Nonlinear wave diffraction and radiation around a ship-shaped FPSO in oblique seas

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1. Introduction

Greenwater on deck is a complex phenomenon that involves highly nonlinear wave-floating vessel interactions. It is one of the most important design and operational considerations for the cost effective and safe use of ship-shaped FPSOs [1]. Even accurate prediction of the freeboard exceedance, the first stage of greenwater overtopping, is a challenging task due to its inherent complexity associated with nonlinear hydrodynamics [2]. Yet accurate predictions are necessary to assess greenwater susceptibility and ultimately to provide reliable estimates of greenwater loading.

The nonlinearity in the relative wave-vessel motion (and hence freeboard exceedance) could result from nonlinearities in local (disturbed) wave and/or vessel motions, and their nonlinear interactions. As yet, contributions from each individual nonlinear process, and their combined effects, remain unclear. Stansberg and Karlsen [3] found that the relative wave-vessel motion statistics can be well described by the linear Rayleigh model since the nearly linear pitching motions are dominant. In contrast, Buchner [2] argued that the pitch motion is nonlinear due to the effect of water on deck, and has an effect opposite to the non-linearity in local wave peaks that leads to an increase in the relative wave-vessel motions. Ruggeri et al. [4] state that the vessel motion can be nonlinear regardless of the water on deck, in particular in steep waves. Obviously, a more thorough investigation is required to verify the influence of nonlinear effects.

Our present work investigates wave runup around, and greenwater overtopping of, a representative FPSO hull using CFD-based numerical modelling complemented by diffraction analysis. CFD modelling should be able to capture all the various nonlinear effects involved, however, its application in practical engineering design is challenging. Previous work [5] showed that the measured run-up on the bow of a simplified fixed model was entirely consistent with 2nd order diffraction theory. The sum and difference terms were both important and the difference term corresponded to a substantial and persistent mound of water formed around the bow. The main purpose of this work is to examine if 2nd order theory is accurate enough for the prediction of wave diffraction and radiation around a freely floating ship-shaped body, with emphasis on accurate extraction of the harmonics. This would allow the development of a simpler model for fast estimation of greenwater risks. A fixed model is also analysed for comparison.

2. Results and discussion

Here, the OpenFOAM CFD scheme is utilized with the toolbox ‘waves2Foam’ for greenwater simulations [6]. This model was previously validated for greenwater overtopping over a fixed FPSO model in head seas [7]. Now, we consider a simplified FPSO subject to oblique seas, and the model is either fixed or freely-floating (Figs. 1-2). The vessel heading, the vessel direction relative to the incident wave, is 30°. In line with the global geometry of real FPSOs, L/D = 16 and L/B = 5.5, where L is the length of the vessel, D the draft and B the width. And f/D ~ 0.55, where f = 0.055 m is the freeboard.

A design wave group causing maximum relative linear wave-vessel motion at the bow is identified [8] and used as the CFD input. Changing the absolute phase of the input wave group allows extraction of the higher harmonics in wave-structure interactions using either ‘phase-inversion’ [9] or the four-phase based decomposition methods [10]. The assumed underlying sea-state has a JONSWAP spectral shape with a peak wave period of 1.05 s, and the peak wave amplitude is 0.05 m at 1:200th lab-scale (so ~14.85 s and ~10 m at full scale). In this case, large freeboard exceedance will be a result of pitch motion that is out of phase with local wave motion. Linear diffraction analysis is also performed using the Hydrostar code from Bureau Veritas. The extracted 1st harmonic components from CFD simulations are compared with linear predictions, and then the nonlinear wave run-up around the FPSO is examined.

2.1 Verification of the first-order solutions

Fig. 1 shows time series of the linear wave run-up around the fixed FPSO from both CFD and the linear diffraction analysis. The results of the linear undisturbed waves calculated without the structure in place are also included. It is clear that for the cases with waves slightly off the bow, the wave crest is amplified along the weather side of the vessel as waves approach the hull and reflect. In contrast, a reduction of passing wave fronts on the sheltered side is observed. Both the CFD model and the linear diffraction analysis capture this evolution. It is worth noting that the wave crest amidships at the weather side just exceeds the freeboard level but this is not large enough to induce any significant overtopping (the middle figure). But overtopping along the side could happen if vessel motions are allowed and the vessel stern pitched down when the wave crest reaches the mid-ships.

