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1 **Study on green water prediction for FPSOs by a practical numerical approach**

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Abstract

The growing usage of permanently moored floating production storage and offloadings (FPSO) in harsh environment regions increases the frequency and severity of the green water problem. Many numerical researches on green water prediction for FPSOs have been carried out. Most of the past researches chose to neglect or consider only part of the effects by appendages and attachments, such as bilge keel, mooring lines, and risers. The influences of these appendages on green water prediction have not been thoroughly studied. This paper presents a practical numerical approach of green water prediction for FPSOs in irregular waves. The calculation of relative wave elevation is conducted in frequency domain, including linear and nonlinear effects of bilge keels, spread mooring system, and asymmetrically arranged risers. Numerical approach was applied to calculate the statistical distribution of relative wave elevation for an FPSO. Comparison with experimental results showed that the accuracy of relative wave motion prediction is significantly improved by incorporating the linear and nonlinear effects of bilge keels, mooring, and risers. Analysis of the results by different numerical models further indicated that the relative wave elevation at sides of the FPSO in oblique waves was strongly affected by bilge keel, mooring, and risers.

Keywords: FPSO green water; Relative wave elevation; Quadratic damping linearization; Asymmetric risers.

1 Nomenclature

2	ζ_0	Incident wave elevation
3	$\zeta_{1\sim 6}$	Radiation wave elevation
4	ζ_7	Diffraction wave elevation
5	ω	Frequency
6	b	FPSO breadth
7	$\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}$	Vessel motion, velocity, and acceleration matrix
8	$x_{1\sim 6}$	FPSO vessel motions
9	z	Vertical motion of target location on FPSO due to vessel motions
10	$\mathbf{M}$	Generalized mass matrix
11	$\mathbf{A}$	Added mass matrix
12	$\mathbf{A}_{\text{rad, bk, m, riser}}$	Added mass matrix due to radiation, bilge keel, mooring lines, and risers
13	$\mathbf{A}_{\text{asym}}$	Added mass matrix due to asymmetric risers
14	$\mathbf{B}_1$	Linear damping matrix
15	$\mathbf{B}_{\text{rad, bk, m, riser}}$	Linear damping matrix due to radiation, bilge keel, mooring lines, and risers
16	$\mathbf{B}_{\text{asym}}$	Linear damping matrix due to asymmetric risers
17	$\mathbf{B}_2$	Quadratic damping matrix
18	$\mathbf{B}_{\text{qbk, m, riser}}^{\text{q}}$	Quadratic damping matrix due to bilge keel, mooring lines, and risers
19	$\mathbf{B}_{\text{Lin}}$	Equivalent linearized damping matrix from quadratic damping
20	$\mathbf{K}$	Stiffness matrix
21	$\mathbf{K}_{\text{hs, m, riser}}$	Stiffness matrix due to hydrostatics, mooring lines, and risers
22	$\mathbf{K}_{\text{asym}}$	Stiffness matrix due to asymmetric risers
23	$\mathbf{F}_w$	Wave excitation matrix
24	$\mathbf{V}_{\text{rms}}$	Root-mean-square velocity matrix
25	$V_{\text{rms}}^{\text{riser}}$	Root-mean-square heave velocity at the location of riser connector
26	R_{sig}	Significant relative wave elevation
27	R_{MPM}	Most probable maximum relative wave elevation
28	T_Z	Wave mean zero crossing period

1	S_{η}	Power spectral density of incident wave
2	$S_{\eta\eta}$	Response spectral density of relative wave elevation
3	M_0, M_2	Zeroth and second moment
4		
5		
6		

1 Introduction

1.1 Green water assessment

Floating production storage and offloading units (FPSOs) moored in harsh ocean environments often encounter “green water” incident, which is a nonlinear local phenomenon caused by large relative movement between a ship and wave. When a green water incident occurs, the water exceeds the freeboard and runs up over the ship deck. The growing usage of permanently moored offshore floating platform in harsh environment regions increases the frequency and severity of the green water problem. A number of green water impacts occurred on Norwegian production ships during 1998 to 2000 (Ersdal and Kvitrud, 2000), causing damage risk to various topside structures and outfitting equipment, as described below.

