Influence of Partially Standing Waves on Offloading Operations for Shuttle Tanker

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Abstract The side-by-side configuration of a shuttle tanker undergoes more complex hydrodynamic behavior. This is more critical in extreme weather conditions. The gap between the FPSO and shuttle tanker adds to complexity of hydrodynamic behavior. Past studies have been performed to understand the gap resonance and other behavior of water column between the FPSO and shuttle tanker. This paper aims to study the effect of partially standing waves on the offloading operation, which occurs between the gap of FPSO and shuttle tanker pertaining to different encountering time period of waves for shuttle tanker. The velocity potential and wave kinematics of partially standing waves are derived and subsequently the different percentage of reflected wave height on the wave kinematics are studied. The objective of studying the influence of partially standing waves offloading operation is achieved by studying two types of waves as moderate and extreme waves. The higher wave height affects the kinematics of waves between the vessels. Also, the higher percentage of reflected wave height contributes to greater kinematics of waves. The conclusions of study and scope of future work is presented at the end.

Keywords Side-by-side · Partially standing waves · FPSO · Offloading · Shuttle tanker

1 Introduction

With continuous and monotonous efforts in searching oil fields, most of the Floating Production Storage and Offloading systems (FPSO) are now converting to side-by-side configuration [1]. The offloading is one of the key operations during production.

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The shuttle tanker is usually stationed adjacent to the FPSO for 8–12 h. The safe offloading operation is a concern as the shuttle tanker is usually connected through hawsers and is comparatively unrestrained compared to a moored FPSO [2]. In an event of extreme weather conditions and longitudinal waves attacking the vessel, there can be possibility of extreme vessel response and hydrodynamic behavior leading to non-feasibility of safe offloading operations [3, 4]. The gap between the vessels play a very crucial role in hydrodynamic interactions [5]. Due to close proximity of side vessel, strong hydrodynamic interactions are believed to take place which affects the wave forces on the bodies [6]. Moreover, sharp peaks are observed between the gaps of side-by-side vessels which affect the hydrodynamic parameters [7].

The dynamic characteristics and wave-body interactions differ with respect to configuration. The roll response of a vessel is usually attributed to resonance and tends to shoot higher in presence of closed vessels in head seas [8, 9]. Furthermore, the gap between the vessels is sensitive to Hemholtz type resonance as well [10]. The present study tends to evaluate the effect of partially standing waves on the offloading operation by studying the wave kinematics between the gap. The effect of percentage of wave reflection and different water depth on wave kinematics between the vessels gap is studied.

2 Mathematical Modeling and Analysis

A partially standing wave is made of incident wave height Hi and reflected wave height *Hr*. Due to closing spacing of the FPSO and adjacent shuttle tanker in close proximity, there would be waves generated between the gap of the vessels. When an incident wave of certain height from one vessel propagates and reaches the other vessel, part of the incident wave is reflected and the reflected wave travels in the opposite direction. Such repetitive occurrences of this event causes next incoming wave height and already reflected wave height superimposes to generate partially standing waves [11–13]. However, the wave kinematics of partially standing wave depends on the percentage of reflected wave height. The wave elevation for partially standing waves is given as follows:

$$\eta_t = \frac{H_i}{2}\cos(kx - \omega t) + \frac{H_r}{2}\cos(kx + \omega t + \epsilon) \tag{1}$$

where,

- η_t is the wave elevation.
- H_i is the incident wave height.
- H_r is the reflected wave height.
- k is the wave number and ω is the wave frequency.

The velocity potential for the wave surface ($z = 0$) [14],

$$\phi = g \int \eta_t \tag{2}$$

Further solving of Eq. (2) with the assumption that wave elevation has zero spatial and temporal mean yields the final velocity potential as

$$\phi_{z=0} = \frac{g}{2\omega}[H_r \sin(kx + \omega t + \epsilon) - H_i \sin(kx - \omega t)] \tag{3}$$

$$\phi_{z>0} = \frac{g}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r \sin(kx + \omega t + \epsilon) - H_i \sin(kx - \omega t)] \tag{4}$$

where,

- d is the wave depth.