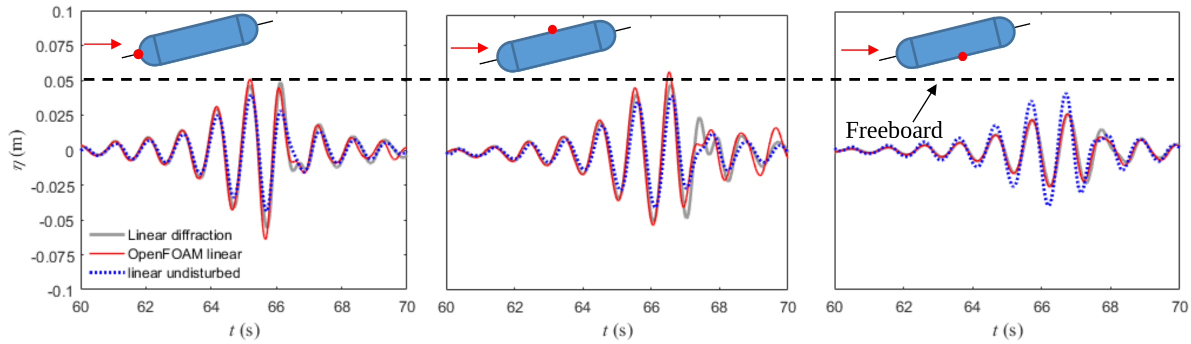

Fig.1 Time series of the linear wave run-up around the fixed FPSO. The locations of the wave gauges are shown on the top left of each figure. The black dashed line indicates the assumed freeboard, and red arrows indicate the wave approaching direction.

The vessel motion is now released for the heave and pitch DOFs as these are most important for greenwater overtopping at the bow. The extracted 1st harmonic CFD-based vertical displacement of the bow is compared to the linear Hydrostar solution in Fig. 2 left. Greenwater overtopping occurred around the bow area as expected due to the vertical motion occurring out of phase with the local wave crests, as shown in Figs. 1 and 2 left. Indeed, the vessel is pitching with the stern moving downwards when the wave crest reaches the mid-ships as shown in Fig. 2 (d). However, overtopping at the sides does not happen. The amplification observed for the fixed vessel (Fig. 1 middle) is weakened by the radiated waves and the vessel motion. Clearly, both the vessel heading and motions are important for estimating greenwater risks. The 1st harmonic OpenFOAM result deviates slightly from the linear diffraction solution after t = 66.5 s (Fig. 2 (b)) when water overtopping onto the deck occurs. The total moment acting on the vessel now consists of the wave exciting moment and the moment due to greenwater on deck. The ratio of the latter and the former is non-negligible as stated in [2], and the main effect is on the pitch motion. This is confirmed by comparisons of the pitch and heave motions individually (not given here for brevity, to be shown at the workshop). Overall, the level of agreement with the linear diffraction solution is rather satisfactory.

2.2 Higher order wave diffraction around a fixed ship-shaped FPSO

Fig. 3 left shows the harmonic structure of the run-up at the bow of a fixed FPSO in time, and the spatial distribution of the various harmonics at two times (when the relative wave-vessel motions are maximum at the bow and amidships at the weather side, respectively) are shown in Fig. 3 right. There is relatively weak diffraction of the incoming linear component. The 2nd harmonic difference term is observed to form a local hill at the bow and this is in phase with the linear component, as presented in [10]. This decreases the effective freeboard. Interestingly at this moment, the 2nd harmonic sum term is however out of phase with both linear and 2nd harmonic difference terms, visible as a plane blue set-down in the right snapshot. An opposite trend is observed amidships at the weather side where the 1st and 2nd harmonic sum terms are in phase (Fig. 3 rightmost snapshots), resulting in a larger wave run-up here. Both 2nd harmonic sum and difference terms are important, with the contribution of 2nd order terms ~20% of the linear 1st harmonic component. All harmonics higher than 2nd are small, less than ~5%. These results imply that 2nd order theory is a potentially useful approximation, capturing much of the local free-surface displacement around the FPSO as well as the hull motion.

Clear in the snapshots in Fig.3 are rings of higher harmonic waves scattered around the bow, and a significant interaction occurs off the weather side of the model as the higher harmonic bound components of the incident wave and part of the diffracted ones cross. Then there is strong diffraction around the stern of the model, leading to higher harmonic components propagating back upstream along the sheltered side (this is clearer for the relatively weak 3rd and 4th harmonics).