- Norne ($L_{pp} = 242$ m, water depth = 380 m) encountered a green water event at aft of mid-ship leeward side, in the sea state with $H_s = 7.5$ m and $T_p = 13$ s. Fire equipment storage and a crane were damaged.
- Asgard A ($L_{pp} = 278$ m, water depth = 300 m) encountered green water impact at mid-ship tank deck, in the sea state with $H_s = 7$ m, $T_p = 12$ s, and 10 min mean wind speed of 31 m/s. Fire equipment stock, piping to fire hydrant, steel cabinets, rails on deck, and cable trays were damaged.
- Varg B ($L_{pp} = 200$ m, water depth = 84 m) was once damaged by green water at mid-ship. Modification had been done, and the vessel was renamed “Petrojarl Varg” in 1999. However, in January 2000, green water damage was reported at fore, mid, aft ship, and living quarter of the vessel, in a sea state with $H_s = 12.5$ m and $T_p = 14.5$ s. The reported damage included water ingress into rooms from broken window and ceiling as well as damaged, deformed, and missing equipment and outfitting.
- Balder FSU ($L_{pp} = 200$ m, water depth = 127 m) experienced moderate green water incident during the winter season of 1999–2000.

Although the green water incidents rarely threat the survival of FPSOs, they can cause damage to equipment and structures, threat the safety of crew, and cause economic loss due to repair and production downtime.

There are mainly three numerical approaches to assess green water threat for ships and FPSOs. The first and fastest approach is to calculate the statistical distribution of relative wave elevation and freeboard exceedance and compare with criteria of on-board water height or deck wetness probability. In this approach, several safety criteria have been proposed, including deck wetness frequency below 30 hits/h (Karppinen, 1987; Smith and Thomas, 1989; NATO STANAG 4154-2000), deck wetness probability below 0.05 (Nordforsk, 1987; Faltinsen, 1990), or freeboard exceedance of 3 and 6 m as threshold for low/medium and medium/high risk of green water (Morris, Millar and Buchner, 2000). A detailed review of researches using this approach is provided in the next subsection.

The second approach is to evaluate the on-board green water hydrodynamics, including deck pressure, flow speed, impact loads, or water amount, based on a two-step method. The freeboard exceedance is first calculated via a method same as the first approach. Instead of assessing the results directly, the freeboard exceedance is then used as input to analyze the local interaction between green water and structures. The on-deck green water may be modeled by dam-break theory (Goda et al., 1979; Vermeer, 1980) or shallow-water theory (Dillingham, 1981; Greco, Lugni and Faltinsen, 2014; Greco et al., 2015). Based on this approach, many efforts have been made to derive analytical and empirical

formulas to predict hydrodynamic loads caused by green water flow, which can be found in Buchner (1995, 2002), Hamoudi and Varyani (1994), Ogawa (2003), Greco (2001), Kapsenberg and de Kat (2000), and Stansberg and Berget (2009). Alternatively, there have also been researches that used CFD methods for the local interaction between green water flow and structures, including Pham and Varyani (2005), Shibata and Koshizuka (2007), and Pakozdi et al. (2014).

The third approach is to perform CFD simulation for the entire event, including the global body motions in waves and local interaction between green water flow and structures. Examples of this approach can be found in Le Touze et al. (2010) with SPH method and Ostman et al. (2014) with VOF method. The advantages of this approach are its consistency and accuracy. However, to correctly capture the local behavior of the green water flow, very fine mesh is needed, which leads to high computational cost. Some attempts, such as fixed or pre-calculated vessel motion (Wan and Wu, 1999; Nelsen and Mayer, 2004; Zhu et al., 2009; Guo et al., 2010) and domain decomposition (Greco et al., 2004), have been made to reduce the computational cost. However, this approach is not yet feasible for practical engineering design purpose and may only be applied for detailed study of one specific incident.

As explained above, while the direct CFD approaches were considered less practical, the first two approaches of green water assessment both require the prediction of relative wave elevation. As recognized by Buchner (1998), accurate prediction of relative wave elevation is therefore critical for the evaluation and analysis of green water problems. This paper focuses on the numerical calculation of relative wave elevations for FPSOs. A detailed review of past research on this subject is provided below.

