Nonlinear wave runup on a FPSO bow causing greenwater events

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1. INTRODUCTION

Wave runup and possible greenwater flow on the deck of a FPSO (Floating Production Storage and Offloading) unit in harsh environments is an important safety problem. An accurate description of the relative wave runup/wave-vessel motion around the bow, an essential input to greenwater assessment, is required to obtain a reliable prediction of greenwater occurrence and loading.

To date, no generalized method is available to estimate relative motions due to the complexity inherent in the wave-structure interactions. The Rayleigh distribution has been used with the assumption of narrow-banded linear motion response [1]. However, the statistical analysis of Soares and Pascoal [2] suggested that the crest distributions of local (disturbed) waves (hence the relative wave-vessel motion) deviate significantly from the Rayleigh model, though the FPSO motions (pitch and heave) are essentially linear. Cox and Scott [3] stated that the probability distribution for the wave crests upstream of a fixed horizontal plate can be well described by a second-order nonlinear model. Buchner [4] proposed a modified Rayleigh distribution for calculating the nonlinear relative wave-vessel motion in front of a FPSO bow. Nonlinearity is approximated by assuming that the nonlinear relative motion is a third order polynomial function of the linear solution, similar to the perturbation method following a Stokes expansion. In contrast to Soares and Pascoal [2], Buchner [4] and Ruggeri et al. [5] argued that the vessel motion can be nonlinear.

Chen et al. [6] applied the idea of a Stokes-like approximation to extreme wave runup around a simplified FPSO hull in transient wave groups, representative of individual extreme wave events. The higher harmonic components across the full spatial domain are identified, for (we believe) the first time, by applying a separation method based on phase manipulation of the results from CFD simulations. The generalization is supported by comparison to diffraction analysis up to 2nd order. It is found that only linear and 2nd harmonic (both low- and high-frequency components), and possibly 3rd harmonic, are important for wave scattering around the hull. For body motion, the linear responses are dominant.

The possible application of the methodology in Chen et al. [6] to a wider range of wave conditions and vessel headings (of practical interest) is explored experimentally in this work. It is also our aim to provide a benchmark/useful experimental dataset for validating existing numerical methods, such as 2nd order diffraction analysis and CFD simulations.

2. EXPERIMENTAL ANALYSIS

2.1 Experimental setup

A series of physical model tests on nonlinear wave runup around a representative FPSO were carried out at Dalian University of Technology, China. A wave flume measuring 60 m (length) by 4 m (width) was used, and the water depth was set to 1 m to ensure deep water conditions. A numerically controlled piston-type wave paddle was used to generate transient wave groups and a wave absorbing beach was installed at the end of the wave flume for minimizing reflected waves.

As shown in Fig. 1, a simplified FPSO that has a semi-circular bow and stern was moored in a horizontal soft spring mooring system (spring stiffness was 5.85 N/m at the 1:200 laboratory scale) and was free to move with six degrees of freedom. The main dimensions of the model FPSO were: 1.6 m (length), 0.29 m (width), and 0.175 m (height). The draft was 0.1 m and the radii of gyration in roll and pitch at lab-scale were 0.0936 m and 0.4473 m, respectively. It is noted that the greenwater events are not intended in this work; a large vertical freeboard in the form of clear and stiff plastic sheet was used in the experiments reported herein to avoid greenwater. The effect of water on deck, so tests with the sheet removed, was also investigated and will be reported in the future.

