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Wave Exciting Forces of a Free Floating Semi Submersible in Regular Waves

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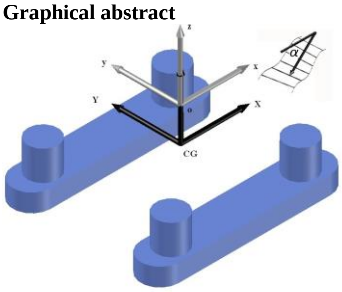
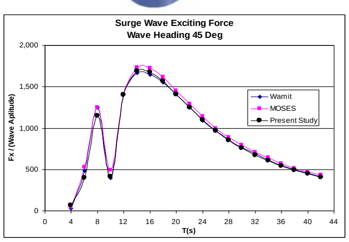
Graphical abstract





Abstract

Drilling and production of oil by semi submersible take place in many locations throughout the world. Generally, floating structures play an important role in exploring the oil and gas from the sea. The force and motion prediction of offshore structures may be carried out using time domain or frequency domain models or model tests. In this paper the frequency domain analysis used because it is the simplified and linearized form of the equations of motion. The time domain analysis, unlike frequency domain models, is adequate to deal with non-linearities such as viscous damping and mooring forces, but it requires sophisticated solution techniques and it is expensive to employ. In this paper, the wave exciting forces of a free floating semi-submersible were carried out using 3D source distribution method within the scope of the linear wave theory. The results obtained from computations were also compared with the results obtained using commercial software MOSES and WAMIT.

Keywords: Semi submersible; floating structures; 3D source density distribution technique

1.0 INTRODUCTION

Floating structures such as ship, semi-submersible, FPSO, TLP, breakwater and other free floating or moored structures, are subjected to wave, wind and current at sea. They have six-coupled degrees of freedom of motions. Namely, linear motions are surge, sway and heave, and angular motions are roll, pitch and yaw. Oscillating of floating structure affects the loading and offloading operation systems.

There are different theories for studying motion of floating structure such as strip theory and potential theory. In this paper 3D source density distribution technique is used to get the potential over the floating structure. Having flow velocity potentials on and off the panels, hydrodynamic coefficients of floating structure can be determined. Using Bernoulli's equation leads to calculation of pressure distribution and forces over the floating structure. L. Hess and A. M. O. Smith [1] studied on the calculation of nonlifting potential flow about arbitrary 3D bodies. They utilized a source density distribution on the surface of the body and solved for distribution necessary to lake the normal component of the fluid velocity zero on the boundary. Plane quadrilateral source elements were used to approximate the body surface, and the integral equation for the source density is replaced by a set of linear algebraic equations for the values of the source density on the quadrilateral elements. By solving this set of equations, the flow velocity both on and off the surface was calculated.

Van Oortmerssen [2] dealt with the hydrodynamic forces between two structures floating in waves by using a three-dimensional linear diffraction theory and the results agree with experiments well.

S. Wu *et al*. [3] studied the motion of a moored semi in regular waves and wave induced internal forces numerically and experimentally. In the mathematical formulation, they modeled the moored semi as an externally constrained floating body in waves, and derived the linearized equation of motion.

O. Yilmaz and A. Incecik [4] analyzed the extreme motion response of moored semi. They developed and employed two different time domain techniques since there are strong nonlinearities in the system due to mooring line stiffness and damping and viscous drag forces. First one is for the simulation of wave frequency motions in which the first-order wave forces are the only excitation forces. First-order wave forces acting on semi-submersibles are evaluated according Morison equation, current effect is taken into account by altering the drag term in Morison equation. Second one is to simulate the slowly varying and steady motions under the excitation of slowly varying waves, current and dynamic wind forces. Slowly varying wave forces are calculated using the mean drift forces in regular waves and applying an exponential distribution of the wave force record in irregular waves.

Muhittin Soylemez [5] developed a prediction technique to simulate the motion response of the damaged platform under wave, wind and current forms. The equation of motion was obtained using Newton's second law and the numerical solution technique of nonlinear equations of motion is explained for intact and damaged cases. The analysis technique employs large displacement non-linear equations of motion. Solutions were obtained in the time domain to predict the motion characteristics.

Clauss, *et al*., [8] analyzed numerically and experimentally the sea-keeping behavior of a semi submersible in rough waves in the North Sea. They used panel method TiMIT (Time-domain investigations, developed at the Massachusetts Institute of Technology) for wave/structure interactions in time domain. The theory behind TiMIT is strictly linear and thus applicable for moderate sea condition only.

Newman [9] carried out convergence studies using WAMIT in the frequency domain for representative floating bodies using different discretization schemes.

