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Dynamic Analysis of Topside Module in Lifting Installation Phase

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ABSTRACT: *The installation phase for a topside module suggested can be divided into 9 stages, which include start, pre-lifting, lifting, lifted, rotating, positioning, lowering, mating, and end of installation. The transfer of the topside module from a transport barge to a crane vessel takes place in the first three stages, from start to lifting, while the transfer of the module onto a 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 significant wave height (1.52 m), with suggested force equilibrium diagrams. The effects of the hydrodynamic interactions between the crane vessel and barge during the lifting stage have been considered. The internal forces caused by the load transfer and ballasting are derived for the lifting phases. The results of these internal forces for the calm water condition are compared with those in the irregular sea condition. Although the effect of pitch motion on the relative vertical motion between the deck of the floating structure and the topside module is significant in the lifting phases, the internal force induced pitch motion is too small to show its influence. However, the effect of the internal force on the wave-induced heave responses in the lifting phases is noticeable in the irregular sea condition because the transfer mass-induced draught changes in the floating structure are observed to have higher amplitudes than the external force induced responses.*

1. Introduction

Using a lift crane vessel is the most common installation method for offshore floating structures and is assumed in this study. The mass-transfer force and the wave drift force induced large horizontal relative motions between barge and crane vessel can be significant for the lifting procedure. But the horizontal motions of floating bodies are restricted with mooring line in the whole procedure and maneuvering to the spar can be simply described as that the structure is lifted from the transportation barge by a lift crane and lowered to the target position in vertical and rotational aspects.

The heavy lift operation by means of a crane vessel consists of three distinct systems: the crane vessel, the lifting slings and the structure being lifted away from the transport barge. The loads experienced by the crane vessel are the hook load, and the various wave-induced loads. The hook load 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 transportation barge (Choo, et al. 1993). The loads experienced by the transportation barge are wave-induced loads, the loss of structure weight by the lifting, and an impact load if the vertical motion of the barge 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 lift analysis in the time domain, the following information needs to be examined: a) External forces induced by waves b) Internal forces arisen from the mass of the lifted structure and the lifting velocity c) Motion responses of the crane vessel and the barge for lifting due to the various external and internal forces.

In the present investigation, the lifting operations for a topside module by means of a crane vessel are examined. The assumed 6000 tonne topside module is carried by the flat top barge S44, and is lifted by the crane vessel specified in Section 3.

The hydrodynamic analysis of two floating structures is accomplished by using of a diffraction theory based program MBMOTION3D (Chan 2003). The interacting coupled body hydrodynamics are separately considered for the lifting operation of the crane vessel and barge S44. Each of the two floating structures (the crane vessel and barge S44) has potentially six degrees of freedom but the topside module has three degrees of freedom. Therefore, theoretically a total of 15 degrees of freedom can be considered for the lifting operations. In the present investigation however, lateral motion is assumed to be small and is thus not considered because the floating structure is assumed to be constrained by mooring lines. During the lifting, 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 barge are examined in time domain results. The topside module is hooked with sling through the crane and this sling is assumed as rigid i.e. no elasticity. Long-crested irregular waves with seven different heading directions are considered in order to check directional wave effects.

The installation phase is divided into 9 stages: start, pre-

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This research is based on authors's Ph.D thesis in Newcastle (2010) lifting, lifting, lifted, rotating, positioning, lowering, mating and end of installation. However after the lifting stage is over, rotating to the spar at -90 deg and mating stages are not included in the present study.

