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# A combined first- and second-order theory for the deckwetness prediction of sandglass-type floating body in irregular head waves

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ABSTRACT

Deckwetness is one of the most important problems for seakeeping performance. With regard to the conventional ship-type Floating Production, Storage, and Offloading Units (FPSOs), the deckwetness depends on the relative vertical motion which is dominated usually by the first-order wave frequency loads. However, it can not apply to the deckwetness prediction of the sandglass-type FPSO since the influence of second-order slowly varying loads is remarkable. In this paper, a combined first- and second-order theory accounting for the first-order wave loads and nonlinear second-order slowly varying loads, is established to predict the deckwetness occurrence. By using the second-order Volterra series model, the relative vertical motion between the bow and incident wave surface can be described as a stationary non-Gaussian process. Then general formulas are derived for the prediction of the deckwetness occurrence for the sandglass-type floating body, based on the mathematical characteristics of the relative vertical motion process. As an application, the theory presented is discussed with reference to the deckwetness prediction of the sandglass-type floating model. Therein, a time domain analysis is employed to get the relative vertical motion response whereby the above formulas can be efficiently calculated. The influence factors including the length of the time simulation and the randomness of the wave phase are examined. Next, the convergence of the results is investigated with the increase of the order of non-Gaussian terms included in the formulas. By comparing with the experimental data, the reasonability and validity of the proposed method are proved.


## 1. Introduction

Deckwetness occurrence at high seas endangers the operation and crew safety for the Floating Production, Storage and Offloading unit (FPSO), thus its correct evaluation is one of the tasks of prime importance yet in the initial design stage.

For an FPSO moored permanently in a specified offshore oil and gas field, the heave, pitch and roll motions account for the vertical plane motion of the FPSO when dealing with the deckwetness problem. Probabilistic estimations of deckwetness are mostly applied in the deckwetness evaluation, following works of Ochi and Motter [1]. They utilized the assumption for Rayleigh distribution of relative motion amplitudes to calculate the probability and number of freeboard exceedance at the

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ship bow. Afterwards, the probability of deckwetness occurrence has been investigated by many researchers, and the linear potential flow theory combined with probability theory has been used successfully in most cases [2,3]. Therein, the assumption that the vertical motions are excited by the first-order wave frequency forces is usually adopted by the approaches. The rationality of the assumption can be found in the paper by Kim et al. [4] as well as in other papers. However, for the sandglass-type FPSO [5], the validity of the assumption remains to be doubted. Due to the distinctive configuration design, the floating body exhibits excellent hydrodynamic performance [5,6]. On the other hand, the natural frequencies of heave and pitch motions are so low [6] that there may exist resonance responses to the second-order slowly varying loads in heave and pitch modes. Consequently, the first-order wave frequency motions and second-order slowly varying motions should be considered in the prediction of deckwetness for the sandglass-type floating body when it encounters irregular waves.

Generally, the second-order slowly varying motions are considered in the horizontal motion modes (surge-sway-yaw) due to the existence of the mooring system in the context of marine structures. Over the past decades, considerable efforts have been directed toward establishing probabilistic methods of the analysis of the second-order slow drift response of compliant offshore structures in random seas, which were almost based on the work by Kac and Siegert [7]. Stansberg [8] investigated the statistical properties of slow drift motion response by using a spectral analysis of second-order responses. Naess [9] established an explicit, closed-form solution for the probability density function of the slow-drift response by extending the Kac-Siegert approach. Langley [10] explored the application of Gram-Charlier series expansion in the statistical distribution of the slow drift response. Meanwhile, a compliant offshore structure exhibiting second-order slowly varying response is often also showing significant first-order wave frequency response. For such structures, the problem of predicting the combined total response immediately presents itself. Naess and Johnsen [11] gave an explicit expression for the probability distribution of the combined first- and second-order slowly varying response using the saddle point integration technique [12]. Langley and McWilliam [13] presented a method yielding an analytic expression for the probability density function by a series expansion of the joint probability density function of the first- and second-order components of the response, obviating the need to calculate the full set of eigenvalues and eigenvectors of the transfer functions for the force or the response.

Though the probability distributions of pure second-order response or combined first- and second-order response have been well developed by the researchers, yet the distributions of other characteristic values, such as the peak or period of the response, cannot be derived directly through the forementioned distributions due to the complexity of the problem. Up to now, only the distribution of extreme response has been gained. Assuming that the extreme response statistics can be calculated using the Poisson assumption of independent peaks, the distribution of the extreme values can be expressed by the mean upcrossing rate. Notable contributions have been given: e.g., by McWilliam and Langley [14], Naess and Karlsen [15], Naess and Gaidai [16] and Zhang and Langley [17].

However, the problem of predicting the deckwetness occurrence for sandglass-type FPSO can be a kind of special. In terms of deckwetness, the occurrence of the deckwetness is usually defined as the peak of the relative vertical motion response process surpassing the freeboard at the bow, instead of the problem relating to the extreme response. Usually, the term "peak" refers to the pure local extrema of a time history, viz. the point where the first derivative of the time history is zero and the second derivative is negative. By contrast, the extreme problem belongs to the more global problem, involving the extreme value of the stochastic process during a fixed time interval, such as $0 \leq t \leq T$. To the author's knowledge, only a handful of papers with significance to the peak distribution of the combined first- and second-order response. Despite Vinje [18,19] has done some initial research on the problem, the statistical distribution of the local maxima was approximated by the function of upcrossing rate, ignoring the mathematical characteristics of peak occurrence. The problem associated with the peak distribution of combined first- and second-order response has so far not been solved.

In this paper we shall expound on the establishment of the peak distribution in connection with the deckwetness prediction accounting for the combined first- and second-order slowly varying response. The motion responses are expressed by a second-order stochastic Volterra series with Gaussian input. Thus the relative vertical motion between the bow and incident wave surface, which has close connection with the deckwetness occurrence, can be described as a stationary non-Gaussian process. Based on this, general formulas are developed for the deckwetness prediction by using the Gram-Charlier series expansions. Then the application of the present method is investigated with reference to the deckwetness prediction of sandglass-type floating body in irregular waves. Therein, a time domain analysis is employed to get the relative vertical motion response whereby the above formulas can be efficiently calculated. The variations of the probability of deckwetness and the number of occurrence per hour over different time simulation durations and random seeds of wave phase are examined. Next, the convergence of the results is investigated with the increase of the order of non-Gaussian terms included in the formulas. Finally, by comparing with the experimental data, the reasonability and validity of the proposed method are proved.

## 2. Representation of the combined first- and second-order force and response

### 2.1. Combined first- and second-order force induced by the waves

Over the years, considerable efforts have been put on the application of the second-order stochastic Volterra series in describing the motion response with Gaussian input. In this paper, the motion responses associated with the deckwetness are discussed within the same framework of second-order stochastic Volterra series model. Let $F_j(t)$ $(j = 1, ..., 6)$ represent the