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Analytical Research of Topside Installation in Mating phase with Crane Vessel

Jong-Hyun Lee*

**Offshore Wind Power Research Project Team, RIST, Incheon, Korea*

KEY WORDS: Topside installation, Crane Vesse, Mating phase, Analytical Model, Coupled multi-body interaction, Motion Trajectory Analysis, Deepwater installation

ABSTRACT: *The installation of a topside structure can be categorized into the following stages: start, pre-lifting, lifting, lifted, rotating, positioning, lowering, mating, and end of installation. The transfer of the module onto the floating spar hull occurs in the last three stages, from lowering to the end. The coupled multi-body motions are calculated in both calm water and in irregular waves with a significant wave height (1.52 m). The effects of the hydrodynamic interactions between the heavy lifting vessel and the spar hull during the lowering and mating stages are considered. The internal forces caused by the load transfer and ballasting are derived for the mating phases. The results of the internal forces for the calm water condition are compared with those in the irregular sea condition. Although the effect of the pitch motion on the relative vertical motion between the deck of the floating structure and the topside module is significant in the mating phases, the internal force induced pitch motion is too small to have this influence. However, the effect of the internal force on the wave-induced heave responses in the mating phases is noticeable in the irregular sea condition because transfer mass-induced draught changes for the floating structure are observed to have higher amplitudes than the external force induced responses. The impacts of the module on the spar hull in the mating phase are investigated.*

1. Introduction

Once the mooring lines are installed, the spar is prepared and made ready to receive the topside deck. This requires a derrick vessel to lift, or a lift barge to float-over, the deck module. So far, various decks weighing from 3000 to more than 20,000 tons have been installed on spars. Larger decks typically require multiple lifts to install a complete topside structure and this entails a protracted period for offshore hook-up and commissioning of the deck. Using a lift crane vessel is the most common installation method for offshore floating structures and is assumed in this study. The crane vessel and the wave drift force induced large horizontal relative motions between spar and crane vessel can be significant for the mating procedure.

Three distinct systems: the crane vessel, the lifting slings and the structure being lowered down to the spar are need to be considered in the mating operation by means of a crane vessel. The lifted structure induces hook load and the various wave-induced loads are applied to the crane vessel. The loads consists of the weight of the deck structure, the weight of the rigging, external wind forces and dynamic loads caused by the dynamic motions of the crane vessel and the spar during mating. The experienced loads of the crane vessel and the spar are coupled wave-induced loads, variable structure weight during mating, and an impact load if the vertical motion of the spar relative to the deck structure is greater than the transient air gap between them (Cveticanin, 1995; Schellin, et al. 1993).

In order to carry out a dynamic analysis for a deepwater installation in the time domain, the following information needs to be examined 1) External forces induced by waves 2) Internal forces arisen from the mass of the lifted structure and the mating velocity 3) Motion responses of the crane vessel and the spar, due to the various external and internal forces.

In the present research, the mating operations for a topside module by means of a heavy lift vessel are examined. The assumed 6000 tonne topside module is lifted by the heavy lift vessel and lowered to the spar.

The interacting coupled body hydrodynamics are considered for the crane vessel and the spar. The hydrodynamic analysis of two floating structures is computed by using of a diffraction theory based program MBMOTION3D (Chan 2003). The two floating structures and the hanging topside module has 15 degrees of freedom to express their motion. Therefore, theoretically a total of 15 degrees of freedom can be considered for the mating operations. In the present investigation however, lateral motion of floating structure is assumed to be small because of the floating structure is assumed to be constrained by mooring and is thus not considered. During the mating operations, crane induced motions are most interesting part of this research so the pitch and heave motions of crane vessel and the heave motion of the spar are examined in time domain results. The topside module is hooked with rigid sling through the crane. Long-crested irregular waves with

Corrending author Jong-Hyun Lee: 180-1 Songdo-Dong, Yeonsu-Gu, Incheon, 032-200-2486, naoe@rist.re.kr
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seven different heading directions are considered in order to check directional wave effects. And the impacts of the module on the spar hull are investigated.