2. Equations of Motion

2.1 Governing Equation

The equations of motions of two hydrodynamically interacting bodies (i.e. either the crane vessel with the barge S44 or the crane vessel with the installed spar), and the 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 crane vessel, barge S44 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 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 can be obtained by means of sine Fourier transform of frequency dependent added mass and Fourier transform of damping coefficients (Oortmerssen and Pinkster, 1976) respectively as:

$$A_{ij}^{\overline{\overline{mn}}}(\infty)=A_{ij}^{\overline{\overline{mn}}}(\overline{\omega})+\frac{1}{\overline{\omega}}\int_0^\infty A_{ij}^{\overline{\overline{mn}}}(t)\sin(\overline{\omega}t)\,dt \tag{2}$$

$$L_{ij}^{\overline{\overline{mn}}}(t)=\frac{2}{\pi}\int_0^\infty B_{ij}^{\overline{\overline{mn}}}(\omega)\cos(\omega t)\,d\omega \tag{3}$$

where $\overline{\omega}$ is an arbitrarily chosen value of frequency ω. $A_{ij}^{\overline{\overline{mn}}}$ and $B_{ij}^{\overline{\overline{mn}}}$ are respectively the added mass and damping coefficients of body m due to the j-th mode of motion of body n at frequency ω. It should be noted that $A_{ij}^{\overline{\overline{mn}}}$, $L_{ij}^{\overline{\overline{mn}}}$, $B_{ij}^{\overline{\overline{mn}}}$ are zero for m or n = 3 due to no interaction and no contact with water.

2.2 Forces

The applied forces are classified into external and internal forces. The external force is the excitation force $(F_j^{\overline{\overline{n}}})^E$ induced by the irregular waves while the internal force $(F_j^{\overline{\overline{n}}})^I$ is derived from the effect of lifting motions. Both internal and external forces are mainly used for the equations of coupled bodies motion given by Eq. (1) for lifting events. After first investigations of the motions, impact forces can be calculated from the converted relative motion results. The impact forces should be 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 by:

$$\zeta=\sum_1^N a_i\sin(k_i(X\cos\beta+Y\sin\beta)-\omega_i t+\epsilon_i) \tag{4}$$

where a_i is the amplitude component at wave frequency ω_i and ϵ_i is the random phase, and N is the number of components. The body $\overline{\overline{n}}$ may experience the following wave exciting force:

$$(F_j^{\overline{\overline{n}}})^E=\sum_1^N a_i f_i\,\sin(k_i(X\cos\beta+Y\sin\beta)-\omega_i t+\epsilon_i+\alpha_i) \tag{5}$$

in which f_i and a are respectively the amplitudes of wave excitation force and the phase of the wave exciting force component. The wave amplitude component for a given wave spectrum $S(w_i)$ is given by:

$$\zeta_i=\sqrt{2S(\omega_i)\triangle\omega} \tag{6}$$

where $\triangle\omega$ is a constant difference between two successive frequencies.

In the present study, the Pierson-Moskowitz, P-M, spectrum, given by Eq. (7) for a fully developed sea, is used for the installation site of the topside module in the Gulf of Mexico.

$$S(\omega)=\frac{5}{16}H_s\frac{\omega_0^4}{\omega^5}e^{-1.25(\omega/\omega_0)^{-4}} \tag{7}$$

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 will be conducted in a very mild sea condition, a 1.52 m significant wave height with a zero-crossing period of 6 sec is assumed in the present investigation.

2.2.2 Internal forces

The source of internal forces on the crane vessel in the lifting phase is mainly from the lifting action on the topside module and due to water ballast pumped into the ballast tanks of the vessel. When the lifting is started by winding the crane winch, the weight of the topside module is gradually transferred to the lifting cables at a typical rate of 1185 ton/sec. Furthermore, the water ballast being pumped into the vessel generates a tilting moment M_B which in turn produces a lifting force equal to M_B/d_{deck} where d_{deck} is the distance from the centre of gravity of the crane vessel to the lifting point on the topside module. Hence, the total lifting force acting on crane vessel: $(\bar{\bar{F}}_3^1)^I$ shown in Fig. 1 is:

$$(\bar{\bar{F}}_3^1)^I = \frac{\min(r_w, r_{\max})}{v_{lif}} + \frac{M_B}{d_{deck}} \tag{8}$$

where r_w and r_{max} are the applied winch power and its maximum value respectively and υ_{lif} is the lifting velocity. The maximum lifting velocity is assumed to be 0.197 m/s in the present investigation.

