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Computational Simulation of Current Forces on Floating Production Storage and Offloading in Irregular Waves

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Abstract. *This paper presents the effect of current forces on the motion of forces on Floating Production Storage and Offloading (FPSO) in irregular waves. The objective of this research is to compute the motion of FPSO in irregular waves by time domain simulation including the effect of current forces. A study is made on the slowly varying oscillations of a moored single body system in a current and waves. Linear potential theory is used to describe the fluid motion, and three-dimensional source distribution techniques are applied to obtain the hydrodynamic forces and transfer function of the wave exciting forces. OCIMF (1994) data are used for estimation of the current forces. The non-linear time domain simulations have been carried out in irregular waves. Based on it, slowly varying motion responses are examined including the effect of the current forces. Several environmental conditions, such as the current angle of attack, current velocity, significant wave height and mean wave period are considered, which may significantly affect FPSO motion in surge, sway and yaw moments. It is found that the effect of current forces is quite significant when the current velocity is increased. In this simulation, while the current velocity is increased to 3.0 meter/seconds, the impact on FPSO motion is quite significant, which should be taken into consideration from the point of view of safety, failure of mooring systems, operating responses and the dynamic positioning of the FPSO.*

Keywords: *FPSO; Current forces; Irregular waves; Motion; Seakeeping.*

INTRODUCTION

Floating Production Storage and Offloading (FPSO), a ship-shaped vessel similar to a trading tanker, is one of the offshore platforms currently being used in offshore industries. FPSO systems represent an important engineering solution for the exploitation of deep-water oil and gas fields. The floating type platform used is designed to gather oil or gas produced from the seabed, as well as from nearby platforms, and to store it until the oil or gas can be offloaded onto shuttle tankers or sent through a pipeline. The main reason for choosing FPSO as the offshore platform is due to its storage capacity and the provision of large topsides, particularly in marginal deep water fields. Offloading operations require a safe relative positioning between two vessels under the action of environmental forces such as wind, waves and currents. Waves, winds and currents can subject the vessel to quartering or beam seas that can significantly influence the response of FPSO.

The effect of irregular seas is represented by second-order forces and moments; namely, mean and slow drift forces, as well as by wave current interaction terms (wave drift damping). The inclusion of wave drift forces into the analyses helps complete the picture of the dynamics of these systems under a marine environment, now constituting wind, current and wave effects. These forces affect the floating structure in terms of safety, sustainability, operating response and display positioning. Current forces have significant effects on FPSO positioning and under extreme circumstances may cause failure to the mooring lines.

Current behavior impacts on the FPSO depend on

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current speeds, angles of attack and, most significantly, the water depth to ship draught ratios. Under-keel clearance also has a large influence on the current coefficients. For example, according to Ref. [1], the lateral force coefficient for water depth to draft ratio of 1.0 are, approximately, three times larger than the coefficients for water depth to draft ratio equal to 3.0. This increase is primarily due to the blockage effect of the FPSO, which cause a proportionately larger volume of water to pass around, rather than under the FPSO as the under-keel clearance decreases.

Remery and Van Oortmerssen [2] presented a method to predict current forces on moored tankers, based on several model tests conducted at the Netherlands Ship Model Basin (currently MARIN). The authors proposed that the ITTC 1957 frictional resistance formula be used to predict the longitudinal force. For transverse force and yaw moment coefficients, they calibrated a separate fifth order Fourier cosine series to the test results and proposed these to model the variation of each coefficient with a relative current heading. They suggested that the lateral current force and yaw moment coefficients should be independent of the Reynolds number. A curve was provided for adjusting the force coefficients for shallow water effects.

Edwards [3] found that, contrary to results by Remery and Van Oortmerssen, the influence of Reynolds number on the lateral current force and yaw moment is significant, in particular due to changes in the nature of the vortex shedding from the bow and stern.

Experimental results for steady current forces on tanker-based FPSO are given in [4]. The authors claimed that a longitudinal force near 180 and 90 degree angles of attack is strongly dependent on the details of the bow and stern configuration. These resulted in larger lateral force and yaw moments than those indicated by OCIMF in [5].

Inoue et al. [6] presented some numerical results for a moored FPSO and a parallel connected LNG carrier. The authors presented the effects of current, wind and drift forces on this multi-body floating system. They analyzed the interaction effect between the two vessels for one current heading angle and concluded that the effect of current on the motion of FPSO is significant. Heidari et al. [7] presented some numerical results of a moored semi-submersible in short crested waves and also compared the results with long crested waves; critical cases being examined. The effect of current forces was not included.