2. Equations of Motion in Time Domain Analysis

2.1 Governing Equation

The equations of motions of two hydro-dynamically interacting bodies (i.e. the heavy lift vessel with the installed spar), and the lifted topside module can be written as:

$$\sum_{j=3,5}[(m_{ij}^{\overline{\overline{mn}}}+A_{ij}^{\overline{\overline{mn}}}(\infty))\ddot{\xi}_j^{\overline{\overline{n}}}+\int_{-\infty}^{t}L_{ij}^{\overline{\overline{mn}}}(t-\tau)\dot{\xi}_j^{\overline{\overline{n}}}(\tau)d\tau+C_{ij}^{\overline{\overline{mn}}}\xi_j^{\overline{\overline{n}}}=(F_j^{\overline{\overline{n}}})^E+(F_j^{\overline{\overline{n}}})^I] \tag{1}$$

Where, $()^{\overline{\overline{m}}}$ and $()^{\overline{\overline{n}}}$ = $()^{\overline{\overline{1}}}$, $()^{\overline{\overline{2}}}$, $()^{\overline{\overline{3}}}$ refer to body 1, 2 and 3 respectively for the heavy lift vessel, transport barge and the topside module. The indices i = 3, 5 indicate the direction of force, and j = 3, 5 refer to heave and pitch modes of motion respectively. $\xi_j^{\overline{\overline{n}}}$, $\dot{\xi}_j^{\overline{\overline{n}}}$, $\ddot{\xi}_j^{\overline{\overline{n}}}$ are the motion, velocity and acceleration of body n in the j-th mode respectively. $(F_j^{\overline{\overline{n}}})^E$ and $(F_j^{\overline{\overline{n}}})^I$ are respectively the external wave exciting force (moment understood hereafter) and internal force on body n. $m_{ij}^{\overline{\overline{mn}}}$ is an element of mass matrix, $A_{ij}^{\overline{\overline{mn}}}(\infty)$ is the added mass at infinity frequency, $L_{ij}^{\overline{\overline{mn}}}(\tau)$ is the retardation function at time τ and $C_{ij}^{\overline{\overline{mn}}}$ is the restoring force due to a change in buoyancy.

The added mass at infinity frequency and the retardation functions (Oortmerssen and Pinkster, 1976) can be obtained by means of sine Fourier transform of frequency dependent added mass and Fourier transform of damping coefficients.

2.2 Applied Forces

The applied forces are classified into the wave excitation induced external force, $(F_j^{\overline{\overline{n}}})^E$, and the effect of motion induced internal force, $(F_j^{\overline{\overline{n}}})^I$. Both external and internal forces are mainly used for the equations of coupled hydrodynamic bodies motion given by Eq. (1) for mafting events. After first investigations of the motions, impact forces is calculated from the converted relative motion results. The impact forces is treated as local event forces that occur at a specific time.

2.2.1 External forces

When a body $\overline{\overline{m}}$ is subject to irregular long-crested waves of elevation ζ, at the origin of the space-fixed system, is given in Eq. (2) and the wave amplitude component for a given wave spectrum $S(w_i)$ is given in Eq. (3).

$$\zeta=\sum_{1}^{N}a_i\sin(k_i(X\cos\beta+Y\sin\beta)-\omega_it+\epsilon_i) \tag{2}$$

$$\zeta_i=\sqrt{2S(\omega_i)\triangle\omega} \tag{3}$$

where a_i is the amplitude component at wave frequency ω_i with wave heading angle β, and ϵ_i is the random phase, and N is the number of components. $\triangle\omega$ is a constant difference between two successive frequencies.

