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Stochastic extreme motion analysis of jack-up responses during wet towing

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ABSTRACT

This paper aims to perform stochastic motion analysis and the system probability estimation of exceedance in motion of a jack-up unit in wet tow mode to assess its safety in terms of its translational and rotational motions. When a jack-up unit is afloat and towed in seaways, it is important to determine the extreme motion response for the stability of the platform and to ensure the safety of equipment on the deck. This paper discusses the hydrodynamic characteristics and motion behavior of a jack-up unit with mat at a certain towing speed in various sea states with significant wave height ranging from 2 m to 5 m and wave directions ranging from 0° to 90°. The significant motion responses, such as heave, roll and pitch, are estimated by the frequency domain method. The probability of exceedance of the motion responses of the jack-up in random seas is estimated by means of system reliability analysis, considering wave overtopping, instability for roll, instability for pitch, and their series system. In order to efficiently determine the limit state exceedance probabilities due to time varying random variables, the Monte Carlo simulation technique and the subset simulation method have been employed in this study. The results from deterministic analysis and probabilistic analysis are comparably discussed, and the estimation of the extreme value statistics of motion responses in various sea states is provided. The approach developed in this paper can be applied to predict an unsafe condition of the jack-up and other platforms during wet towing in seaways supporting the officer's decisions on the action taken if excessive responses are foreseen for the present course and speed.

1. Introduction

A jack-up unit is an offshore structure composed of a hull, legs, footings, and self-elevating systems. The unit allows the platform to be towed to a site, to lower its legs into the seabed, and to lift its hull to support a stable work deck capable of withstanding the environmental loads. Generally, a jack-up unit operates in the three main modes: (i) the transit mode from one location to another, (ii) the elevation mode with its legs, and (iii) the jacking up or down mode between (i) and (ii). There are two main footing types: mat footings and spud cans (Zhao and Sun, 2014). Generally, mat footings exert a lower bearing pressure on the soil and provide considerable buoyancy than spud cans in the afloat transit mode (Vazquez et al., 2005). Based on this provided buoyancy, a jack-up can be transported from one location to another, taking the *wet tow* approach, in which the jack-up floats on its own hull and mat with its legs raised.

Many researchers have studied the dynamic response of a jack-up with footings on/into the seabed, and its structural risks during each stage of a jack-up deployment. Wang et al. Wang et al. (2014) applied sub-structural identification and genetic algorithms for the structural health monitoring of a jack-up unit in time and frequency domains. Vlahos et al. (2008) presented experimental investigation of the system behavior of a three-legged jack-up model on clay. Bienen and Cassidy (2006) advanced a three-dimensional fluid–structure–soil interaction analysis of offshore jack-up structures. Leira and Karunakaran (1995) analytically estimated fatigue damage and the extreme response exceedance probability of a jack-up platform with respect to relative operation time at two sites different in terms of wave environment and water depth. Jensen and Capul (2006) predicted the extreme response for jack-up units in the second order stochastic waves based on the theory of random vibrations and the first order reliability method (FORM). Jensen (2011) further investigated the

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reliability index estimation for overturning of a jack-up rig and a nonlinear wave induced hogging bending moment in a ship based on a FORM approach in combination with proper scaling function obtained from a Monte Carlo simulation analysis.

The management of risk for an in-situ jack-up is important, such as the drilling risks, the in-transit, jacking, and pre-loading phases of a jack-up under operation (Hunt and Marsh, 2004). In particular, a moving jack-up over long distances appears to be dangerous because it often encounters substantial risks, including a loss of towline or headway, green water damage, flooding, and capsize. World Offshore Accident Databank, commonly known as WOAD (Det Norske Veritas, 2007), even records that many jack-ups have been lost while afloat. Many jack-ups have sunk while they were under tow in the North Sea when a single vessel was used for tow. The well-known examples were *Rowan Gorilla I* located off the east coast of Canada when being towed by *M/V Smit London*, and *West Gamma* when being towed by *Normand Drott* (Gibson, 2000). As can be learnt from these examples, the roll and pitch motions of the platform can lead to various types of failures, ranging from seasickness and equipment shift to capsize of the platform. Also, green water will occur with a large heave, roll and pitch in uncalmed seas, causing severe structural and equipment damages. A tow analysis should be conducted to verify if a hull has sufficient buoyancy and stability to withstand the target motions, which can typically be defined as the probability of deck wetness, or a maximum pitch/roll angle at a given oscillating period, acting in conjunction with heave accelerations. As such, many studies regarding the development of stochastic analysis techniques for offshore platforms including a jack-up platform under transit condition have already been carried out. However, they have not been essentially extended to a reliability analysis of a specific jack-up model during a wet towing condition in practice considering the uncertainty in the stochastic wave input process and the joint-first passage probability of multiple limit states. In addition, few studies exist in the literature regarding the dynamic motion response of a jack-up unit with mat foundation in transit by the wet tow approach.