This paper presents the effect of current forces on a moored FPSO at various current speeds and relative current headings. The resulting surge, sway and yaw motions under the influence of current are compared with those without current forces and significant effects are highlighted.

EQUATION OF MOTION IN THE TIME DOMAIN

The time domain motion analysis of a floating structure, a motion equation, can be derived on the basis of the equation proposed originally by Cummins [8]. In this method, the frequency dependency of hydrodynamic reaction forces is taken into account by means of a convolution integral and no other assumption is required other than the linearity of hydrodynamic forces.

The equation of motion in the time domain is the same as in Inoue et al. [6] and is given by:

$$\sum_{j=1}^{6}(M_{kj}+m_{kj})\ddot{X}_j+\int_{-\infty}^{t}R_{kj}(t-\tau)\dot{X}_j d\tau + B_n|\dot{X}_j|\dot{X}_j+CX_j=F_k+F_c+F_m, \quad (1)$$

where:

M_{kj} :	inertia matrix of kj,
M_{kj} :	frequency independent added mass matrix of kj,
R_{kj} :	retardation function matrix of kj,
B_n :	non linear damping coefficient matrix of kj,
C :	restoring coefficient matrix of kj,
F_k :	wave exciting force vector in k-mode,
F_c :	current force vector in k-mode,
F_m :	mooring force vector in k-mode,

Components of m_{kj} and R_{kj} matrices have the following forms:

$$m_{kj}=a_{kj}(\omega^*)+\frac{1}{\omega^*}\int_0^{\infty}R_{kj}(t)\sin(\omega^* t)dt, \quad (2)$$

$$R_{kj}(t)=\frac{2}{\pi}\int_0^{\infty}b_{kj}(\omega)\cos(\omega t)d\omega. \quad (3)$$

Here, a_{ij} and b_{ij} are frequency dependent added mass and damping coefficient matrices, respectively (k and j take values from 1 to 6). These hydrodynamic forces and the transfer function of the wave exciting forces are calculated using three dimensional source distribution techniques within the linear wave theory [9]; ω^* is the constant frequency, which can be chosen arbitrarily. The mooring forces are calculated based on [10].

CURRENT FORCES

The current force and current moment components are defined in a body-fixed coordinate system and are identical to that presented in OCIMF [5]. They are given by:

$$F_{xc} = \frac{1}{2} C_{xc} \rho L T V_{cr}^2,$$

$$F_{yc} = \frac{1}{2} C_{yc} \rho L T V_{cr}^2,$$

$$M_{mc} = \frac{1}{2} C_{mc} \rho L^2 T V_{cr}^2,$$

where F_{xc} is the longitudinal current force, F_{yc} is the lateral current force and F_{mc} is the current yaw moment. The associated dimensionless force and moment coefficients are longitudinal current forces coefficient, C_{xc}, lateral current forces coefficient, C_{yc}, and current yaw moment coefficient, C_{mc}. The remaining variables are the vessel draft, T, length between perpendiculars, L, current velocity, V_{cr}, and fluid density, ρ.

The current forces and moment coefficients are primarily a function of current angle, θ, Froude and Reynolds numbers, hull form, vessel draft and water depth to vessel draft ratio. For currents flowing past a moored FPSO in deep water, the associated Froude numbers are sufficiently small that free surface effects are not significant. In this paper, the coefficients are obtained from the curves proposed by the Oil Companies International Marine Forum (OCIMF) [1,5], which are based on extensive tank tests on typical tankers. These coefficients are independent of Reynolds and Froude numbers.

SIMULATION AND ANALYSIS

Based on the mathematical model, a computer program using FORTRAN77 is developed in the time domain for six degrees of freedom, using the Newmark-Wilson method. In this program, the hydrodynamic coefficients and wave exciting forces and moments are utilized as a transfer function for the unit amplitude wave. These transfer functions are calculated by a 3-D source distribution method [10].

An analysis was carried out on an FPSO having mooring lines whose details are given in Table 1 originally taken from [10]. The time domain simulation for the FPSO was carried out in irregular waves using an ISSC wave spectrum. The resulting data consists of the motion of the FPSO in surge, sway and yaw motion at each time step. The current angles of attack to the hull of the FPSO are considered for 0, 90, 190, and 270 degrees, respectively. The conditions that are considered in each of the current angles of attack are with and without current, different current velocities, different significant wave heights and different mean wave periods. Other effects, such as the use of thrusters or other devices, are not taken into consideration for the present simulation.