In the present study, the Pierson-Moskowitz, P-M, spectrum, given by Eq. (4) for a fully developed sea, is used for the site installations of the spar hull and the topside module in the Gulf of Mexico.

$$S(\omega)=\frac{5}{16}H_s{}^2\frac{\omega_0^4}{\omega^5}e^{-1.25(\omega/\omega_0)^{-4}} \tag{4}$$

where w_0 is the modal frequency and is related to the significant wave height, H_s, by $w_0=0.161\ g/H_s$. Since the installation operations should be conducted in a very mild sea condition, with a 1.52 m of H_s and 6 sec of zero crossing period is assumed in the present investigation.

The body $\overline{\overline{n}}$ may experience the following wave exciting force, $(F_j^{\overline{\overline{n}}})^E$, with the expression of the amplitudes of wave excitation force, f_i, and the phase of the wave exciting force component, α_i.

$$(F_j^{\overline{\overline{n}}})^E=\sum_{1}^{N}a_i f_i\sin(k_i(X\cos\beta+Y\sin\beta)-\omega_it+\epsilon_i+\alpha_i) \tag{5}$$

2.2.2 Internal forces

For the mating phase illustrated in Fig. 1, the module is being lowered down by the crane and is gradually transferred to the spar. Its lowering velocity is controlled by winding the crane winch at a typical rate of 1185 ton/sec and the maximum lowering velocity is assumed to be 0.197 m/sec in the present investigation. It is assumed that there are four ballast tanks whose capacity is 6000 tonnes each and that the operating rate of ballast pump, r_B, is 6.7 tonnes/sec. The distance, d_B, between the combined centres of gravity of the tanks, each being loaded equally and simultaneously, and the heavy lift vessel is taken as 74.9 m. The ballast trim moment, M_B, is shown as follows:

$$M_B=4\int_{t_1}^{t_{\max}}\gamma_B d_B\,dt \tag{6}$$

When the module is lowered, the air gap between the module and spar is computed as the relative vertical motion, $\overrightarrow{\overline{\overline{\xi_3^{2-3}}}}$, of the module to the spar in the form with respective point A and B in Fig. 1:

$$\overrightarrow{\overline{\overline{\xi_3^{2-3}}}}=\left[A^{\overline{\overline{2}}}\right]\left(\overrightarrow{\xi^{\overline{\overline{2}}}}-\overrightarrow{\xi_A^{\overline{\overline{2}}}}\right)-\left[A^{\overline{\overline{3}}}\right]\left(\overrightarrow{\xi^{\overline{\overline{3}}}}-\overrightarrow{\xi_B^{\overline{\overline{3}}}}\right) \tag{7}$$

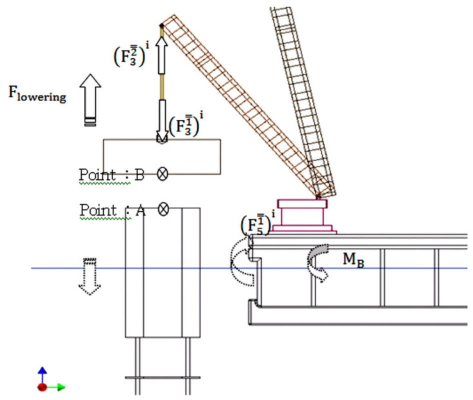


Fig. 1 Force diagram of mating procedure

where, $[A]$ is a transformation matrix (Chakrabarti, 2005) for a successive roll, pitch and yaw motions derived in the form:

$$[A]=\begin{bmatrix} \cos\xi_5\cos\xi_6 & \cos\xi_5\sin\xi_6 & -\sin\xi_5 \\ \sin\xi_4\sin\xi_5\cos\xi_6-\cos\xi_4\sin\xi_6 & \sin\xi_4\sin\xi_5\sin\xi_6+\cos\xi_4\cos\xi_6 & \cos\xi_5\sin\xi_4 \\ \cos\xi_4\sin\xi_5\cos\xi_6+\sin\xi_4\sin\xi_6 & \cos\xi_4\sin\xi_5\sin\xi_6-\sin\xi_4\cos\xi_6 & \cos\xi_5\cos\xi_4 \end{bmatrix} \tag{8}$$