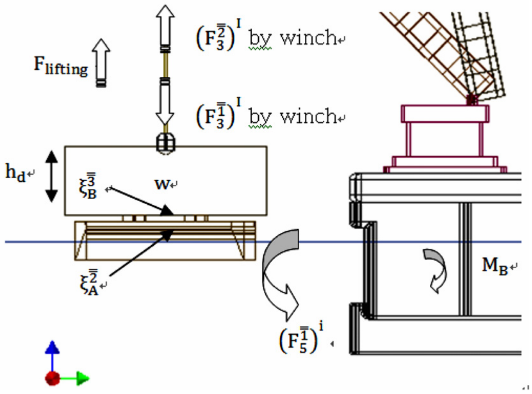


Fig. 1 Force diagram of lifting procedure

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 centre of gravity of the tanks, each being loaded equally and simultaneously, and the C.O.G of the crane vessel is taken as 74.9 m. The ballast trim moment M_B is shown in Eq. (9):

$$M_B = 4\int_{t_i}^{t_{\max}} \gamma_B \, d_B dt \tag{9}$$

The module will not be lifted off the barge until the force $(\bar{\bar{F}}_3^2)^I$ is enough to overcome the weight of the module. By Newton's third law of motion, this force acts downward as $(\bar{\bar{F}}_3^1)^I$ on the crane block while it acts upward as $(\bar{\bar{F}}_3^2)^I$ on the barge before the module is lifted off. This lift force can also be interpreted as the loss of deck load on the barge. Thus, as shown in Fig. 1, we have:

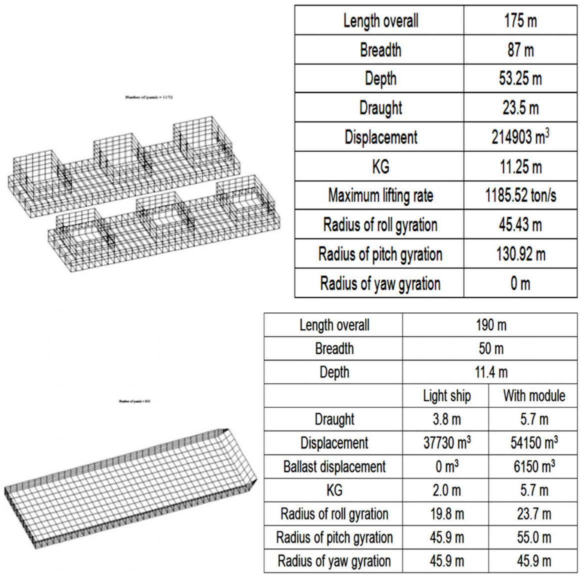
$$(\bar{\bar{F}}_5^1)^I = (\bar{\bar{F}}_3^1)^I \, d_{deck} \tag{10}$$

$$(\bar{\bar{F}}_3^2)^I = -(\bar{\bar{F}}_3^1)^I = F_{lifting} \tag{11}$$

3. Numerical Computations

3.1 Numerical Modeling

Prior to the time-domain dynamic lift analysis, a multi- body diffraction analysis in the frequency domain was carried out for the crane vessel together with barge S44. The crane vessel with 1172 panels, and barge S44 with 810 panels as shown in Fig. 2.



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

Length overall	190 m	
Breadth	50 m	
Depth	11.4 m	
	Light ship	With module
Draught	3.8 m	5.7 m
Displacement	37730 m^3	54150 m^3
Ballast displacement	0 m^3	6150 m^3
KG	2.0 m	5.7 m
Radius of roll gyration	19.8 m	23.7 m
Radius of pitch gyration	45.9 m	55.0 m
Radius of yaw gyration	45.9 m	45.9 m

Fig. 2 Panel model and principal particulars of crane vessel and Barge S44

Considering the lift capacity and range, the longitudinal distance from the upper-deck of the crane vessel to the side hull of the topside module is set to 25 m and which corresponds to 137.5 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 as shown in Fig. 3 for the lifting case. Clearly, undertaking lifting operations in waves is of great interest. Figure 3 shows the time series of the assumed wave profile for irregular waves of 1.52 m significant wave height.