1.2 Numerical prediction of relative wave elevation

There have been many researches focusing on the relative wave elevation prediction for ships. Ochi (1964) calculated the statistical distribution of relative wave elevation for a mariner class cargo ship model. The good agreement between numerical results and measurements indicated the validity and encouraged the application of potential theory in relative wave elevation calculations. Following his work, methods based on potential theory have been dominating the calculations of relative wave elevation. The most simplified method is based on linear strip theory and to calculate relative wave elevation by using ship motions and undisturbed incident wave profile (Bales, 1977). More advanced methods may account for one or more of the below effects:

- Disturbance on incident wave profile due to radiation and diffraction;
- Viscous damping, mainly for transverse motions of the vessel;
- Three dimensional effect of the hull.

Dillingham (1981) conducted calculation in time domain based on impulse response function method using strip theory. The roll damping coefficient measured from free roll decay test and quadratic sway damping calculated from frictional drag of flat plate were included. Lee (1982) presented a numerical method based on strip theory for predicting the relative wave elevation responses, including the effects of wave disturbance due to diffraction and radiation. Grochowalski (1982) calculated the statistical distribution of free board exceedance with consideration of the diffraction and radiation waves. Nonlinear roll damping was considered by adding a linearized viscous damping coefficient based on the mean resonance amplitude. Kapsenberg and de Kat (2000) calculated the relative wave motion for a cargo ship advancing in irregular waves with different headings, using 3D panel method (PRECAL) in frequency domain. Only the diffracted wave disturbance was considered when

calculating the relative wave elevation. Viscous damping was not considered. Carette and van Walree (2010) evaluated the relative wave elevation of a DDG51 navy ship model in time domain, using commercial software FREDYN, based on the hydrodynamic coefficients pre-calculated by strip theory (SHIPMO).

With the rapid development of offshore oil and gas industries, more researches have been published focusing on the relative wave elevation predictions for FPSOs. Buchner (1995) analyzed the relative wave elevation at bow of an FPSO model in regular and irregular head waves in frequency domain, using linear 3D panel method (DIFFRAC), with consideration of radiation and diffraction waves. In this study, Buchner recommended to include the vertical stiffness and weight of mooring systems into the simulation for real projects. This method was further developed by Buchner (1996, 1998, 1999 and 2002), Buchner and Garcia (2003), and Buchner et al. (2002) and was integrated in the MARIN software GreenLab. Applications of this method can also be found in HSE UK (2001) and Fyfe and Ballard (2003). Stansberg and Berget (2009) used 3D potential flow software (WAMIT) to analyze relative wave elevation RAOs from solved ship motion and disturbed wave profile. Based on the frequency domain results, an in-house code Waveland/Kinema was then used to generate the time-domain simulation, including adjustment for second-order wave component and local wave particle kinematics. The simulation was further corrected by some semi-empirical approaches for nonlinearities due to bulwark and limit water volume before the velocity and impact load of green water on deck was calculated. The software Kinema was further developed to extend applicable wave directions and was used to study green water on FPSOs in Santos Basin (Schiller et al., 2014). In Pakozdi et al. (2014), the selected relative wave elevation and freeboard exceedance (corrected by Kinema3) were used to setup local CFD simulation for critical green water event by using VOF-based software Star-CCM+. Greco et al. (2015) proposed a 3D domain-decomposition approach, combining a weakly nonlinear potential flow solver with a 2D shallow-water approximation of shipped water. In this method, the mooring lines were simulated as quasi-static nonlinear cables; viscous damping on mooring lines and FPSO hull were obtained from free decay test measurement; bilge keel damping was evaluated with Ikeda's method. This approach was applied to analyze the parametric roll and water-on-deck event of an FPSO in regular head and bow waves.