Eq. (8) can be used for the general case. However because heave and pitch motions are mainly focused and computed in the scope of the present research, the air gap formulation can be simplified as follows:

$$\overline{\overline{\xi_3^{2-3}}}=-\xi_3^{\bar{\bar{2}}}+d_{deck}\tan\xi_5^{\bar{\bar{1}}}+\xi_3^{\bar{\bar{1}}}+\frac{1}{2}h_d \tag{9}$$

The ballast control is started when the air gap between the module and the spar is arbitrary chosen 3m distance. The air gap between the module and the spar can also be calculated using Eq. (9).

$$F_{lowering}=\frac{r_{\max}}{v_{lif}}+\frac{M_B}{d_{deck}} \tag{10}$$

The lowering force, $F_{lowering}$, given by Eq. (10) during the mating phase is derived with the maximum crane winch power, r_{max}, lifting velocity, v_{lif}, and distance from the COG of the heavy lift vessel to the lifting point on the topside module d_{deck}.

Hence, the internal force $(F_3^{\bar{\bar{1}}})^I$ and the moment $(F_5^{\bar{\bar{1}}})^I$ on the heavy lift vessel given with deck mass, m_{deck}, and gravity acceleration, g, are as follows:

$$\begin{aligned}(F_3^{\bar{\bar{1}}})^I &= -m_{deck}\,g+F_{lowering} \\ (F_5^{\bar{\bar{1}}})^I &= (F_3^{\bar{\bar{1}}})^I\,d_{deck}\end{aligned} \tag{11}$$

2.2.3 Inertial impact force

The risks of impact between the topside module and the spar are expected because of wave induced motions in the assumed sea conditions. The impact loads are mainly due to global motions, but it is also important to check loading of the sling wire, supporting base (permanent supports and horizontal guides) and workability. The impact event occurs when the transient relative vertical motion of the module towards the spar exceeds the air gap in other words the impact means negative air gap . When the module hits with an impact velocity, it will vibrate on the supporting base of the spar. This vibration motion is governed by the stiffness of the appropriate base structure and the inertial impact velocity.

The equation of the vibration motion $\xi_V^{\bar{\bar{3}}}$ of the module can be written as:

$$m_{deck}\,\ddot{\xi}_V^{\bar{\bar{3}}}=m_{deck}\,g-C\dot{\xi}_V^{\bar{\bar{3}}}-K\xi_V^{\bar{\bar{3}}} \tag{12}$$

where C and K are the damping and stiffness of the supporting base structure respectively. C is taken as 5% of critical damping. The value of K is $(EA/L)^{\bar{\bar{2}}}$ for the structural properties with modulus of elasticity, E, effective spar area, A, and spar length L of the supporting base on the spar in the present study. The inertial impact velocity $v_{inertial}$ is assumed as the relative vertical velocity of the module relative to the barge or the spar in the form:

$$v_{inertial}=\left|\frac{d\overline{\overline{\xi_3^{2-3}}}}{dt}\right| \quad when\ \overline{\overline{\xi_3^{2-3}}}\approx 0 \tag{13}$$

In the case of the mating operation, the spar itself will experience an internal force $(\xi_3^{\bar{\bar{2}}})^I$ which is expressed as being per unit length on a cylinder of diameter $D^{\bar{\bar{2}}}$ with water density ρ by:

$$(\xi_3^{\bar{\bar{2}}})^I=\frac{1}{2}\rho\,C_S D^{\bar{\bar{2}}}(v_{ap})^2 \tag{14}$$