The FPSO is moored to a single point catenary mooring system of four equal mooring lines; each mooring line being 90 degrees apart. The characteristics of the mooring lines are as follows:

Table 1. Main particulars of FPSO.

Length (L)	295.0 (m)
Breadth (B)	60.0 (m)
Depth (D)	25.0 (m)
Draft (T)	8.5 (m)
Displacement (W)	143,845 (tonne)
Centre of gravity from midship (XG)	0.75 (m)
Centre of gravity above base line (KG)	18.16 (m)
Metacentric height (GM)	23.24 (m)
Transverse radius of gyration (K_{xx})	19.80 (m)
Longitudinal radius of gyration (K_{yy})	82.60 (m)

- Length of each mooring line = 800.0 m,
- Weight of unit length (in water) = 9.43 KN/m,
- Initial tension = 603.8055 KN.

The setting parameters are as follows:

- Simulation time, $t = 2000$ seconds;
- Time step, $dt = 0.1$ seconds;
- Water depth = 260 meters.

The simulation cases are summarized in Table 2. The current and wave directions are designated according to Figure 1, with current velocity $V_C = 1.5$ meters/seconds (3 knots). The significant wave height, $H = 5$ meters, and mean wave period, $t = 15$ seconds, are taken as the default normal sea condition study case.

RESULTS AND ANALYSIS: CASE 1

The simulation was carried out for a wave heading angle of 270 degrees and a current angle of attack of 0 (zero) degrees. It is observed in Figure 2 that as current forces are included, FPSO oscillates with

Table 2. Simulation cases.

Case	Current Angle of Attack
1	0
2	90
3	180
4	270

amplitudes equal to 1.5-2 m. Furthermore, it is seen in Figure 3 that the higher the current velocity, the higher the surge amplitude; at current velocity of 3.0 meters/seconds (m/s) or 5.83 knots, the surge motion is increased significantly.

Here, the current velocity of 3 m/s is considered as an extreme case because during hurricanes or other extreme situations, the current velocity may exceed 3 m/s. It is to be mentioned that during Hurricane Rita in 2007, the maximum hurricane induced current speed was 3.2 m/s (6.4 knots) [11].

Sway motion is expected to be the same, since the current angle of attack is 180 degrees and this sway motion arises only from the effect of the wave exciting forces for a wave heading angle of 270 degrees. Current forces at 0 (zero) degree angle of attack is not considered significant as shown in Figure 4. It is also understood from Figure 5 that with the increase of current velocity, significant change is made on the FPSO yaw angle. At current velocity of 3.0 m/s (5.83 knot), the FPSO yaw angle changed to a maximum of -40 degrees. The yaw motion is quite high, since

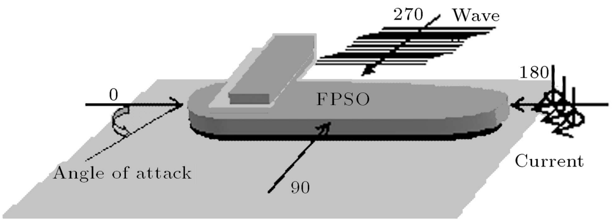

Figure 1. Schematic drawing showing the wave and current angle of attack.

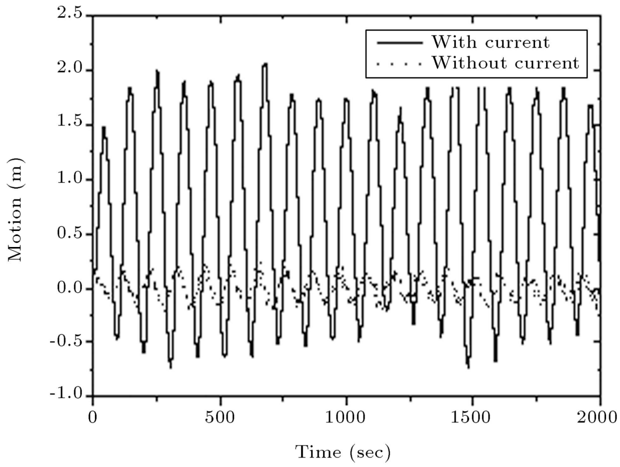

Figure 2. Surge motion with and without current velocity (V_C = 1.5 m/s, H = 5 m, t = 15 s, wave heading of 270° and current angle of 0°).