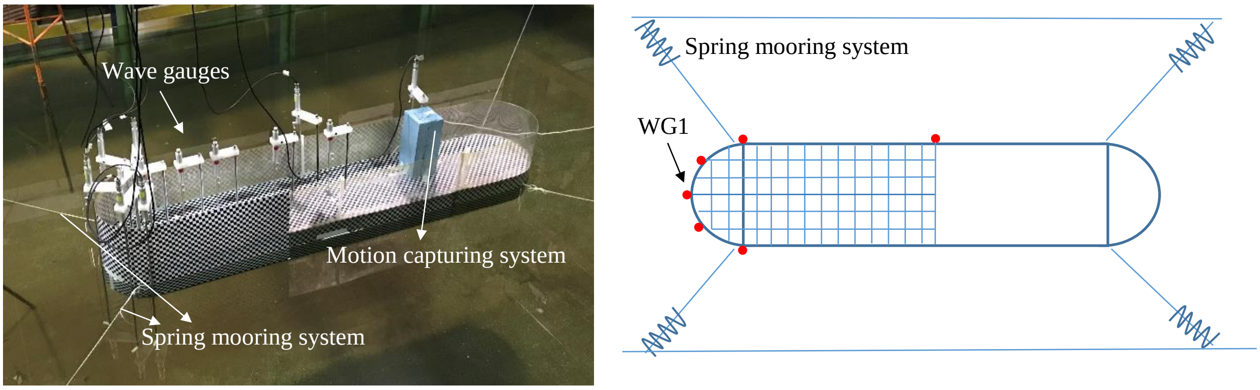

Fig. 1 Experimental setup. Left: Photo from the experiments; Right: Schematic experimental setup. Dots represent wave gauges fixed to the vessel measuring the relative motion, and the wave incident from the left.

The incident wave field characterized in § 2.2 is based on the records at wave gauge 1 (WG1) for tests without the model FPSO in place. Relative wave runup was measured at the various wave gauges located around (and fixed to) the hull; the locations of the wave gauges are shown in Fig. 1 right. FPSO motions were measured with an optical motion capturing system, as shown in the photo of Fig. 1.

2.2 Incident wave field

Only long-crested waves can be created in the flume, and the model was oriented to achieve desired wave incident angles, i.e. 0, 10 and 30 degrees relative to the model centreline. The assumed underlying sea-state had a JONSWAP spectral shape with $\gamma = 3.3$. The spectral peak wave periods ranged from 0.96 to 1.15 s, in line with the least desirable sea-states for greenwater identified by the response-based analysis for the model geometry within the framework of linear wave theory [7]. These corresponded to wave conditions that would excite resonance in both the pitch and roll response of the vessel considered. The incident wave group was calibrated to have a certain shape at the location of the model so as to excite the desired response [7]; in this work, maximum linear relative vertical wave runup at the bow. In order to apply the separation method of Fitzgerald et al. [8], four different wave groups were generated using the same paddle signal, but with each component shifted by a relative phase of 0, 90, 180, or 270 degrees, respectively. Example undisturbed wave shapes for the case with a spectral peak period of 1.05 s are shown in Fig. 2 left.

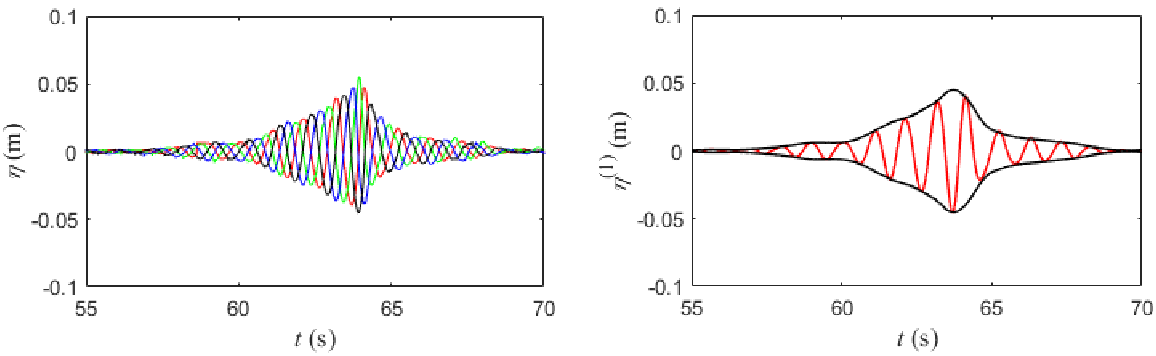

Fig.2 Time series of the free surface elevation measured at the location of WG1 without the model FPSO in place. Left: The full signals for all four wave groups; Right: the corresponding extracted linear wave component (red line) and its envelope (black line). The spectral peak wave period is 1.05 s and $A_f = 0.035$ m.

The undisturbed wave field was characterized at the position where the model FPSO would be mounted, i.e. the location of WG1 in Fig. 1. Based on the time series at WG1, the actual peak of the linear envelope in time can be obtained using the separation method of [8], as shown in Fig. 2 right. This is defined as A_f, and the local wave slope $A_f k_f$ at WG1 was varied from 0.07 (small, close-to-linear waves) up to 0.33 (large, nearly breaking waves). If the phase separation method works for our analysis and similar findings as in [6] hold, the methodology proposed for the nonlinear relative wave motion, i.e. the free surface corrected to 2nd order allowing for linear vessel motions, should be valid for practical use, at least for the simplified hull geometry used here.