Theoretically, the calculation of relative wave elevation for FPSOs is essentially same as for ships. However, there are two challenges that make the calculation for FPSOs more difficult. One challenge is that the 3D effect is more significant due to blunt hull geometries of FPSOs. This challenge can be accounted for by adopting 3D panel methods, which have been already used by most of the past researches on FPSOs. The other challenge is the linear and nonlinear effects caused by appendages and attachments. An FPSO vessel is usually attached with bilge keels, mooring lines, and risers. For spread mooring FPSOs, beam sea can often be encountered, which makes the linear and nonlinear effects of these appendages and attachments more significant. There have been researches considering part of these effects, including viscous damping caused by bilge keel, stiffness, and damping of the mooring systems. However, the effects on relative wave elevation caused by the appendages and attachments have not been fully studied.

In the present paper, the statistical distribution of relative wave elevation for an FPSO was predicted based on a 3D panel method. The calculation was performed in frequency domain, including added mass, stiffness, linear and nonlinear damping caused by bilge keels, spread mooring system, and unsymmetrical risers. Through comparison with model tests results, the accuracy of the present method and the effects of the appendages and attachments have been investigated.

2 Methodology

In the present method, relative wave elevation is calculated by using the ship motions and the disturbed wave profile, including undisturbed incident and diffracted and radiated waves.

$$R(\omega) = \zeta_0 + \sum_{i=1}^6 \zeta_i(\omega) + \zeta_7(\omega) - z(x_3(\omega), x_4(\omega), x_5(\omega)) \quad (1)$$

The motion of the vessel is expressed in the form of Eq. (2):

$$(\mathbf{M} + \mathbf{A})\ddot{\mathbf{x}} + (\mathbf{B}_1 + \mathbf{B}_2|\dot{\mathbf{x}}|)\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}_W \quad (2)$$

where

$$\mathbf{A} = \mathbf{A}_{rad} + \mathbf{A}_{bk} + \mathbf{A}_m + \mathbf{A}_{riser} + \mathbf{A}_{asym}$$

$$\mathbf{B}_1 = \mathbf{B}_{rad} + \mathbf{B}_{bk} + \mathbf{B}_m + \mathbf{B}_{riser} + \mathbf{B}_{asym}$$

$$\mathbf{B}_2 = \mathbf{B}_{bk}^q + \mathbf{B}_m^q + \mathbf{B}_{riser}^q$$

$$\mathbf{K} = \mathbf{K}_{hs} + \mathbf{K}_m + \mathbf{K}_{riser} + \mathbf{K}_{asym}$$

$\mathbf{A}_{rad}$, $\mathbf{B}_{rad}$, and $\mathbf{F}_W$ are obtained from the solutions of the classic boundary value problems of radiation and diffraction. In this paper, the commercial software ANSYS® AQWA™ is used, which is based on 3D panel method. By solving the radiation and diffraction problems, ζ_{1-7} in Eq. (1) can also be obtained.

$(\mathbf{A}_{bk} + \mathbf{A}_m + \mathbf{A}_{riser})$, $(\mathbf{B}_{bk} + \mathbf{B}_m + \mathbf{B}_{riser})$, and $\mathbf{B}_2$ can be obtained by analyzing the results of free decay tests. Bilge keel damping may also be calculated empirically by using various empirical formula based on experiments (Himeno, 1981; Kawahara et al., 2008, 2012; Falzarano et al., 2015). Damping caused by mooring and risers can also be calculated using lump-mass type dynamic line model with Morison drag and added mass defined on each element. Free decay tests may also be performed numerically by using CFD (Veer et al., 2011; Yang et al., 2012; Avalos et al., 2014; Ommani et al., 2016).

$\mathbf{K}_m$ and $\mathbf{K}_{riser}$ are calculated based on static catenary theory, using AQWA.

As motion Eq. (2) contains nonlinear term $\mathbf{B}_2$, the equation is solved iteratively with stochastic linearization of $\mathbf{B}_2$. The quadratic damping term can be transformed to an equivalent linear damping term by harmonic linearization method (Vossers, 1962; Vassilopoulos, 1971; Faltinsen, 1990) or stochastic linearization method (Borgman, 1967; Vassilopoulos, 1971; Gachet et al, 2008; Veer et al., 2011). Stochastic linearization is valid for systems as Gaussian process and is often used for ship motion analysis in irregular waves. Therefore, it is used in the present method, as below.

$$\mathbf{B}_{Lin} = \mathbf{B}_2 \sqrt{\frac{8}{\pi}} \mathbf{V}_{rms} \quad (3)$$

An iterative approach is adopted to calculate $\mathbf{B}_{Lin}$ and $\mathbf{V}_{rms}$. The motions of the vessel and thus relative wave elevations can be obtained when convergence reached.