2.0 MATHEMATICAL MODEL

2.1 Coordinate System

The individual semi submersible is treated as a rigid body having six degrees of freedoms. It is subjected to hydrodynamic forces due to incident waves and radiated and diffracted waves due to other vehicle(s). Two right hand coordinate systems are defined in Figure 1. One is fixed to the space on water surface and the other one is fixed to the centre of gravity.

The fluid is assumed to be incompressible, inviscid and irrotational and the vessel is assumed to be freely floating in open water. Then there exists a velocity potential satisfying Laplace equation together with boundary conditions on the free surface, on the body, and at the bottom, and the radiation condition in the far field. The time dependence of the fluid motion to be considered here is restricted to simple harmonic motion and accordingly the flow filed can be characterized by the following velocity potential:

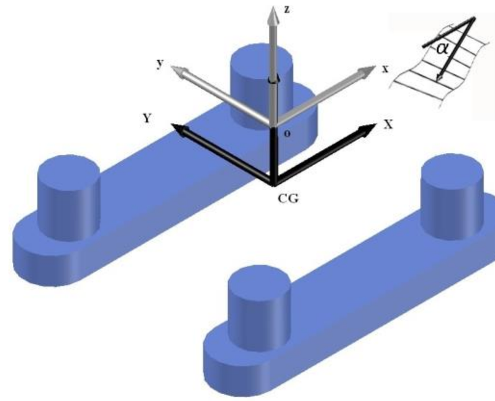


Figure 1 Definition of co-ordinate system

$$\Phi = Re[\phi(x,y,z)e^{i\omega t} \quad (1)$$

$$\phi = -i\omega\left[(\phi_0+\phi_7).\zeta_a + \sum_{j=1}^{6}\left(X_j\phi_j\right)\right] \quad (2)$$

$$\phi_0 = -\frac{ig\zeta_a}{\omega}\frac{\cosh[k(z+h)]}{\cosh kh}e^{ik(x\cos\alpha+y\sin\alpha)} \quad (3)$$

Where,

φ_0=incident wave potential,
φ_7=diffraction wave potential on body
φ_j=potential due to motion of the body in j-th mode,
ω=circular frequency of incident wave
ζ_a= incident wave amplitude,
α= wave heading angle from X –axis

The differential equation governing the fluid motion follows from the application of the continuity equation which yields the Laplace equation. The individual potentials are the solutions of the following Laplace equation:

$$\nabla^2\phi = 0 \quad (4)$$

2.2 Boundary Condition

On the mean wetted surface area of body S, the above linear velocity potentials must satisfy the Laplace equation and also the following boundary conditions:

-linearized free surface condition:

$$\frac{\partial\phi}{\partial z} + \frac{\omega^2}{g}\phi = 0\,, \quad \text{at } z=0 \quad (5)$$

-boundary condition on the sea floor:

$$\frac{\partial\phi}{\partial z} = 0 \quad on\ z = -h \quad (6)$$

Another boundary condition is the wetted surface of the floating bodies. Due to linearization, this boundary condition may be applied on the wetted surface of the floating body in its equilibrium position.

$$\frac{\partial \phi_o}{\partial n} + \frac{\partial \phi_7}{\partial n} = 0\,,\ \ 0n\ \ S \tag{7}$$

$$\frac{\partial \phi_j}{\partial n} = -i\omega n_j\ \text{, on}\ \ S \tag{8}$$

In which n_j is the direction cosine on the surface of the body in the j-th mode of motion and has the following form:

$$n_1 = \cos(n,x)\,,\qquad n_2 = \cos(n,y)\,,\qquad n_3 = \cos(n,z)$$
$$n_4 = (y - y_G)n_1 - (z - z_G)n_2$$
$$n_5 = (z - z_G)n_1 - (x - x_G)n_3$$
$$n_6 = (x - x_G)n_2 - (y - yz_G)n_1$$

And where,
x_G, y_G, z_G = Co-ordinate of the centre of gravity of the body
x, y, z = Investigating point on the wetted surface of the body

The radiation condition of the potentials φ_j, in which in polar co-ordinate:

$$\lim_{r\to\infty}\left(r^{\frac{1}{2}}\left(\frac{\partial \phi}{\partial r} - \frac{i\omega^2}{g}\phi\right)\right) = 0 \tag{9}$$

2.3 Velocity Potential

However, there is no analytical solution for φ_7 and φ_j, so the problem should be solved numerically. According to the 3-D source sink method, the potentials φ_7 and φ_j can be expressed in terms of well known Green functions that can be expressed by the following Equation [4].