The equations of wave kinematics for partially standing waves are as follows:

$$u = -\frac{gk}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r \cos(kx + \omega t + \epsilon) - H_i \cos(kx - \omega t)] \tag{5}$$

$$w = -\frac{gk}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r \sin(kx + \omega t + \epsilon) - H_i \sin(kx - \omega t) \tag{6}$$

The horizontal velocity is given by Eq. (5) while the vertical velocity is given by Eq. (6). Further derivative of the velocities with respect to time and space will yield the local and convective accelerations respectively as represented from Eq. (7) to Eq. (12)

$$\dot{u}_x = -\frac{gk^2}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_i \sin(kx - \omega t) - H_r \sin(kx + \omega t + \epsilon) \tag{7}$$

$$\dot{u}_z = -\frac{gk^2}{2\omega}\frac{\sinh(k(d+z))}{\cosh(kd)}[H_r \cos(kx + \omega t + \epsilon) - H_i \cos(kx - \omega t) \tag{8}$$

$$\dot{w}_x = -\frac{gk^2}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r \cos(kx + \omega t + \epsilon) - H_i \sin(kx - \omega t) \tag{9}$$

$$\dot{w}_z = -\frac{gk^2}{2\omega}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r \sin(kx + \omega t + \epsilon) - H_i \sin(kx - \omega t) \tag{10}$$

$$\dot{u}_t = \frac{gk}{2}\frac{\cosh(k(d+z))}{\cosh(kd)}[H_r \sin(kx + \omega t + \epsilon) + H_i \sin(kx - \omega t) \tag{11}$$

$$\dot{w}_t = -\frac{gk}{2}\frac{\sinh(k(d+z))}{\cosh(kd)}[H_r \cos(kx + \omega t + \epsilon) + H_i \sin(kx - \omega t) \tag{12}$$

In this study, the spacing of the vessel is considered for percentage of reflected wave height. Furthermore, it is based on the assumption that greater spacing of the vessel would relate to lower percentage of reflected wave height. An incident wave propagating from a distantly spaced vessel will gradually reduce in the momentum before getting reflected and the percentage of reflected wave would be less as opposed to a closely spaced vessel which would correspond to a higher reflected wave. The above wave kinematics equations from Eqs. (5)–(12), were solved in a multi-paradigm numerical computing software, MATLAB, by evaluating the kinematics for different conditions of wave through direct substitution as explained in the succeeding section.

3 Results and Discussion

Two cases of reflected wave height for the initial phase of our present study. A wave reflected percentage of 10% relates to widely spaced vessel while 40% relates to closer spaced vessels respectively. The water depth for our study is 50 m and as the derived wave equations are sinusoidal, observations are made for initial 1000 s only. The discussion is further subdivided into two cases as following.

3.1 Partially Standing Waves: Moderate Waves

An incident wave of 3 m is considered for initial phase of analysis. The result is plotted for two different time periods of wave as given in Table 1.

From the plots of kinematics in Fig. 1, it is clearly observed that the wave elevation for 3.5 s time period wave, is higher for greater percentage of reflected wave height while the horizontal velocity and horizontal acceleration is comparatively higher for lesser percentage of reflected waves respectively. This nature is repeated for 16 s wave as well. Moreover, the vertical velocity and vertical acceleration remains to be higher for greater percentage of reflected wave heights.

The wave elevation for the 16 s wave stretches longer over time and the time taken to reach peak values of velocity is more. It is further observed that for the same time of observation of 1000 s, the wave with lower time period undergoes higher number of transitions in peak velocities. Hence, a wave with a lower time period is more critical and prone to cause higher wave turbulence. It can also be related to greater motion response of vessel.