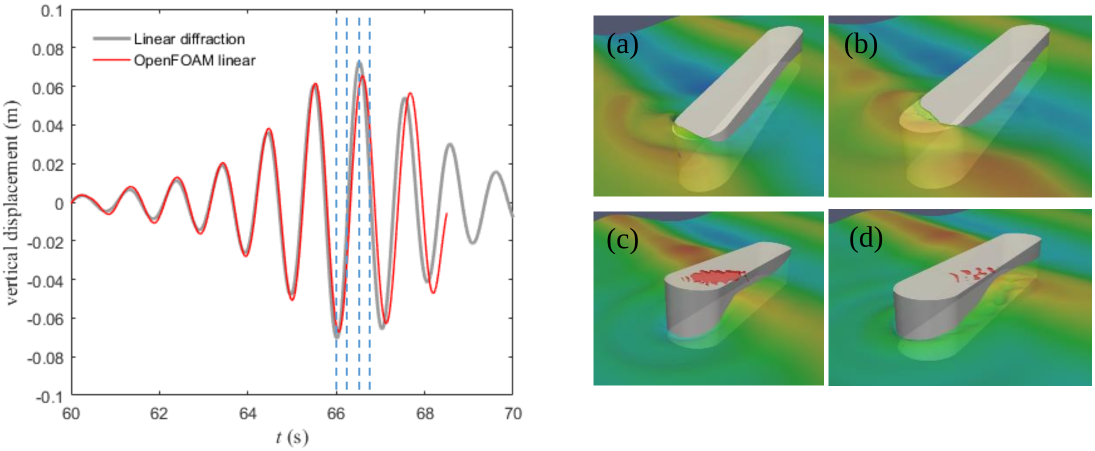

Fig. 2 Time series of the linear vertical displacement of the bow of the floating FPSO. The snapshots on the right indicate the free surface elevation (visualised from CFD) at various instances indicated by dashed lines; from left to right corresponds to (a) - (d).

3. Conclusions

CFD-based numerical modelling is found to be an effective tool for exploring the physics of wave-structure interaction leading to the onset of greenwater on deck for a simplified FPSO geometry. Using the 4-phase decomposition method, all the harmonic interactions up to (at least) the 4th are resolved. The verified models are utilized to demonstrate that both 2nd order difference and sum harmonic terms would lead to wave run-up at significantly higher levels than expected. Additionally, there are no large higher harmonics beyond 2nd order, which indicates that 2nd order diffraction theory may be accurate enough to justify development of an advanced screening tool that would reduce statistical uncertainty in random sea-states. At present widely used screening tools for greenwater are generally based on linear wave theory. Further results will be presented at the workshop, including the results of physical model tests (at Dalian, due in Feb. 2019).

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References

[1] Health and Safety Executive (HSE), 2005. Findings of an expert panel engaged to conduct a scoping study on survival design of floating production storage and offloading vessels against extreme metocean conditions. Research Report NO: 357.

[2] Buchner, B., 2002. Green water on ship type offshore structures (Ph.D. thesis), Technische Universiteit Delft.

[3] Stansberg, C.T., Karlsen, S.I., 2001. Green sea and water impact on FPSO in steep random waves, Paper 1135, In: Proc. PRADS'01 Conference, Shanghai, China, September.
[4] Ruggeri, F., Watai, R.A., de Mello, P.C., Sampaio, C.M.P., Simos, A.N. and de Silva, D.F.D.C., 2015. Fundamental green water study for head, beam and quartering seas for a simplified FPSO geosim using a mixed experimental and numerical approach. Marine Systems & Ocean Technology, 10(2), pp.71-90.
[5] Zang, J., Gibson, R., Taylor, P.H., Eatock Taylor, R., Swan, C., 2006. Second order wave diffraction around a fixed ship-shaped body in unidirectional steep waves. Journal of Offshore Mechanics and Arctic Engineering, 128 (2), pp. 89-99.
[6] Jacobsen, N.G., Fuhrman, D.R., Fredsøe, J., 2012. A wave generation toolbox for the open-source CFD library: OpenFOAM. Internat. J. Numer. Methods Fluids 70, 1073–1088.
[7] Chen, L., Taylor, P.H., Draper, S. and Wolgamot, H., 2019. 3-D numerical modelling of greenwater loading on fixed ship-shaped FPSOs. Journal of Fluids and Structures, 84, pp.283-301.
[8] Chen, L., Draper, S., Wolgamot, H., Taylor, P.H., Milne, I.A., 2018. Greenwater evaluation for FPSOs during cyclones. In: 2018 Offshore Technology Conference Asia. Offshore Technology Conference, OTC 28538.
[9] Baldock, T.E., Swan, C. and Taylor, P.H., 1996. A laboratory study of nonlinear surface waves on water. Phil. Trans. R. Soc. Lond. A, 354(1707), pp.649-676.
[10] Fitzgerald, C., Taylor, P.H., Eatock Taylor, R., Grice, J., Zang, J., 2014. Phase manipulation and the harmonic components of ringing forces on a surface-piercing column. Proc. R. Soc. A. 470, 941 20130847.