Asymmetrically arranged risers can couple the roll and heave motions. Following the proposal by Ferreira et al. (2012), the equivalent damping coefficients for heave-roll coupling effect caused by asymmetric risers can be calculated as below.

$$\mathbf{B}_{asym} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & B_{34} & 0 & 0 \\ 0 & 0 & B_{43} & B_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

where

$$B_{34} = B_{43} = (B_{33} + B_{33}^q \sqrt{\frac{8}{\pi}} V_{rms}^{riser}) \cdot \frac{b}{2}; \quad B_{44} = (B_{33} + B_{33}^q \sqrt{\frac{8}{\pi}} V_{rms}^{riser}) \cdot \left(\frac{b}{2}\right)^2$$

B_{33} is the heave damping coefficient due to risers, which can be found in $\mathbf{B}_{riser}$;

B_{33}^q is the heave quadratic damping coefficient due to risers, which can be found in $\mathbf{B}_{riser}^q$;

V_{rms}^{riser} is the root-mean-square heave velocity at the location of the riser connector.

The mathematical formulation derived from the concept of roll-heave force coupling is not restricted to linear damping only, but can also be extended to stiffness and added mass.

$$\mathbf{A}_{asym} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{34} & 0 & 0 \\ 0 & 0 & A_{43} & A_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (5)$$

where

$$A_{34} = A_{43} = A_{33} \cdot \frac{b}{2}; \quad A_{44} = A_{33} \left(\frac{b}{2}\right)^2$$

$$\mathbf{K}_{asym} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{34} & 0 & 0 \\ 0 & 0 & K_{43} & K_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

where

$$K_{34} = K_{43} = K_{33} \cdot \frac{b}{2}; \quad K_{44} = K_{33} \left(\frac{b}{2}\right)^2$$

A_{33} and K_{33} are the heave added mass and stiffness due to risers, which can be found in $\mathbf{A}_{riser}$ and $\mathbf{K}_{riser}$.

It is worth to mention that in the original proposal by Ferreira et al. (2012), only the linear damping coefficient B_{33} was used to represent the asymmetric effect caused by risers in frequency domain. The present study has also considered the contribution from heave quadratic damping and asymmetric added mass and stiffness, following a similar approach.

After solving the motion equations, vertical motions at designated locations can be obtained. Thus, relative wave elevation $R(\omega)$ in Eq. (1) can be calculated in frequency domain. The power spectral density of relative wave elevation is then calculated as

$$S_{\eta\eta}(\omega) = \left[\frac{R(\omega)}{\zeta_0} \right]^2 \cdot S_{\eta}(\omega) \quad (7)$$

The most probable maximum (MPM) and significant value of relative wave elevation in a typical 3 h sea state can be then obtained as

$$R_{sig} = 2 \sqrt{M_0(S_{\eta\eta})} \quad (8)$$

$$R_{MPM} = R_{sig} \cdot \sqrt{\frac{1}{2} \ln \left(\frac{3hr}{T_Z} \right)} \quad (9)$$

where

$$M_0(S_{\eta\eta}) = \int S_{\eta\eta}(\omega) \cdot d\omega,$$

$$M_2(S_{\eta\eta}) = \int S_{\eta\eta}(\omega) \cdot \omega^2 \cdot d\omega,$$

$$T_Z = 2\pi \sqrt{\frac{M_0}{M_2}}.$$

The flow chart of the numerical method used in this paper is summarized in Figure 1.

3 Green water prediction of a spread mooring FPSO

3.1 FPSO model and experiment conditions

The above presented method was applied to calculate relative wave elevation for a spread mooring FPSO model, with risers arranged at port side. The main particulars of the model are shown in Table 1. The layout of mooring lines and risers are shown in Figure 2. Experiments for this model have been carried out (Figure 3). Table 2 presents the test cases. Relative wave elevations at seven locations along the ship were measured. The locations are presented in Figure 4.