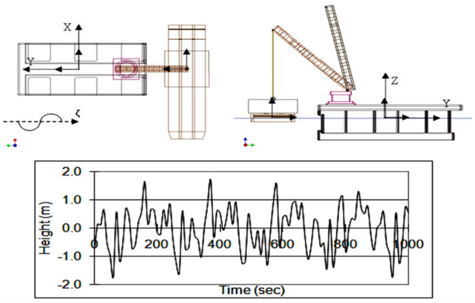


Fig. 3 Schematic view of lifting set-up and applied wave profile during lifting

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 crane vessel and the barge S44 for the lifting phase at seven different headings and a range of wave frequencies in frequency domain in each case.

3.2 Numerical Results

The lifting operation starts with winding the winch and controlling ballast water in the crane vessel and then the weight of the topside module on the barge is reduced progressively and transferred to the crane vessel. The crane vessel suffers an increasing pitching moments to an acceptable level because of the lifted module's weight, so ballast water control is needed to reduce lifting-induced pitching moment.

The effective weight transfer results of the module from the barge shown in Fig. 4 demonstrates the variance of weight on the crane vessel. The increase of weight on the crane vessel includes not only the transferred weight of the module but also the on-loading of ballast water weight into the cranevessel. Until 70% of the weight of the module is transferred to the crane, the sea-fastenings are not removed, while the winch is used to approximately 70~80% of its power. Rapid ballasting and winding of winch are executed when the topside module is finally detached from the barge. This takes place at about 348 sec as calculated in the present study.

The trim angle change of the crane vessel in still water during lifting is demonstrated in Fig. 4. The effects of ballast water on the draught and trim of the vessel are observed after the module is lifted off. Since the centre of gravity of the module is in line with the centre of gravity of barge S44, no trim change occurs for the barge in still water during lifting.

The response motions of the S44 and of the crane vessel in different wave angles are shown in Fig. 5 that shows respectively the corresponding time series of the heave motion of

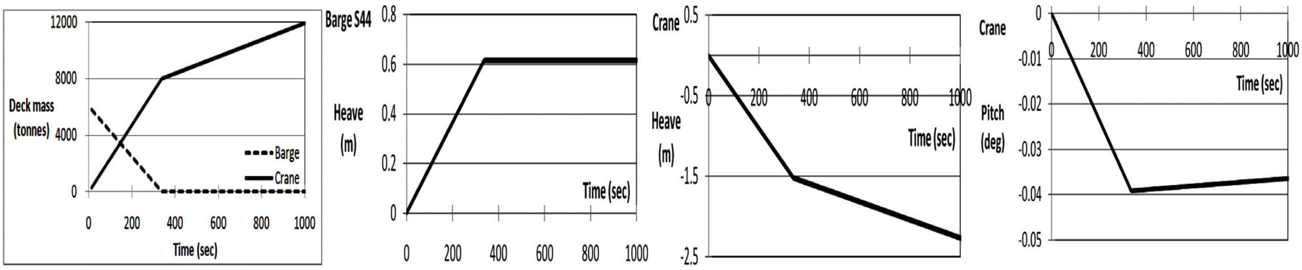


Fig. 4 Effective module weight, heave movement of barge and heave and pitch movement of crane vessel in still water