Table 1 Encountering wave time period on shuttle tanker

Parameter	Case 1	Case 2
Time period (s)	3.5	16

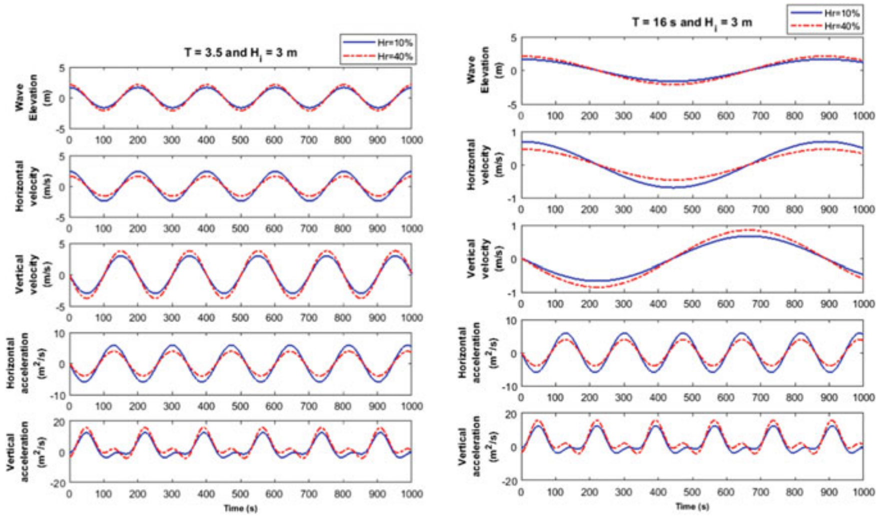

Fig. 1 Wave kinematics of partially standing waves for $H_i = 3\,\text{m}$

3.2 Partially Standing Waves: Extreme Waves

The study on wave kinematics of partially standing waves was extended to higher incident wave heights of 6 m and 10 m respectively. Two major case was studied as tabulated in Table 1. An exact similar nature is observed for the wave kinematic profile as observed for moderate wave case. The only difference lies in the peak values. From Figs. 2 and 3, it can be concluded again that higher percentage of

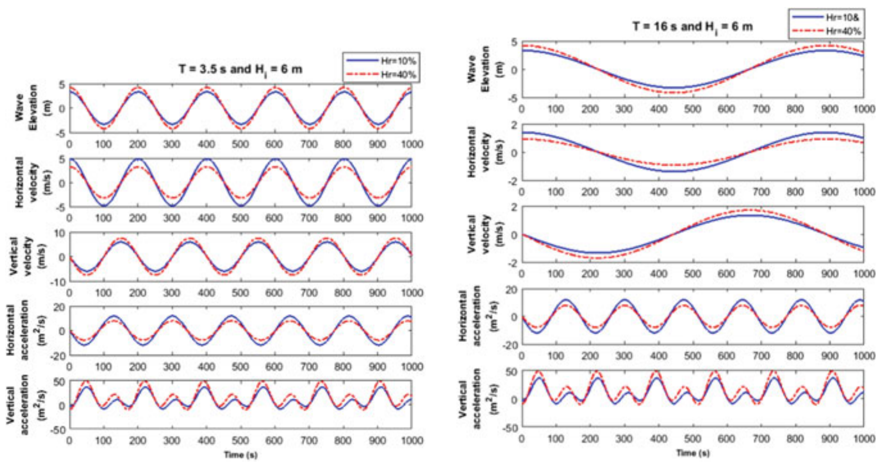

Fig. 2 Wave kinematics of partially standing waves ($H_i = 6\,\text{m}$)