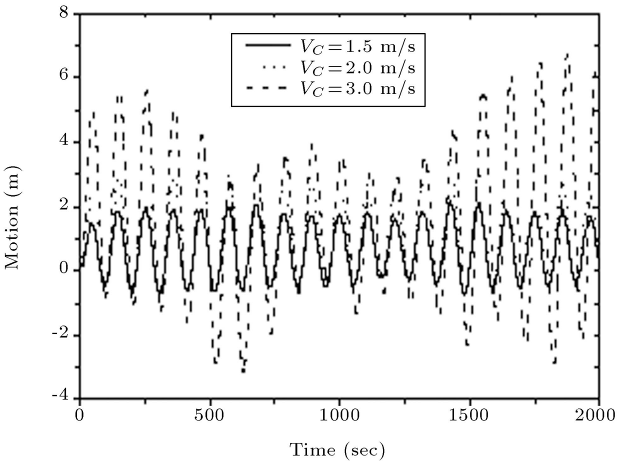

Figure 3. Surge motion at different current velocity (H = 5 m, t = 15 s, wave heading of 270° and current angle of 0°).

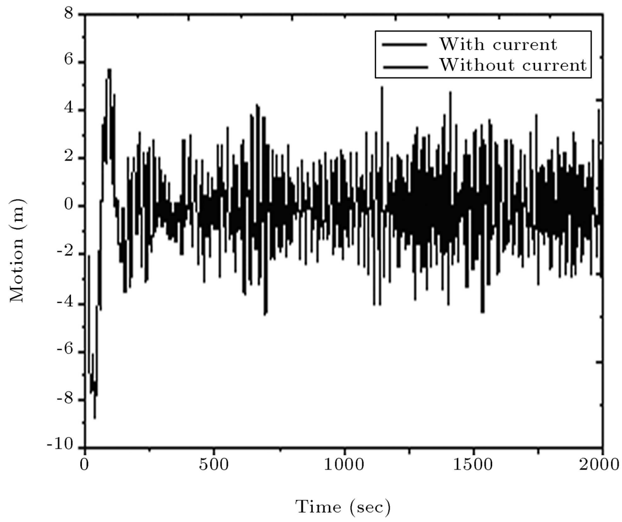

Figure 4. Sway motion with and without current velocity (V_C = 1.5 m/s, H = 5 m, t = 15 s).

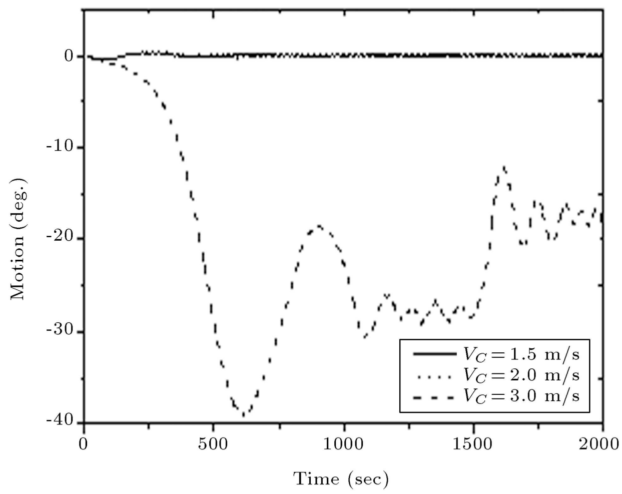

Figure 5. Yaw motion at different current velocity (H = 5 m, t = 15 s, wave heading of 270° and current angle of 0°).

the hull viscous damping is neglected, resulting in an overestimation of yaw motion. Therefore, to predict the reasonable dynamic yaw motion of FPSO, the use of proper hull viscous drag is important. However, this is beyond the scope of the present work, since hydrodynamic forces are computed using linear wave theory.

RESULTS AND ANALYSIS: CASE 2

The simulation has also been carried out for a wave heading angle of 270 degrees and current angle of 90 degrees. It is seen in Figure 6 that the higher the current velocity, the more significant impact on the amplitude of the FPSO. The FPSO cannot resist the impact from current forces, as the current velocity is 3 m/s (5.83 knots) in the middle of the simulation time and the amplitude becomes ± 40 meters. Under extreme irregular wave conditions (i.e. at a higher significant wave height and a less mean wave period), the sway amplitude of FPSO becomes higher, as shown in Figures 7 and 8.