2.3 Spectral decomposition of nonlinear wave runup at the bow

The phase-based separation method of [8] is applied to the measured relative wave-vessel motion and the FPSO motion to investigate the respective nonlinear contributions from each underlying nonlinear process, i.e. nonlinearity in local waves and vessel motions. Example extracted harmonic structures are shown in Fig.3. Similar phenomena as Chen et al. [6] are observed; the sizes of low- and high-frequency 2nd harmonic components are comparable (left; relative motion), and the former forms a local set-up around the bow, decreasing the effective freeboard. A nearly linear vessel motion is found (shown on the RHS of Fig.3), with contribution from higher-order harmonics less than 2% for this particular case, and the 3rd and 4th harmonics are so small that they are contaminated by noise. This confirms that the nonlinearity in locally diffracted and radiated waves rather than vessel motion is the key mechanism for the excitation of nonlinear extreme wave runup.

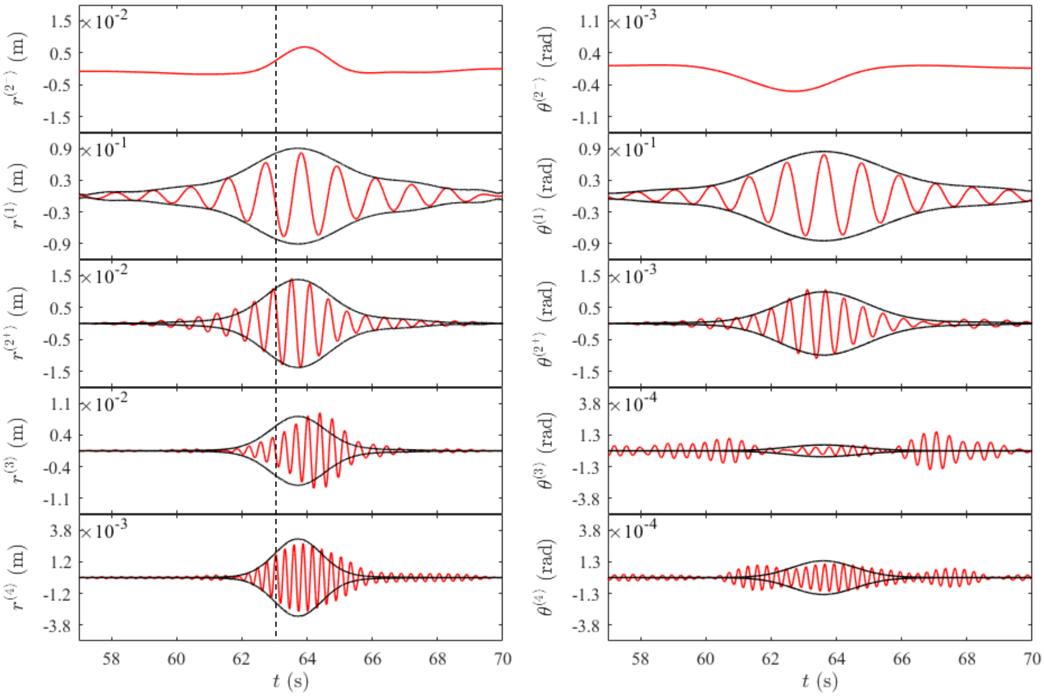

Fig. 3 The harmonic structures of the relative wave-vessel motion at WG1 (left) and the pitch motion (right) in time in order from top: low-frequency 2nd harmonic, linear, high-frequency 2nd harmonic, 3rd and 4th harmonics. The peak wave period is 1.15 s and A_f = 0.037 m. The vessel heading is 0 degree. Also shown is the envelope of the linear component, scaled and raised to the appropriate power for each of the sum harmonics.

The relative contributions of the higher-order harmonics up to the 3rd harmonic are investigated for the relative wave-vessel motion in Fig. 4 for a wide range of wave conditions (3 wave incident angles and 11 wave steepness, hence, 33 cases in total). The result for the 4th harmonic is not shown for brevity and because they provided little contribution (see e.g. Fig. 3). The linear component always dominates the higher harmonic wave runup, although its relative value decreases with increasing local wave steepness. The 2nd harmonic (both low- and high-frequency components) are found to be important; the contribution is larger than 10% of the total wave runup even for the smallest, close-to-linear wave considered. For certain wave cases, linear runup is less than 70% of the total wave runup, with higher-order harmonics contributing more than 30%. All harmonics higher than 2nd are however relatively small, less than 6% of the total wave runup except for the two steepest waves considered. The vessel bow was observed to be lifted above the disturbed water surface for these two waves, and the subsequent slamming may result in the increased contribution of local high frequency components. Investigating the effects of bottom slamming is beyond the scope of this work, so is left for future work.

