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A hybrid time/frequency domain approach for efficient coupled analysis of vessel/mooring/riser dynamics

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Abstract

The dynamic analysis of a deepwater floating structure is complex due to dynamic coupling between the platform and the moorings/risers. Furthermore, the system response at the incident wave frequency and at the resonant low frequency is coupled due to geometric and hydrodynamic nonlinearities. As such, it is generally held that a fully coupled time-domain analysis should be used for an accurate prediction of the dynamic response. However, in a recent work, it is found that for an ultra-deepwater floating system, a fully coupled frequency-domain analysis can provide highly accurate response predictions. One reason is the accuracy of the drag linearization procedure over the motions at two time scales, another is the minimal geometric nonlinearity of the moorings/risers in deepwater. In this paper, the frequency-domain approach is investigated for intermediate water depths, and it is found that the accuracy reduces substantially as geometric nonlinearity becomes important. Therefore, a novel hybrid approach is developed, in which the low-frequency motion is simulated in the time domain while the wave frequency motion is solved in the frequency domain at regular intervals. Coupling between the two analyses is effected by the fact that (i) the low-frequency motion affects the line geometry for the wave frequency motion, and (ii) the wave frequency motion affects the modeling of the drag forces, which damp the low-frequency motion. The method is found to be nearly as accurate as fully coupled time domain analysis even for a system with a preponderance of nonlinear and coupling effects, but requiring only one-tenth of the computational effort.

Keywords: Floating structures; Coupled analysis; Time domain; Frequency domain; Linearization

1. Introduction

As the offshore oil and gas industry moves towards deeper waters, many proven shallow water technologies need to be revamped. In particular, the dynamic analysis of a deepwater floating production system is challenging due to several types of coupling inherent in the system, which are referred to here as Type 1 and Type 2 coupling. Type 1 coupling is the dynamic interaction between the platform, mooring lines and risers. This coupling is more pronounced in deepwater and requires a simultaneous analysis of the platform and all the connected lines. Type 2 coupling is between the mean offset, the response at the incident wave frequency (WF) and the response at the resonant low frequency (LF) excited by second-order difference frequency forces. The interdependency is caused by the geometric nonlinearity of the moorings and risers (hereinafter collectively referred to as *lines*) and the nonlinear drag forces. The presence of Type 2 coupling implies that the analysis of the mean offset, WF and LF dynamics cannot be separated. As a result of these complications, a fully coupled time-domain dynamic analysis that incorporates both types of coupling is held to be the only means of obtaining a reliable and cost-effective design. Many researchers have developed tools for fully coupled time domain analysis (e.g. Ormberg and Larsen, 1998), and today there are several commercial packages that employ this approach, such as DeepC (DNV Software, 2003a).

Notwithstanding the advances in computer hardware, the computational effort that a fully coupled time domain analysis demands is still far too excessive for routine design