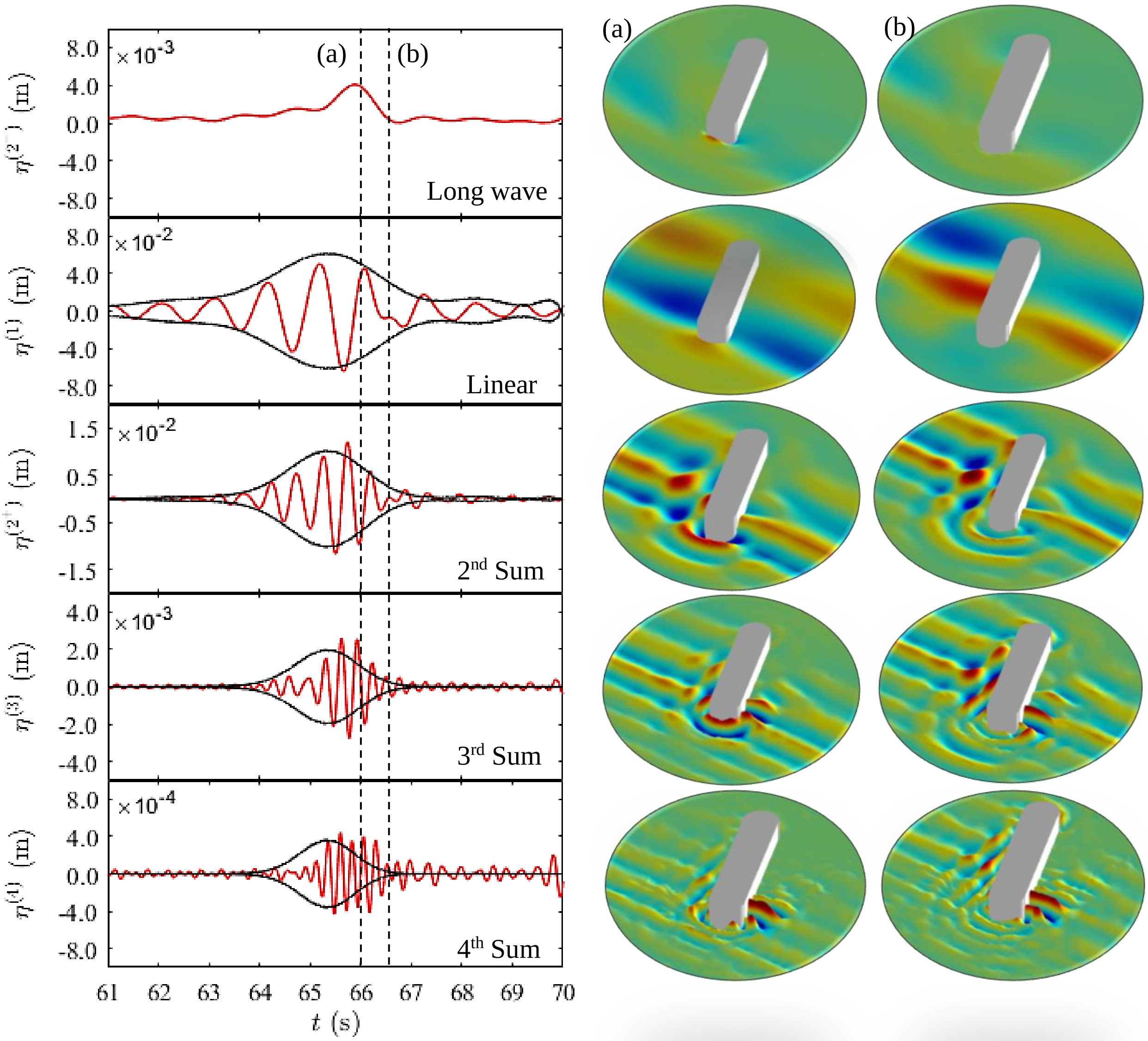

Fig. 3 Harmonic structures of the free surface elevation at the bow of the fixed FPSO in time (left), and their spatial distributions (right) at two significant instants (a) and (b) in order from top: 2nd harmonic diff., linear (1st harmonic), and 2nd, 3rd and 4th harmonic sum terms. The white arrow indicates the wave approaching direction. The magnitudes of the 2nd and higher harmonics are scaled up to improve visibility.