In Figure 6, yaw motion is also shown to have the same behavior; the higher the current velocity, the higher the yaw angle changes from the origin. It is seen from Figure 9 that at a current velocity of 3.0 m/s (5.83 knots), a sudden change of yaw angle from +5 degrees to -20 degrees in a simulation time of between 500 seconds and 1000 seconds, slowly decreased the yaw angle. Again, the higher results are partly due to neglecting the hull viscous damping. It is understood that the higher the significant wave height and the less the mean wave period, the more significantly the yaw angle of FPSO changed, as shown in Figures 10 and 11.

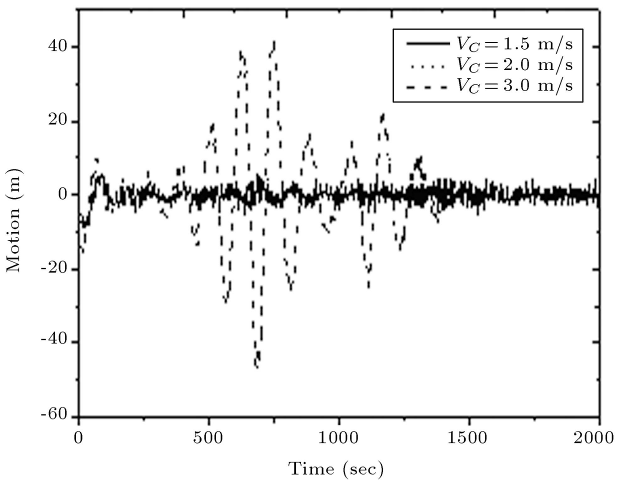

Figure 6. Sway motion at different current velocity ($H = 5$ m, $t = 15$ s, wave heading of 270° and current angle of 90°).

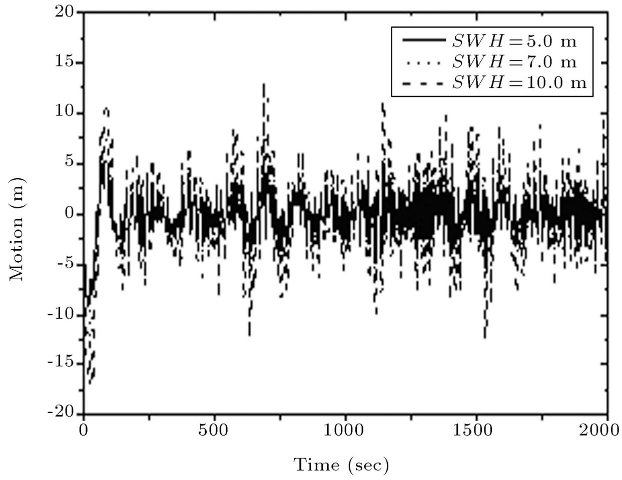

Figure 7. Sway motion at different significant wave height ($V_C = 1.5$ m/s, $t = 15$ s).

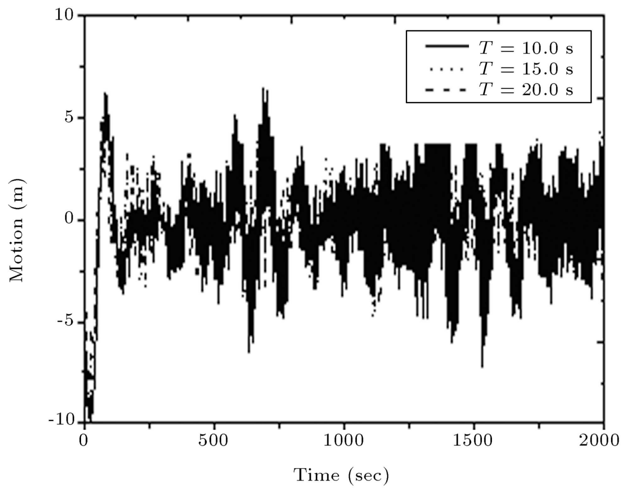

Figure 8. Sway motion at different mean wave period ($V_C = 1.5$ m/s, $H = 5$ m).