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purposes. Owing to practical needs, a number of efficient methods have been proposed in the literature recently. A common characteristic of these methods is that efficiency is achieved by making certain approximations and assumptions regarding the treatment of the coupling effects. Several of these methods consider an uncoupled time domain analysis of the platform, modeling the lines as quasi-static springs, but enhance this model by applying the dynamic influence of the lines as equivalent linear damping and/or inertia coefficients. For example, Senra et al. (2002) proposed the use of a numerical decay test comprising a full model of the vessel and lines. The vessel is brought to an initial offset in each direction corresponding to typical vessel excursions and allowed to oscillate freely. From the decay response, the equivalent inertia and damping coefficients are estimated. However, mooring line damping is known to be highly complicated and not easily estimated by simple methods (Webster, 1995). This attribute is reflected in several limitations of the relatively straightforward decay test method, which fails to consider several important factors. Firstly, drag-induced damping is nonlinear and thus dependent on the amplitude of the oscillation, which is unknown a priori; moreover, the logarithmic decrement used to estimate the damping ratio also depends on the choice of successive peaks. Secondly, the dominant effect of WF line dynamics on damping is neglected. Thirdly, energy dissipation from other rigid-body modes is ignored; for example, heave motions can affect surge damping considerably (Wichers and Huijsmans, 1990). Lastly, line damping can be strongly dependent on the vessel offset due to changes in the line geometry and the associated dynamic behavior, as will be demonstrated later in this paper. Senra et al. (2002) recognized this point and suggested an improvement by performing the decay test over a range of static positions and interpolating to obtain the instantaneous damping based on the vessel offset during time domain analysis. Other approaches for estimating constant line damping coefficients have also been proposed. These methods typically calculate the energy dissipated in forcing a line through a complete slow drift oscillation. It should be mentioned that some or all of the limitations highlighted above are also inherent in these quasi-static approaches, even relatively sophisticated ones such as Liu and Bergdahl (1998) and Bauduin and Naciri (2000). Recently, Lie et al. (2007) presented a simplified efficient method for estimating a constant line damping coefficient that accounts for both the WF and LF line dynamics (i.e. Type 2 coupling is considered). It was shown that the method is conservative as it consistently underestimates the damping coefficient within a maximum error of 30%.

In the search for efficient methods, the frequency domain approach is appealing. However, coupled analysis in the frequency domain has so far received little attention compared with the time domain. One reason may be the need to make approximations regarding the treatment of nonlinearities, whose effects on accuracy may be difficult to assess. In a recent work, Low and Langley (2006) have developed computer programs for analyzing the coupled dynamic response of floating structures in both the time and frequency domain. The analysis tools were implemented on a spread-moored FPSO in 2000 m water depth, and a seastate corresponding to $H_S = 100$ m was selected for the simulations. The vessel motions and line tensions predicted by the two approaches agreed surprisingly well, and the favorable performance of the frequency domain approach was attributed to two factors. Firstly, the dynamic impact of geometric nonlinearity generally decreases with increasing water depth, since the size of the mooring system increases, whereas the wave-induced motions remain roughly constant. For the water depth considered in the test case, geometric nonlinearity is minimal even for extreme storm conditions. Secondly, the linearization procedure is based on minimizing the mean-square error of the relative velocity over the entire spectrum, which includes the WF and LF parts. Considering that the relative velocity is dominated by the WF component, it is not obvious that the linearization scheme is ideal for the LF drag forces on the lines, which are critical for the damping of the LF resonant vessel motions. Fortunately, it was also demonstrated analytically that the linearization scheme does indeed provide an optimal estimate to both the WF and LF parts of the drag forces. This finding is consistent with the results from numerical simulations.

On one hand, the highly efficient frequency domain coupled analysis provides the accuracy and efficiency needed for the analysis of ultra-deepwater floating systems that are not governed by geometric nonlinearity. On the other hand, the traditional two-staged uncoupled analysis has long been held to suffice for shallow water floating systems whereby the dynamic influence of the lines can be considered to be negligible. However, coupling and geometric nonlinearity are not necessarily mutually exclusive, and there are systems for which both effects are influential. One example is a floating system installed in an intermediate water depth and is attached to an extensive riser system. For such a system, it is possible that neither of the above methods is adequate.

In this paper, the accuracy of coupled frequency domain analysis is investigated for a floating system in 200 m water depth. It is shown that frequency domain analysis suffers considerable loss of accuracy when geometric nonlinearity is significant. Geometric nonlinearity affects the system response by two main mechanisms. Firstly, the restoring forces of the vessel due to the mooring lines are affected. Secondly, large changes to the line configuration affect the dynamic response characteristics and therefore the damping levels provided to the vessel. There is a need to develop efficient and accurate coupled analysis tools to cater to this complex scenario.

The LF motions are non-Gaussian due to second-order wave forces, governed by position-dependent damping effects and can be large, thus exercising the geometric