$$\phi_j(x,y,z) = \frac{1}{4\pi}\sum_{j=1}^{6}\int\int \sigma(\xi,\eta,\zeta)\,G(x,y,z,\xi,\eta,\zeta)ds \tag{10}$$

Where, (ξ,η,ζ) denotes a point on surface S and $\sigma(\xi,\eta,\zeta)$ denotes the unknown source distribution. The integral is to be carried out over complete immersed surface of the object. The Green function G (source potential) must in order of the representation in Equation (10) to be valid, satisfy all the boundary conditions of the problem with the exception of the body boundary conditions and have a source like behavior. As a result, boundary conditions are reduced only to on wetted surfaces of the bodies. So, the wetted surfaces should be subdivided into panels to transform integral equations to a system of algebraic equations to determine unknown source density over each panel. The appropriate Green function used in this paper to the boundary value problem posed is given by Wehausen and Laitone [7]. After getting the source density, the velocity potentials on each panel can be obtained using the Equation (10).

2.4 Forces and Moments

Once the velocity potential is obtained, the hydrodynamic pressure at any point on the body can be obtained from the Bernoulli's equation and can be written as:

$$\frac{\partial \Phi}{\partial t} + \frac{1}{2}(\nabla\Phi)^2 + \frac{P}{\rho} + gz = 0 \tag{11}$$

Now after putting the value of φ in the Equation (11), the following expression is obtained,

$$-\frac{P}{\rho} = -i\omega\phi + \frac{1}{2}(\nabla\phi)^2 + gz \tag{12}$$

By neglecting the higher order terms, we can write:

$$P = -\rho gz + i\rho\omega\phi \tag{13}$$

As first part of Equation (13) is associated with the hydrostatic and steady forces, so neglecting this part, the first order wave exciting forces or moments and oscillatory forces and moments caused by the dynamic fluid pressure acting on the body can be obtained from the following integrals:

$$F_k e^{-i\omega t} = -i\rho\omega e^{-i\omega t}\int_s \{\phi_0 + \phi_7\}n_k ds \tag{14}$$

$$F_{kj} e^{i\omega t} = -\rho\omega e^{-i\omega t}\int_s \{\omega^2 \bar{X}_j \phi_j\} n_k.ds \tag{15}$$

Where, F_k denotes the k-th component of wave exciting forces or moments, F_{kj} denotes the k-th component of force arising from the j-th component of motion of the body. Moreover, it is customary to decompose the hydrodynamic forces resulting from motion of the bodies into components in phase with the acceleration and velocity of the rigid body motions. These yield the added mass and damping coefficients respectively. These coefficients can be expressed from equation as:

$$a_{kj} = -\rho.Re\left[\int_s \phi_j n_k.ds\right] \tag{16}$$

$$b_{kj} = -\rho\omega.Im\left[\int_s \phi_j n_k.ds\right] \tag{17}$$

Where,
a_{kj}= added mass coefficient matrix of *kj*,
b_{kj}= damping coefficient matrix of *kj*,

The suffixes, *k, j*=1, 2, 3, 4, 5, 6 represent surge, sway, heave, roll, pitch and yaw modes, respectively.

3.0 VALIDATION

To obtain the wave exciting force and moments a computer program has been developed. The computation model expected to be validated by the model tests. But since the tests have not been carried out yet, the results obtained from the computation of a box (Table 1) have been compared with the published results [6]. From Figure 2, it is seen that the surge wave exciting forces are very good agreement with published results obtained from WAMIT and MOSES. On the other hand, from Figure 3, it is seen that for roll wave exciting moments, a little differences occurred in the resonance frequency region. These differences happened due to different methods used by the MOSES and WAMIT. As these softwares used combined strip, panel and Morison element modeling where is in the present study only panel methods have been used. Another reason is that in the resonance frequency region difficult to compute the forces. But overall, a very good agreement has been obtained in both the cases.

Table 1 Principal particulars of the box [6]