3.2 Numerical calculations

3.2.1 Quadratic damping linearization

Quadratic damping coefficients due to bilge keel, mooring lines, and risers were obtained by analyzing free decay tests conducted in the above experiments. They were then linearized using Eq. (3) with an iterative approach. Comparison of the root mean square of roll velocity between numerical and experimental results is presented in Figure 5. It can be seen that the roll velocity has been reasonably well predicted by stochastic linearization method.

3.2.2 Asymmetric risers

As explained above, the effect of asymmetric risers is considered. The roll response spectra in beam sea with and without the effect of asymmetric risers are presented in Figure 6, together with results from fully coupled time-domain simulation. It is clear that the proposed method agrees well with fully coupled time-domain results, whereas the one without considering asymmetric risers showed

large difference. Ferreira et al. (2012) also considered the asymmetric risers effect in frequency domain and were not able to obtain a good result. The reason could be that in Ferreira's paper, only linear damping coefficients of the asymmetric risers were considered, whereas the present study includes quadratic damping, added mass, and stiffness caused by asymmetric risers.

3.3 Relative wave elevation results and discussions

To analyze the influences of the appendages and compare different levels of numerical modeling, the results of four numerical models have been presented. The details of the numerical models can be found in Table 3. Model B includes only the catenary stiffness of the mooring system; Model C includes other hydrodynamic effects caused by bilge keel, mooring, and risers; Model D considers the asymmetric riser effect.

Comparison of 3 h most probable maximum relative wave elevation (MPM-RWE) between different numerical models and model test results are shown in Figures 7 to 10. The normalized root-mean-square error (NRMSE) is presented in Table 4. Both figures and NRMSE results clearly show that by considering more effects from bilge keels, mooring, and risers, better accuracy can be achieved. Numerical Model D gives the best estimation for relative wave elevation, with significant improvement in accuracy compared with numerical Models A and B. Therefore, to adequately capture the complicated behavior of the FPSO motion and relative wave motion in various sea states, the additional stiffness, added mass, damping, and asymmetric riser effects are recommended to be included in the numerical simulation.

The MPM-RWE results in various wave directions are further compared in Figures 11 to 15. In Figures 11 and 15, the differences between RWE by different numerical models are generally negligible, indicating that the influence of bilge keel, mooring, and risers is not significant to the green water evaluation in head and stern sea conditions. This result also indicates that the green water risk in head and stern sea conditions is not likely to be reduced by design of bilge keel, mooring, and risers.

In Figures 12 to 14, the differences between RWE by numerical Models A, B, and C, D are rather significant. By including additional added mass, damping and stiffness of bilge keel, mooring, and risers, numerical Models C and D showed good agreement with experiment results, whereas numerical Models A and B failed to predict RWE with good accuracy. It is evident that the RWE estimation in oblique wave and beam-sea conditions is strongly affected by the damping and added mass of the appendages, whereas the effect of catenary stiffness of the mooring system is less important. It may also be concluded that bilge keel, mooring, and risers can possibly help to reduce green water at sides of the ship, in oblique and beam wave conditions.

3.4 Effect of stiffness, added mass, and damping of roll motion

Comparison of Figures 11 to 15 also shows that the effect of appendages and attachments on RWE results are highly related to transverse motions. To further explore the effect of bilge keel, mooring, and risers, the additional stiffness, added mass, and damping of roll motion, as relative ratio to the value of the corresponding coefficient of the vessel, are presented in Table 5. Comparison of the ratios indicates that the increase in damping coefficient due to appendages and attachments is most pronounced, which is consistent with the large difference between Models A, B and Models C, D, as observed in Figures 12 to 14. Additional roll damping appears to be the most critical term in considering the effect of bilge keel, mooring, and risers on the relative wave motion.

In addition, comparisons on the roll RAOs of different models are presented in Figure 16 to unveil the effects of added mass and stiffness. The results of five different models in beam-sea condition are presented: a. Model C; b. Model C without additional stiffness; c. Model C without additional added mass; d. Model C without additional stiffness and added mass; e. Model D. The additional stiffness, added mass, and asymmetric effect from risers affect the roll motion in both amplitude and resonance frequency. It can be concluded that in Model C, the effect of additional stiffness is less significant than that of added mass. This coincides with Table 5, where the ratio of additional added mass is larger than the ratio of additional stiffness.

