nonlinear response. Based on this, a more reasonable approach considering frequency-dependent characteristic and memory effect of the hydrodynamic forces are established by the modification of traditional IHB method. The validity of the improvement is demonstrated by the widely used hybrid time-domain numerical simulation method in engineering application. Finally, by comparing the motion responses of two floating bodies with the corresponding linear heave RAO, the results show that even though the hardening-type nonlinearity can lead to the occurrence of unexpected severe heave motion, the wave-free characteristic of the heave motion for this type of floating body can suppress the development of the hardening-type nonlinearity and thus the established wave-free guideline is reasonable. Nevertheless, the frequency of the maximum RAO can exceed the wave-free frequency in the case of strong nonlinearity. Consequently, the nonlinearity of the heave motion should be fully considered and introduced in the existing design criteria.

1. Introduction

Centering on reducing heave motion response, enlarging deck area and suppressing vortex-induced motion (VIM), the sandglass-type Floating Production, Storage, and Offloading unit (FPSO) has been put forward recently [1]. Both the numerical and experimental results have shown that the sandglass-type floating body possesses excellent motion performance [2,3]. The inclined structure with external expansion and the small water-plane area make it possible to strike a balance between the stability and motion performance, which cannot be solved easily for traditional ship-type and cylindrical FPSOs [4].

Meanwhile, unlike the traditional ship-type and the recently developed Mono-Column FPSOs, such as the famous cylindrical

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FPSOs operating in Brazil [5] and North Sea [6] and the concept works by Rueda et al. [7], Campos [8] and Matsumoto et al. [9], which possess bluff body geometry near the water-line, the unique shape characteristic of the sandglass-type FPSO can result in significant and continuous changes in the instantaneous wet surface. Due to the existence and difference in the inclined angles of structures above and under waterline, the heave restoring stiffness shows piecewise nonlinear and time varying characteristic. According to the previously published studies in mechanical systems [10–12], the nonlinear systems with piecewise-nonlinear, time-varying (PNTV) stiffness can exhibit complex behaviors, such as softening or hardening type nonlinearity, multi-solution and chaos phenomena. Hence it is important to study the nonlinearity of the motion response for the sandglass-type FPSO.

Within the context of marine hydrodynamics, the study of the nonlinearity of such systems can be attributed to body nonlinearity. In general, the corresponding hydrodynamic problem can be dealt with by the time-domain simulation based on potential theory or Computational Fluid Dynamics (CFD) solvers [13,14]. Specifically, the dynamic response of the time-varying restoring stiffness can belong to the scope of Mathieu equation [15], which mainly relates to the parametric rolling of the containership [16] and the coupled heave-pitch motions of spar platform [17,18]. Silva and Soares [19] presented a time-domain non-linear strip theory model to simulate the parametric rolling resonance. Good agreement has been found between the time domain results and experimental data. Ahmed et al. [20] applied a three-dimensional (3D) partly non-linear time-domain numerical model to predict the parametric roll resonance for a range of vessel. The results obtained mostly compare reasonably with the experimental data. Studies for the ITTC-A1 containership demonstrated the capability of the method to capture the non-linear stiffness or hardening effect which started appearing once the wave amplitude hit a particular threshold. Zhou et al. [21] developed a hybrid method based on 3D CFD approach and potential theory method. According to the results, the CFD approach could achieve satisfactory agreements with the experiment for both roll damping and roll amplitude of parametric rolling. Liu et al. [22] established the coupled heave-pitch motion equations of Spar platform considering the effects of time-varying displacement and transient wave elevation. The results showed that the coupled motion responses were primarily dominated by wave height and the characteristic wave period, and the heave was underestimated if the transient wave elevation was neglected. As for the dynamic behavior of system with piecewise-nonlinear stiffness, the attention has been mainly paid to the mooring structures. Generally the numerical simulation of this type of problem is based on time domain due to the nonlinear nature [23,24]. Though the time-domain numerical simulation methods help us get insight into the inherent nonlinearities of the system, it is worth noting that one of the main features of nonlinear systems is the possibility in exhibiting multiple solutions for the same set of the characteristic parameters. The numerical simulation usually starts from one particular initial condition that lies in a particular domain of attraction. Coexistence of any other steady state solutions cannot be estimated without changing the initial condition. It is very time consuming to have a global picture of the response curve and bifurcations involved in the phenomenon using numerical simulations.

By contrast, an analytical approach is usually able to give such a global picture in a practical way. Perturbation technique, as the most widely used method, is often employed to handle the responses of nonlinear dynamical systems. Bulian [25] introduced the averaging method to estimate the roll amplitudes in frequency domain and assess the stability properties of the non-trivial steady state solutions by the Routh-Hurwitz criterion. Pesman and Taylan [26] adopted the same method to examine the influence of stability characteristics on roll motion in the main parametric resonance region. Hu et al. [27] designed a bifurcation controller to control the saddle-node bifurcation movements taking place in the ship's nonlinear rolling by the application of multi-scale method. Zhao et al. [28] employed multi-scale method to investigate the Mathieu stability of parametrically excited pitch motion of the conventional spar platform, and analyzed the stability of the trivial solution and steady-state response according to the Floquet theory. Zhao et al. [29] also used the multi-scale method to study the sum type combination resonance of a classic spar platform regarding the time-varying incident wave elevation as a parametric excitation. Choi and Lou [30] performed stability analysis of the articulated loading platform (ALP) by Harmonic balance method and Fast Fourier Transformation technique. The highly non-linear characteristics including subharmonics, instabilities, bifurcations, Lyapunov exponents etc. were examined. However, the weakness of classical perturbation methods restricts them to solve problem with weak non-linearities and within a narrow range of parametric variations. As the common assumption used in the study of parametric rolling, the frequency of the encounter waves is usually near the twice of the natural frequency of rolling.

The incremental harmonic balance (IHB) method is a powerful semi-analytical and semi-numerical method with many advantages. It is capable of dealing with strongly non-linear systems to any desired accuracy and ideally suited to large range parametric studies. It was originally proposed by Lau and Cheung [31], and many works on systems with piecewise-linear (PL) [32], piecewise-nonlinear (PN) [33] or time varying, piecewise-linear stiffness (PLTV) [34] have been fulfilled by IHB. Recently, Kong et al. [12] employed IHB method to analyse the dynamic and stability of the linear guide with PNTV stiffness, for which the piecewise function is just a function of the unknown displacement. For the heave motion of sandglass-type FPSO, given the shape characteristic, the PNTV restoring stiffness should be characterized as the function of both the wave elevation and the unknown displacement. Besides, for large-volume marine structures as the sandglass-type FPSO, the hydrodynamic forces are all frequency dependent and the radiation force exhibits obvious memory effect, which are very different from the forementioned mechanical system or the drag-dominated ALP. Therefore, the widely used IHB method still entails modification to account for the special features.

In the present research, the dynamic behaviors and stability of heave motion response of the sandglass-type FPSO are investigated by the IHB method and Floquet theory. The paper is organized as follows. In Section 2, the dynamic model of the heave motion of sandglass-type FPSO is formulated, where the restoring force is characterized as a PNTV function. In Section 3, the IHB method combined with the incremental arc-length method are developed to obtain the nonlinear response of the system, and the Floquet theory is used to analyse the stability of the solutions. In Section 4, hardening-type nonlinearity of the heave motion is proved by parametric studies. Based on this, a more reasonable approach by the modification of traditional IHB method with considering frequency-dependent characteristic and memory effect of the hydrodynamic forces are established to study the motion response in