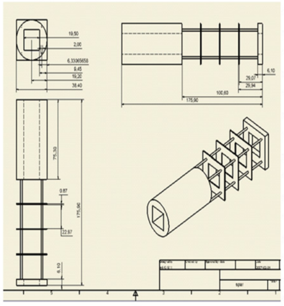
The theoretical value of slamming coefficient Cs , on rigid horizontal cylinders, similar to spar main hull shape, was investigated by (Sapkaya, 1981) and estimated as π which is assumed to be used. By applying the conservation of momentum, the applied velocity $v$ap with the mass of spar mspar after impact is given as:

$$v_{ap}=\frac{m_{spar}v_{inertial}}{m_{spar}+m_{deck}} \tag{15}$$

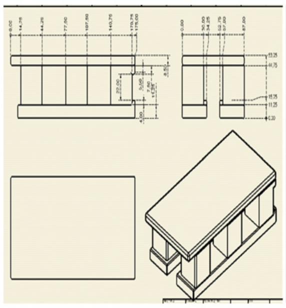
3. Numerical Computations

3.1 Numerical Modeling

The spar used in the present investigation is a truss spar with squared moon pool and three anti-heave plates based on a Horn mountain spar design and its principal particulars are shown in Fig. 2. The topside module is assumed to be an integrated deck unit for the truss spar mentioned above. The module is assumed as a simple box whose mass is 6000 tonnes and dimensions are 60 m long, 60 m wide and 20 m depth. Thus, the centre of gravity of the module is located at its geometric centre. A dynamically positioned heavy lift vessel with cranes based on Saipem S-7000 shown in Fig. 2 is assumed to be employed. The displacement of the spar hull and additional weights due to water ballast and mooring chains are considered for the installation analyses.



Length overall	175.90 m
Buoyancy cylinder	
Length / Diameter	75.30 m / 38.40 m
Moon pool	19.50 m
Anti-heave plate	
Length / Breadth	38.40 m
Depth	0.87 m
Draught	140.9 m
Freeboard	35 m
Displacement	45165 tonnes
KG / KB	82.9 m / 95.6 m
Radius of roll & pitch gyration	33.2 m
Radius of yaw gyration	0 m



Length overall	175 m
Breadth	87 m
Depth	53.25 m
Draught	23.5 m
Displacement	214903 m^3
KG	11.25 m
Maximum lifting rate	1185.52 ton/s
Radius of roll gyration	45.43 m
Radius of pitch gyration	130.92 m
Radius of yaw gyration	0 m

Fig. 2 Basic Drawing and principal particulars of Spar and Crane vessel

Considering the lift capacity and range of crane vessel, the longitudinal distance from the upper-deck of the heavy lift vessel to the side hull of the topside module is set to 25 m and which corresponds to 126.7 m from the vessel's centre of gravity to the module's centre of gravity. The barge's centre of gravity is assumed to be in the vertical centre line with the module's centre of gravity and the applied wave profile in time domain of 1.52 m H_s are illustrated in Fig. 3.

Using the diffraction theory based program MBMOTION3D which accounts for hydrodynamic interactions between multi-bodies, numerical computations have been carried out to predict the added mass and damping coefficients and the wave exciting forces on both the heavy lift vessel and the spar at seven different headings and a range of wave frequencies in frequency domain.

3.2 Numerical Results

The effective transferred weight of the topside module being loaded on the spar and the corresponding variation of module weight on the heavy lift vessel in still water in the mating phase are shown in Fig. 4. The weights of the module and pumped on-board water ballast are treated as additional weights on the heavy lift vessel during the mating phase. The topside module is hoisted at an elevation of 10m above the spar before it is being lowered down by winding the winch and adjustments to the ballasting water. The lowering velocity is controlled by the crane vessel winch and assumed as 0.197 m/s. Four ballast tanks whose capacity is 6000 tonnes each and that the operating rate of ballast pump is 6.7 tonnes/sec. The weight transfer takes place at about 300 sec from the start, and finishes at 650 sec when the weight of the module has been completely transferred to the spar. The elapsed time heave motion of the heavy lift vessel in still water due to the progressive transfer of deck weight and the corresponding heave displacement of the spar due to the transfer of the module weight are shown in Fig. 4. The slope results of transferring mass are affected by winch power and speed and constant winch power control is assumed during mating. The pitch angle of the crane in still water in the mating phase is demonstrated in Fig. 4. The resulted trim angle at 300 sec is caused by the transfer of module weightand ballasting water. The ballast water is used for making anti- pitching moments.