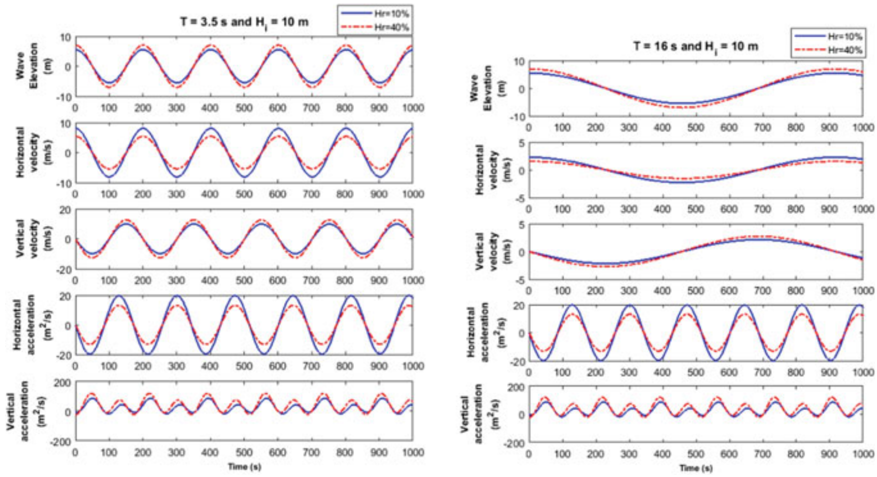

Fig. 3 Wave kinematics of partially standing waves ($H_i = 10\,\text{m}$)

reflected wave heights corresponds to comparatively increase in wave elevation, vertical velocity and vertical acceleration. Furthermore, the time period of the wave affects the number of transitions of peak values respectively. Hence there is more wave turbulence involved for a wave of lower time period. But, it is also clearly seen that increased wave height of 6 m and 10 m has more peak values of wave kinematics.

It is further seen that greater percentage of reflected wave height is more effective on wave kinematics parameters. Thus, it can be said that closer the spacing of vessels, greater is the percentage of reflected waves which further influences the wave kinematics. Since the effect of partially standing waves are higher with 40% reflected wave height and a smaller time period wave is more critical, Fig. 4 represents the 40% reflected wave height for two cases of higher incident wave height but, for a smaller time period wave. It is observed clearly that effect of wave kinematics is dominant for greater height of incident wave. There is a drastic increase in the vertical acceleration. Finally, it can be concluded that higher percentage of reflected wave height for a smaller time period wave is more critical for offloading operations. These waves kinematics can be related to higher vessel behavior and stronger hydrodynamic interaction.

4 Conclusion

The study primarily focused on the contribution of wave height as an influential parameter on the wave kinematics between the floating vessels. The study of partially standing waves between the gap of FPSO and shuttle tanker can be concluded as:

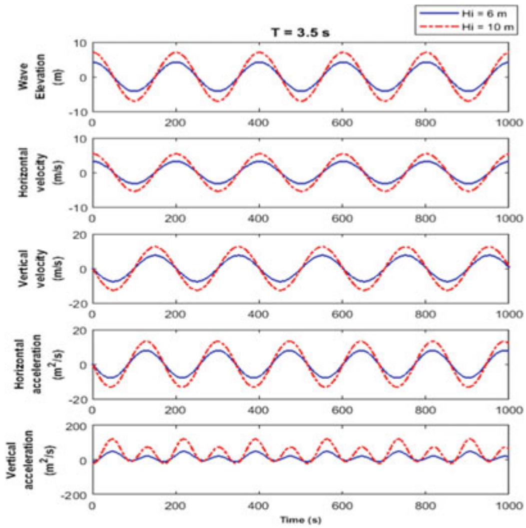

Fig. 4 Wave kinematics of partially standing waves ($H_i = 6\,\text{m}$ and $10\,\text{m}$)

- The influence of wave kinematics in partially standing wave is higher for higher incident wave height.
- The wave kinematics interactions are more susceptible for a wave of lower time period with greater percentage of reflected wave, 40% in the present study as compared to 10%, respectively.

Future Works The future scope of work involves calculating downtime cost of offloading operation under the influence of partially standing waves. A graphic user interface (GUI) would be developed for linking the wave kinematics to cost of production.

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