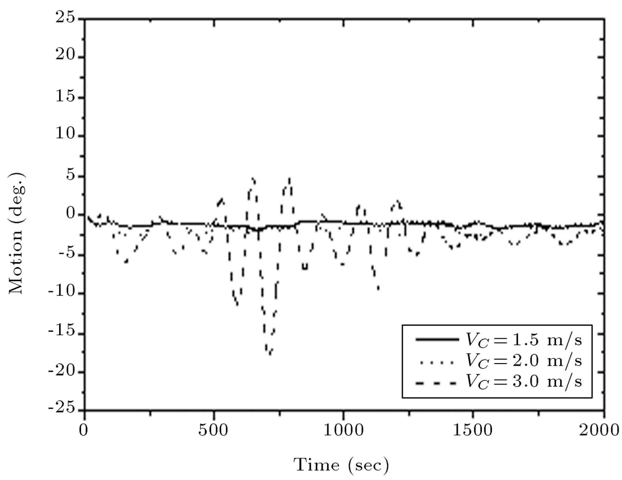

Figure 9. Yaw motion at different current velocity ($H = 5$ m, $t = 15$ s, wave heading angle of 270° and current angle of 90°).

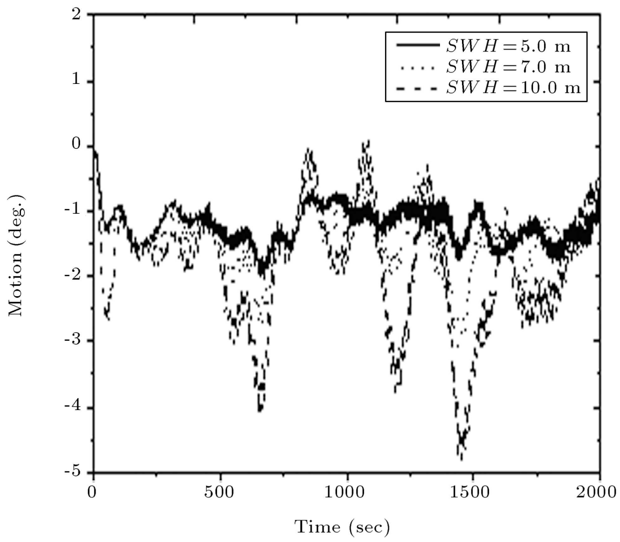

Figure 10. Yaw motion different significant wave height ($V_C = 1.5$ m/s, $t = 15$ s).

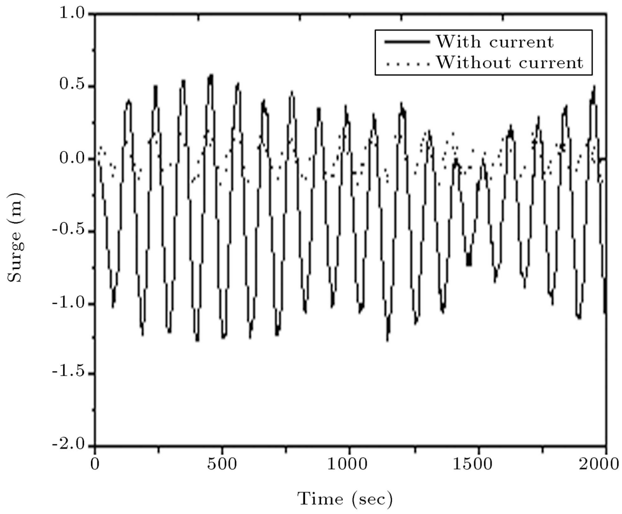

Figure 12. Surge motion with and without current velocity ($V_C = 1.5$ m/s, $H = 5$ m, $t = 15$ s, wave heading of 270° and current angle of 180°).

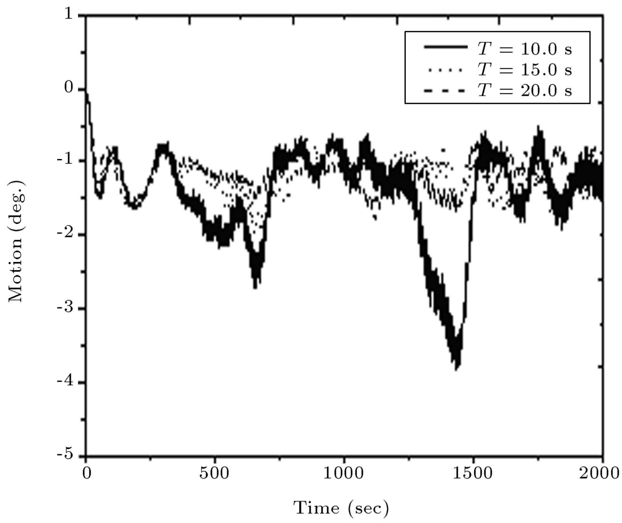

Figure 11. Yaw motion at different mean wave period ($V_C = 1.5$ m/s, $H = 5$ m).