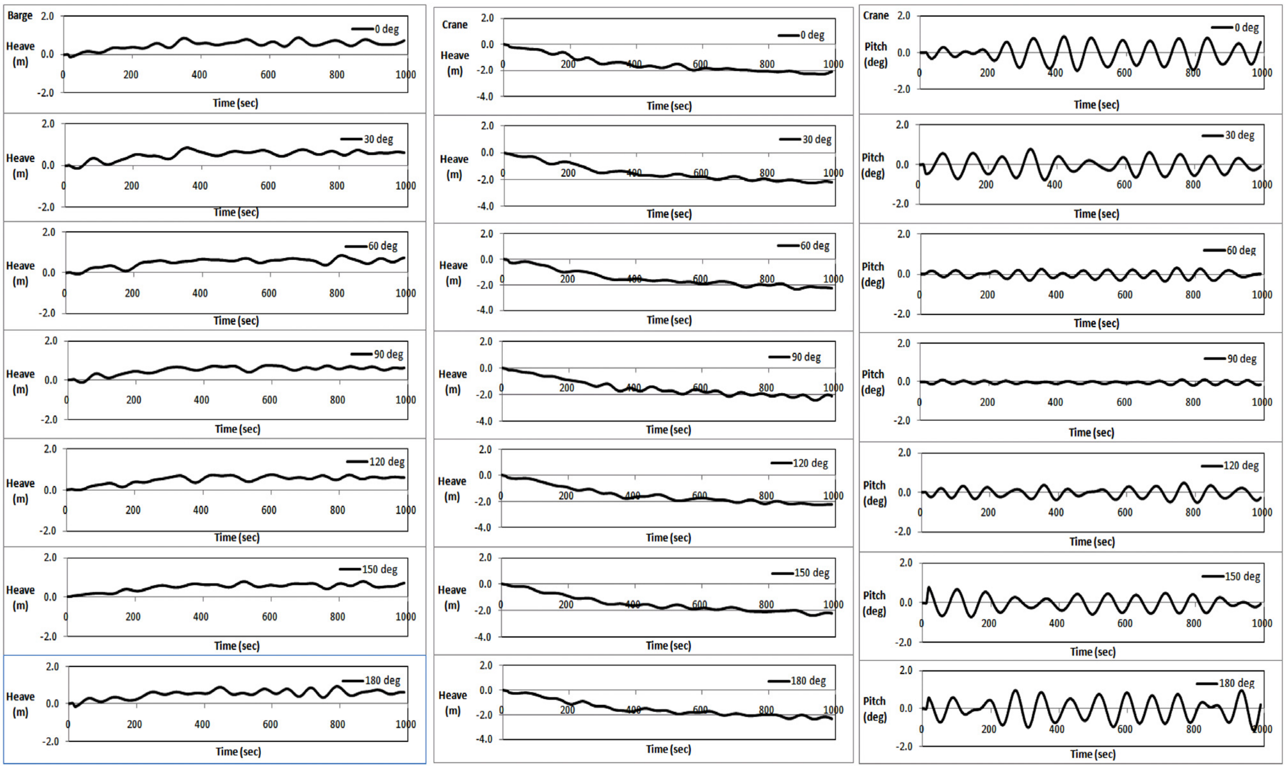


Fig. 5 Heave movement of barge S44 and heave and pitch movement of crane vessel in irregular seas at various wave angles

barge S44 and of the pitch and heave motions of the crane vessel in the lifting phase for seven different wave heading directions. Wave attack angles are set from 0° to 180° at 30° intervals. Stern wave is 0°, beam wave is 90° coming from the starboard side, head wave is 180°, and beam wave is 270° from the port side. However, owing the symmetry, only the starboard side results are given. It is evident in Fig. 5 that the crane vessel in beam seas experiences smaller pitch motions than in other wave directions. The effects of the internal forces on the heave motions of the crane vessel and of the barge S44 are noticeable, as shown in Fig. 4

4. Conclusion

The coupled multi-body motions of the crane vessel, the barge, and the topside module in time domain simulation are calculated in both calm water and in irregular waves with suggested force equilibrium diagrams. The applied wave conditions are 1.52 m significant wave height with 7 different directions.

The expressions for internal forces due to load transfer and ballasting effects are derived. The variation of deck mass results with the crane and the barge are examined in order to obtaininternal forces. Not only internal forces, but also external forces and other hydrodynamic forces were modified to time domain and input to the governing equation.

The effect of ballasting water on the heave and pitch motions of the crane vessel as well as the effect of the internal force on the heave motion of the barge is noticeable in both calm water and irregular sea conditions. 0.6 m and 2.5 m of heave draft change are observed on the heave motion of barge and crane vessel respectively in both conditions. Obviously, the crane vessel suffers smaller pitch motions in beam waves than for other wave directions and internal force induced heave motion shows much higher influence than pitch motion on crane vessel.

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