The corresponding the heave motion of the spar and pitch, heave motions of the heavy lift vessel in irregular waves in various wave directions are shown in Fig. 5. The coupled frequency domain motion characteristics are calculated before computing time domain motion results (Lee, 2010). In the results, the dynamics of spar mooring is negated but considered as constant value. The inertial velocity calculation is based on the relative distance between the module and floating structure. The results show that beam seas (90 degree) induce smaller pitch motion of the heavy lift vessel than for the other wave attack angles. The effect of the internal forces on the pitch motion of the heavy lift vessel during mating in the irregular waves is insignificant as illustrated however the effect of the internal forces on the heave motions of the crane vessel and the spar is noticeable than the pitch motions of crane vessel.

Due to the relative motion floating structure, several impacts

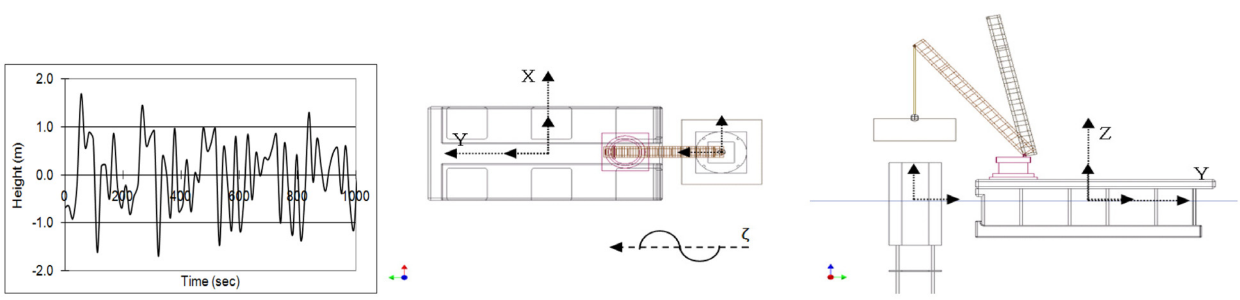


Fig. 3 Applied wave profile and schematic view of mating set-up

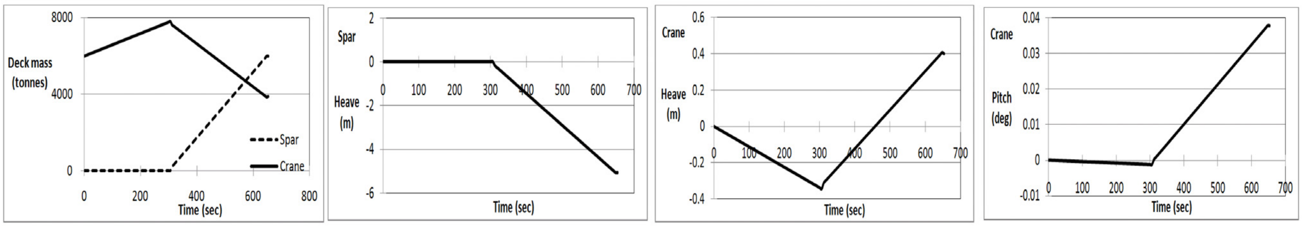


Fig. 4 Mating phase results in still water (Effective module weight, Heave motion of spar, Heave & pitch movement of crane vessel)