L (m)	200
B (m)	40
T (m)	28
Displacement Ton	229640

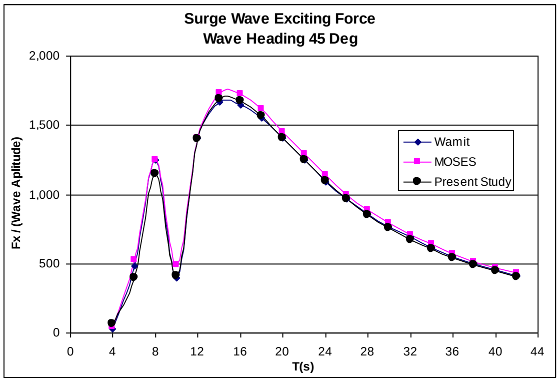


Figure 2 Comparison of surge wave exciting force

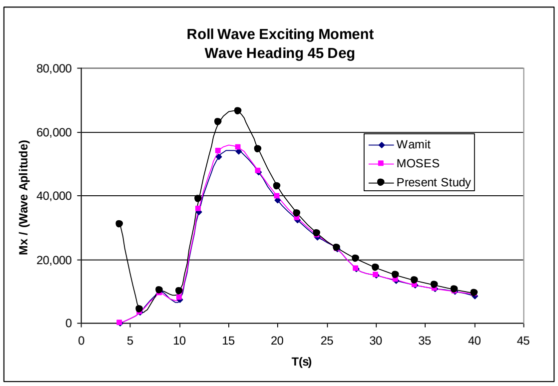


Figure 3 Comparison of roll wave exciting moment

■4.0 RESULTS AND DISCUSSION

To examine the wave exciting forces and moments of a free floating semi submersible, a computer program has been developed to carry out the computation for the Semi submersible mentioned above (Table 2) at a head sea and in a depth of 500 m. In this study the wave exciting forces and moments of a free floating semi submersible are plotted against wave period in Figures 4 to 6, at an angle of incident wave 180 degrees. Figure 4, shows non-dimensional surge wave exciting force that drops to 0.02 at 7.4s period, increases dramatically at 11s, then decreases smoothly at 30s. In Figure 5, heave wave exciting force, reaches to 0.27 at 9.2 s, falls down rapidly to zero at 15.5 s, and then rises slowly to get 0.17 at 30 s. Depends on wave period, sometimes wave passes directly through under the structure and excites a little. Wave exciting moment on the pitch, Figure 6, decreases slowly from 0.06 at 8.4 s, reaches zero at the 20 s and does not change until the 30 s.

Table 2 Principal particulars of the semi submersible

Pontoon length	66.78m
Pontoon depth	6.3 m
Pontoon beam	13.3 m
Pontoon centerline separation	45.15m
Column longitudinal spacing (centre)	45.58 m
Column diameter	10.59 m
Draft	16.73 m
Water depth	175m
Number of Columns	4

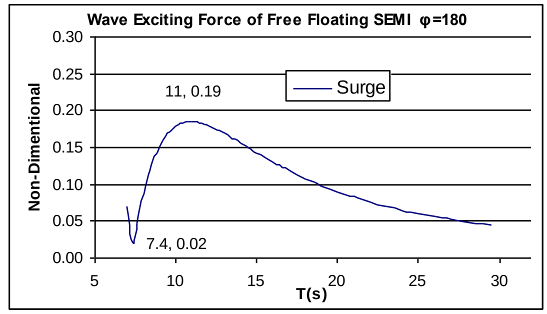


Figure 4 Wave exciting force on surge direction

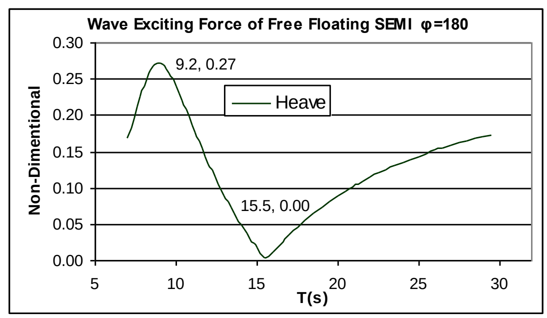


Figure 5 Wave exciting force on heave direction

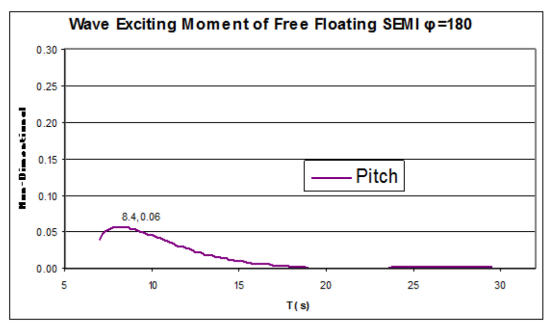


Figure 6 Wave exciting moment on pitch direction

■5.0 CONCLUSION

A method for and results of computational hydrodynamics studies of wave exciting force of a free floating semi submersible have been presented. Wave exciting forces lead to motion of a floating structure, which has significant influence on loading and unloading operation. In this paper, the model is validated only with published results, but it needs to be validated by model experiment.

Also computations need to be carried out for various depths and different incident angles. However, the program developed for computation of wave exciting forces for a freely floating semi submersible numerically expected to be able to predict satisfactorily.

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