This paper aims to present the hydrodynamic performance of a jack-up unit in wet tow mode in terms of the events of wave overtopping and instability for roll and pitch and their system limit state exceedance condition by estimating the unit's responses and limit state exceedance probability. The analysis is targeting at evaluating the joint first passage probability of the jack-up unit's responses with respect to four limit states for these four kinds of events against a stochastic wave input process. This study considers extreme-motion related limit states that can be violated more likely in a system-level reliability estimation. This study limits the scope from the consideration of the structural failure, secondary or long term effects such as wind-load induced fatigue failure although they are important issues in a jack-up unit design (Shabakhty, 2011). Also, they should definitely be considered for a severe sea states mainly for permanent platforms, which will affect the structural integrity. Furthermore, stability issues regarding multiple compartment flooding is also an important issue especially for naval ships rather than commercial ships against a much higher load from extreme flooding events. They can be considered as additional limit states within the proposed framework if a proper analysis algorithm is available, but at the same time they also need to be analyzed based on the number of cycles to failure and have different nature and considered time range from the extreme response analyses.

The proposed analysis framework will be applied to a specific jack-up unit to be operating in Bohai Bay in China. These analysis results are denoted as decision support tools for the application jack-up unit, which are represented by dangerous sea states in terms of significant wave heights and wave headings. The results provided in this paper are useful to ensure the safety margins included in the design of the application jack-up unit under tow operation.

2. Theoretical background

A floating body in waves is normally assumed rigid and has six degrees of freedom motions named surge, sway, heave, roll, pitch, and yaw. In order to determine the floating body's responses, the following equations of coupled motions in various degrees of freedom are required to be solved.

$$\sum_{k=1}^{6}\left[(M_{jk}+A_{jk})\ddot{x}_k(t)+B_{jk}\dot{x}_k(t)+C_{jk}x_k(t)\right]=F_je^{-i\omega t}\quad(j=1,\cdots,6;k=1,\cdots,6) \tag{1}$$

where x_k is the kth motion of the six-degree of freedom motions; M_{jk} are the components of the generalized mass matrix for the structure; A_{jk} and B_{jk} are added mass and damping coefficients; C_{jk} are the restoring force coefficients; and F_j are the complex amplitudes of the exciting forces and moment-components with the force and moment-components given by the real part of F_j $e^{-i\omega t}$ (i is the complex unit). If the floating body has its forward speed, the wave frequency ω in the above equation is replaced by ω_e, which is the circular frequency of encounter obtained by:

$$\omega_e=\kappa(c-V\ \cos\ \mu) \tag{2}$$

where κ is the wave number, c is the wave speed of propagation, V is the forward speed of floating body, and μ is the wave direction with an angle relative to the jack-up's speed direction.

These hydrodynamic coefficients can be obtained by solving a boundary value problem for a velocity potential, which is usually called the potential flow theory (Newman, 1977). Since the motion is assumed harmonic, the solution can be performed both in the frequency domain and in the time domain. This study mainly employs the frequency domain analysis for the deterministic response estimations in Section 3, which has proven to be a suitable approach to provide reasonable predictions for analysis at preliminary stages of ship or floating platform motion control system design (Perez, 2005).

Short-term stationary irregular sea states can be expressed by a wave spectrum $S_\zeta(\omega)$, which is the power spectral density function of the vertical sea surface displacement. Through spectrum analysis, we can set up the mathematical models of the structural responses in a seaway, normally based on irregular and random waves, by using a superposition of regular wave components (Journée and Massie, 2001). A block diagram of this principle is shown in Fig. 1.

Many investigators have attempted to describe a wave frequency spectrum in terms of measured spectra or parameterized

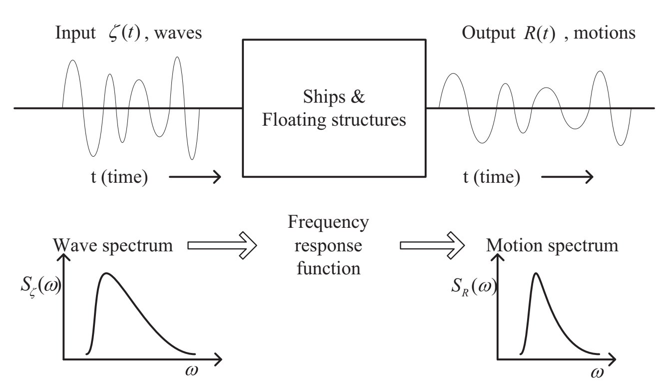

Fig. 1. Relation between sea waves and ship motions.