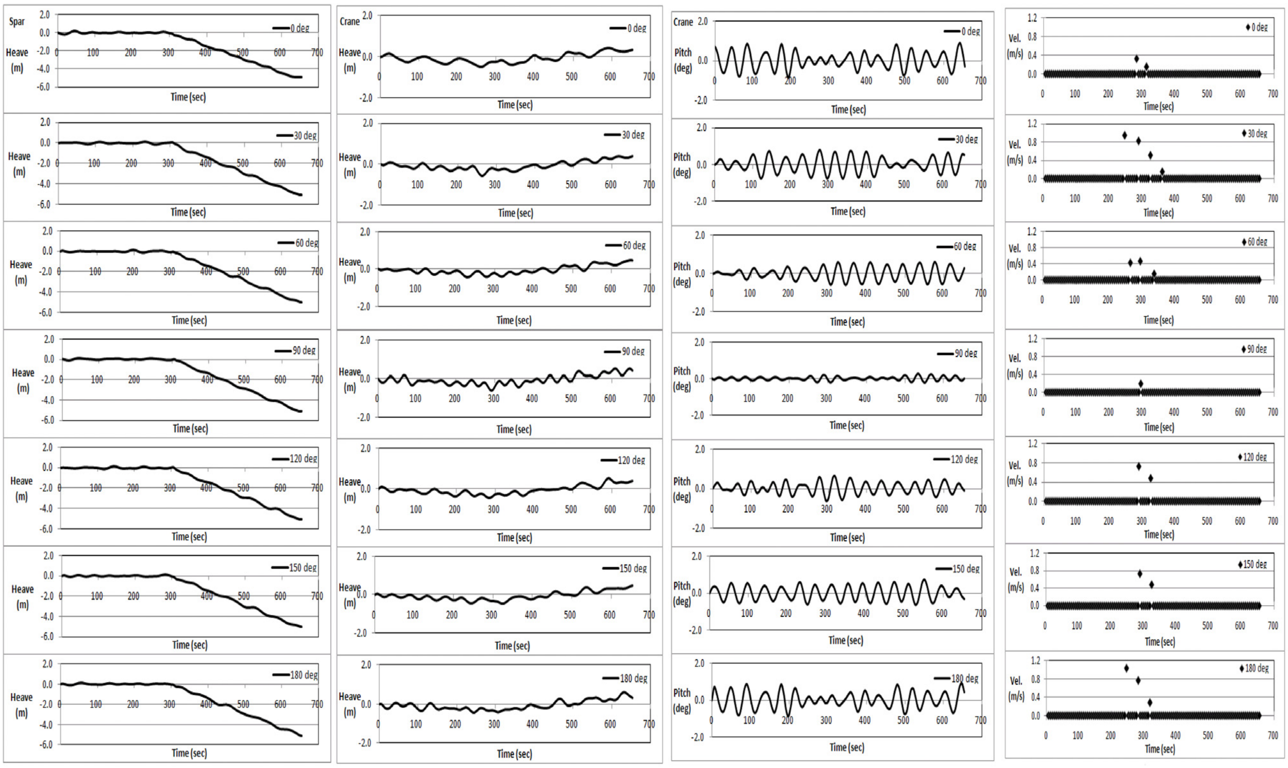


Fig. 5 Mating phase results in irregular seas at various wave angles (Heave motion of spar, Heave & pitch motion of crane, Inertial impact ivelocity)

possibility and its velocity are observed and the results are illustrated in Fig. 5 impact velocity results. Beam-sea is the most favourable condition both in lifting and mating operation.

4. Conclusion

The coupled multi-body motions of the heavy lift vessel, the spar, and the topside module have been calculated for both calm water and for irregular waves coming from different directions. The effects of hydrodynamic interactions between the vessel and the spar hull during the lowering and mating stages have been considered in time domain simulations of the coupled multi-body motions in random seas.

The expressions for internal forces due to load transfer and ballasting effects have been derived and numerical calculation have been computed for mating phases. The effect of ballasting water on the heave and pitch motions of the lifting vessel as well as the effect of the internal force on the heave motions of the spar are noticeable in both calm water and irregular sea conditions. The heavy lift vessel during lifting and mating suffers smaller pitch motions in beam waves than for other wave directions.

The possible impacts of the module on the spar hull in the mating phase have been investigated. Interestingly, the occurrences and magnitudes of the inertial impact velocity in the mating phase are lower in beam sea than those in other wave directions.

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