4 Conclusions

Green water prediction is carried out on a spread mooring FPSO with proposed numerical approach. The numerical approach is based on 3D panel method and accounts for linear and nonlinear effects caused by bilge keel, mooring lines, and risers. The calculation is conducted in frequency domain with an iterative approach. The statistical prediction of relative wave elevation in irregular waves showed good agreement with model test results. The proposed method can be used as a practical tool for preliminary green water assessment in the early design stage of an FPSO.

The main conclusions of this paper are summarized as below.

- In general, by including additional added mass, stiffness, linear and quadratic damping from bilge keel, mooring lines, and risers, the statistical prediction of relative wave elevation can be significantly improved. Therefore, these effects shall not be neglected in green water prediction.
- The numerical results have shown that the relative wave elevation response in beam sea and oblique waves can be largely influenced by the damping of appendages and attachments; the effects by additional stiffness, added mass, and asymmetric terms are less significant in amplitude, but introduce more complexity to the response.
- On the other hand, for head and stern waves, the appendages and attachments generally do not affect the relative wave elevation.
- In oblique and beam waves, bilge keel, mooring, and risers can possibly help to reduce green water at the sides of the ship.

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Table 1 Main particulars of the FPSO model.

PRINCIPLE DIMENSIONS	UNIT	VALUE
Displacement	ton	122637
Operation water depth	m	277
Draft	m	14.62
Transverse metacentric height	m	5.36

Table 2 FPSO model test cases.

Test no.	Wave direction
1, 2	180° Head sea
3–5	135° (From Port Side)
6–9	90° (From Port Side)
10	45° (From Port Side)
11–12	0° Stern sea

Table 3 Definition of numerical models.

Numerical model	A	B	C	D
Radiation and diffraction	√	√	√	√
Catenary stiffness		√	√	√
Diagonal added mass, linear and quadratic damping			√	√
Asymmetric risers				√

Table 4 Normalized root-mean-square error.

Numerical model	NRMSE
Model A	1.836
Model B	1.550
Model C	0.296
Model D	0.215

Table 5 Relative magnitude of additional roll stiffness, added mass, and damping.

	Stiffness	Added mass	Linear damping	Quadratic damping*
Base of Ratio	Hydrostatic stiffness of the vessel	Ixx + Radiation added inertia of the vessel	Radiation damping of the vessel	Radiation damping of the vessel
Bilge Keel	--	14%	32%	740.33%
Spread Mooring	5%	8%	122%	290.99%
Portside Risers	2%	6%	0%	21.75%
Total	7%	28%	153%	1053%

*Quadratic damping is linearized based on selected beam-sea case

Figure 1 Flow chart of relative wave motion estimation for green water assessment.

Figure 2 FPSO model with spread mooring and lazy wave risers.

Figure 3 FPSO model tests.

Figure 4 Wave probes locations for relative wave elevation measurements.

Figure 5 Comparison of root-mean-square roll velocity.

Figure 6 Roll response spectra with and without asymmetric riser effects.

Figure 7 Comparison of numerical and experimental results of relative wave elevation 3 h most probable maximum–Model A.

Figure 8 Comparison of numerical and experimental results of relative wave elevation 3 h most probable maximum–Model B.

Figure 9 Comparison of numerical and experimental results of relative wave elevation 3 h most probable maximum–Model C.

Figure 10 Comparison of numerical and experimental results of relative wave elevation 3 h most probable maximum–Model D.

Figure 11 Comparison of most probable maximum relative wave elevation at various locations with wave direction as 180° (head sea).

Figure 12 Comparison of most probable maximum relative wave elevation at various locations with wave direction as 135°.

Figure 13 Comparison of most probable maximum relative wave elevation at various locations with wave direction as 90°.

Figure 14 Comparison of most probable maximum relative wave elevation at various locations with wave direction as 45° .

Figure 15 Comparison of most probable maximum relative wave elevation at various locations with wave direction as 0° .

Figure 16 Comparison of roll RAOs in beam sea.