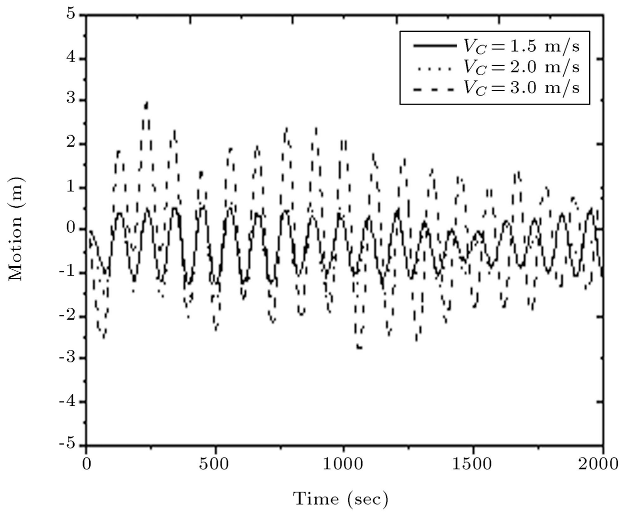

Figure 13. Surge motion at different current velocity ($H = 5$ m, $t = 15$ s, wave heading of 270° and current angle of 180°).

RESULTS AND ANALYSIS: CASE 3

For a wave heading angle of 270 degrees and a current angle of attack of 180 degrees, it is observed that with the inclusion of current forces and at a higher current velocity, the amplitude of FPSO strongly influenced motion, as shown in Figures 12 and 13. Further, it is also observed that the amplitude of the FPSO with the inclusion of current forces increases from +0.5 meter to -1.0 meter, and as the current velocity increased to 3.0 m/s (5.83 knots), the amplitude varies ± 3 meters from the original position.

It is seen from Figure 14 that a current velocity of 3 m/s (5.83 knots) changes the FPSO yaw angle to -25 degrees at a simulation time of 250 seconds; slowly decreasing to -10 degrees at the end of a simulation time of 2000 seconds.

RESULTS AND ANALYSIS: CASE 4

The simulation has also been carried out for the same wave heading and current angle (i.e. 270 degrees). As both environmental forces come from a heading angle of 270 degrees, in a sway motion, it is the critical point to analyze. It is understood that as the current velocity is increased, the amplitude of the FPSO sway motions are increased significantly, as shown in Figure 15. It is also observed that as the current velocity increased to 3.0 m/s (5.83 knots), the motion fluctuates about ± 10 meters from the origin in the first quarter of

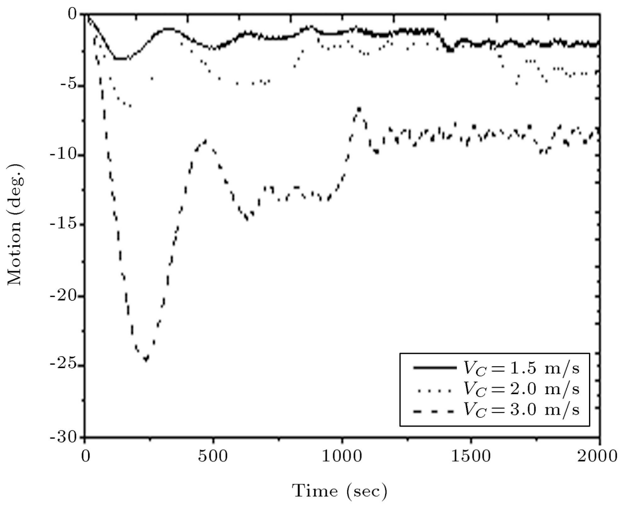

Figure 14. Yaw motion at different current velocity ($H = 5$ m, $t = 15$ s, wave heading of 270° and current angle of 180°).

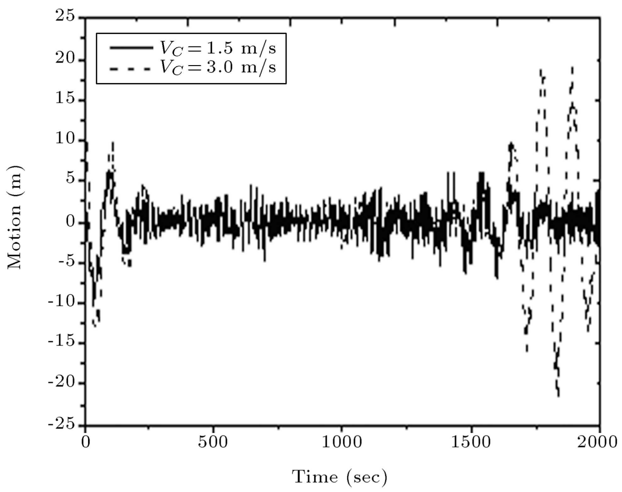

Figure 15. Sway motion at different current velocity ($H = 5$ m, $t = 15$ s, wave heading of 270° and current angle of 270°).

the simulation and suddenly jumped to ± 20 meters at the end of the simulation time. The extreme wave condition also notably affected the amplitude of the FPSO sway motion. It is seen in Figure 16 that with the increases in current velocity, the yaw angle of the FPSO also increased.