Similar analysis has been undertaken for the vessel motion (not shown here for brevity). It is found that the vessel motion is essentially linear even for the large nearly breaking waves; the contribution of the higher harmonic motions is smaller than 5% for all cases considered. This is similar to Soares and Pascoal [2]; they performed a statistical analysis on nonlinear random waves, while we are focused here on individual and isolated extreme wave groups.

These experiments extend as well as confirm the results obtained in Chen et al. [6], providing further insight into the nature of extreme runup on the hull of a ship-shaped FPSO. They support the potential use of 2nd order diffraction analysis for developing an engineering screening tool for greenwater assessment in random sea-states.

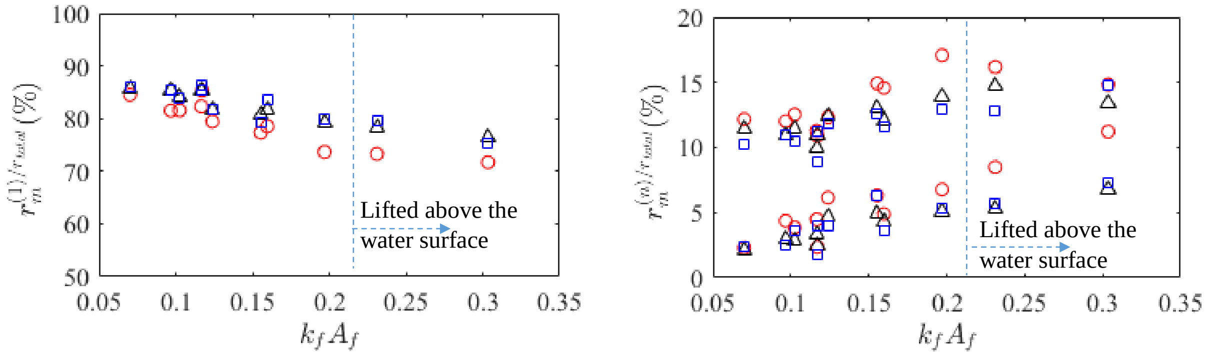

Fig. 4 Contributions of higher harmonic wave runup at the location of WG1 for all wave conditions considered. Left: linear component; right: 2nd harmonic (*n* =2 top) (both low- and high-frequency components) and 3rd harmonic components (*n* = 3 bottom). Red circles are results for a vessel heading of 0 degree, black triangles 10 degrees, and blue rectangles 30 degrees. $r_m^{(n)}$ is the peak of the envelope of the *n*th harmonic.

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REFERENCES

[1] Ochi, M. K., 1964. Extreme behavior of a ship in rough seas: slamming and shipping of green water. *Transactions*, *72*, Society of Naval Architects and Marine Engineers.

[2] Soares, C. G., and R. Pascoal, 2002. Experimental study of the probability distributions of green water on the bow of floating production platforms, *Journal of Offshore Mechanics and Arctic Engineering*, 127, 234-242.

[3] Cox, D. T., and C. P. Scott, 2001: Exceedance probability for wave overtopping on a fixed deck. *Ocean Engineering*, 28, 707-721.

[4] Buchner, B., 1998. A new method for the prediction of non-linear relative wave motions. In *Proc.of the 7th International Conference on Behaviour of Offshore Mechanics and Arctic Engineering*. June 1998, Lisbon.

[5] Ruggeri, F., Watai, R.A., de Mello, P.C., Sampaio, C.M.P., Simos, A.N. and e 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.

[6] Chen, L., Taylor, P.H., Draper, S., Wolgamot, H., Cheng, L. and Ning, D.Z., 2019. Nonlinear wave diffraction and radiation around a ship-shaped FPSO in oblique seas. In *34th IWWWFB*, Newcastle, Australia.

[7] Chen, L., Taylor, P.H., Draper, S., Wolgamot, H., Milne, I.A. and Whelan, J.R., 2019. Response based design metocean conditions for a permanently moored FPSO during tropical cyclones: Estimation of greenwater risk. *Applied Ocean Research*, 89, pp.115-127.

[8] Fitzgerald, C.J., Taylor, P.H., Eatock Taylor, R.., Grice, J. and Zang, J., 2014. Phase manipulation and the harmonic components of ringing forces on a surface-piercing column. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 470(2168), p.20130847.