CONCLUSIONS

In this paper, a study on the effect of current forces to the motion of FPSO is presented. From the foregoing discussion, it can be concluded that the effect of current forces is quite significant for FPSO motion in surge, sway and yaw. It can also be understood that current angle and velocity influences FPSO behavior and, in extreme cases, at a current velocity of 3.0

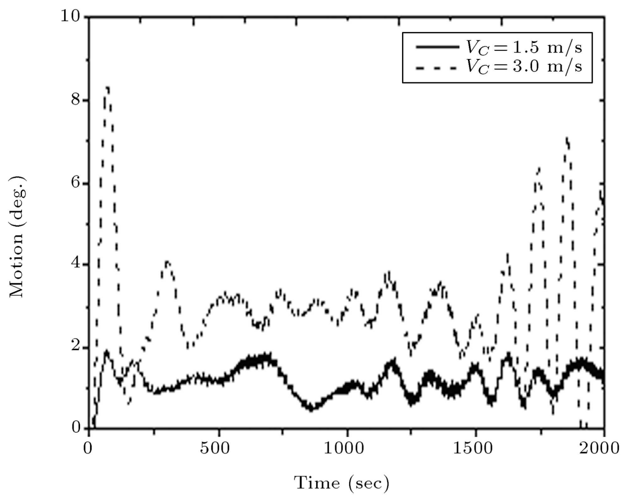

Figure 16. Yaw motion at different current velocity ($H = 5$ m, $t = 15$ s, wave heading of 270° and current angle of 270°).

meter/seconds, FPSO is significantly affected by a huge impact, which should be given importance in the designing of mooring and dynamic positioning systems. The authors recommend carrying out experiments for validating the same and, also, for further studying different bow and stern configurations and the effect of vortex due to current.

REFERENCES

1. Oil Companies International Marine Forum (OCIMF). "Prediction of wind and current loads on VLCCs", Witherby and Co Ltd, London (1977).
2. Remery, G.F.M. and Van Oortmerssen, G. "The mean wave, wind and current forces on offshore structures and their role in the design of mooring systems", *Offshore Technology Conference*, OTC 1741, Houston (1973).
3. Edwards, R.Y. "Hydrodynamic forces on vessels stationed in a current", *Offshore Technology Conference*, OTC 5032, Houston (1985).
4. Mercier, R.S. and Huijis, F.A. "Steady current forces on tanker based FPSOs", *Fluid Structure Interaction and Moving Boundary Problems, WIT Transactions on the Built Environment*, **84**, pp. 259-268, WIT Press (2005).
5. Oil Companies International Marine Forum (OCIMF), "Prediction of wind and current loads on VLCCs", 2nd Ed., Witherby and Co., London (1994).
6. Inoue, Y., Islam, M.R. and Murai, M. "Effect of wind, current and non-linear second order drift forces on a moored multi-body system in an irregular sea", *Proceedings OCEANS 2001*, Hawaii, Honolulu, USA (2001).
7. Heidari, A.H., Borghei, S.M. and Sohrabpur, M. "Dynamic response of a moored semi-submersible in

short crested wave field", *Scientia Iranica*, **12**(2), pp. 131-140 (2005).

8. Cummins, W.E. "The impulse response function and ship motions", *Schiffstechnik*, **9**, pp. 101-109 (1962).
9. Inoue, Y., Islam, M.R. and Murai, M. "A study on motions and drift forces of a multi-body floating system in waves", *Journal of The Society of Naval Architects of Japan*, **188**, pp. 127-134 (2000).
10. Islam, M.R. "A study on motions and non-linear second order drift forces of multi-body floating bodies in waves", Doctoral Thesis, Yokohama National University, Japan (2001).
11. "Deepwater hindcast of Hurricane Rita", Horizon Marine, Inc & Accurate Environmental Forecasting Inc. (2007).