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SECOND ORDER WAVE FORCE EFFECTS ON A SEMI-SUBMERSIBLE PLATFORM

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ABSTRACT

Wave making forces are one of the important design criteria for offshore platforms. Linear or first order wave forces are well explained and offshore platforms are designed such that its natural frequencies of motion are well outside the first order excitation wave forces. But the effects of Nonlinear or second order wave forces are sometimes neglected since its magnitudes are less compared to first order ones. But the low frequency components of second order wave forces can cause slow drift motions of the platform, causing resonant motions of the platform. This work shows the numerical evaluation of second order wave force and its effects.

Keywords: Second Order Wave Forces, Steady Drift Forces; Low Frequency Motion Responses, Semi-Submersible; Taut Mooring, Catenary Riser.

1. INTRODUCTION

Stationary vessels floating or submerged in irregular waves are subjected to large linear or first order wave forces and moments which are linearly proportional to the wave height and contain the same frequencies as the waves. They are also subjected to small nonlinear second order wave forces and moments which are proportional to the square of the wave height. Even though small in magnitude, they are of fundamental importance in structures with natural periods of their movements are in regions of high and low frequency, outside the frequency range of maximum wave energy.

Consider the case of Semi-submersibles, which are usually designed such that their natural frequencies, in various modes of platform motion, lie outside the frequency range of maximum wave energy. However, the slowly varying drift forces and moments have longer periods therefore they may excite the floater and mooring system at their natural frequency, resulting in resonant motions in horizontal and vertical planes. Evaluating the slow motions of such systems is important from the initial stages of their designs. The steady mean forces are important with respect to peak mooring loads. First and second-order forces and responses were calculated using WAMIT V6s. Extensive mesh convergence studies and validations are done to make numerical model fault proof. Analysis involves study on Mean or steady forces, calculation of difference frequency QTF matrix,. Also with the help of spectrum analysis, second order responses characteristics are enlightened. Dynamic analysis of the fully configured, moored platform with risers, is completed using OrcaFlex. The results and conclusions regarding resonant heave and pitch motions and station keeping characteristics of semisubmersible platforms can act as an important feedback to future designs.

2. SECOND ORDER WAVE FORCE

Differential wave elevation around the body and the quadratic velocity component of water particle give rise to second order wave forces and moments in addition to linear first order forces and moments. First order wave forces results in oscillatory displacements of the body at sea excitation frequency with harmonic characteristics. The average value of this force and its accompanying motion generated over a time period is zero. In the case of a regular wave with frequency ω (in rad/s)focusing on a body, second-order loads and responses consists of steady component and a medium harmonic component with frequency 2ω . In an irregular wave, each pair of waves with frequencies ω_i and ω_j can interact quadratically not only to generate steady component, but also a difference frequency (low frequency) component with excitation frequencies $\omega_i - \omega_j$ and sum frequency (high frequency) component with excitation frequencies $\omega_i + \omega_j$ and their magnitudes are proportional to the product of corresponding waves amplitudes.

When the hydrodynamic forces are obtained by direct integration of the pressure on the body surface, the derivation of the second order loads requires the pressure and body normal vectors and they need to expand through perturbation technique. This means that all quantities such as wave height, motions, potentials, pressures etc., are assumed to vary only very slightly relative to some initial static value and may all be written in the following form,

$$X = X^{(0)} + \varepsilon X^{(1)} + \varepsilon^2 X^{(2)} \quad (1)$$

Where $X^{(0)}$ denotes the static value, $X^{(1)}$ indicates the first order oscillatory variation, $X^{(2)}$ the second order variation. The parameter ε is some small number, with $\varepsilon \ll 1$, which denotes the order of oscillation. Assuming that the fluid is inviscid, irrotational, homogeneous and incompressible, the fluid motion may be described by means of the velocity potential ϕ ,

$$\phi = \varepsilon \phi^{(1)} + \varepsilon^2 \phi^{(2)} \quad (2)$$

Where $\phi^{(1)}$ represents first order potential and $\phi^{(2)}$ represents second order potential. Both potentials must satisfy the boundary condition at the horizontal sea bed, for $h = -z$, where h is the water depth.

$$\frac{\partial \phi^{(1)}}{\partial z} = 0, \quad \frac{\partial \phi^{(2)}}{\partial z} = 0 \quad (3)$$

But when we consider second order potential also, the free surface boundary conditions expanded as,

$$g \cdot \frac{\partial \phi^{(2)}}{\partial z} + \frac{\partial^2 \phi^{(2)}}{\partial t^2} = -2 \left(\nabla \phi^{(1)} \cdot \nabla \frac{\partial \phi^{(1)}}{\partial t} \right) + \frac{\partial \phi^{(1)}}{\partial t} \cdot \left(\frac{\partial^2 \phi^{(1)}}{\partial z^2} + \frac{1}{g} \cdot \frac{\partial^2}{\partial t^2} \left(\frac{\partial \phi^{(1)}}{\partial z} \right) \right) \quad (4)$$

When the body is carrying out small first order motions, the orientation of a surface element represented by $\vec{n}$ relative to the global coordinate system becomes,

$$\vec{N} = \vec{n} + \varepsilon \vec{N}^{(1)} \quad (5)$$

Where $\vec{N}$ is the instantaneous normal vector to the surface element relative to the body system of axes. The boundary condition for the second order potential on the body $\varepsilon^2 \phi^{(2)}$ states that,

$$\nabla \phi^{(2)} \cdot \vec{n} = \left(\vec{V}^{(1)} - \nabla \phi^{(1)} \right) \cdot \vec{N}^{(1)} \quad (6)$$

In which the first part $\vec{V}^{(1)} \cdot \vec{n}$, represents the body motions and the second part $\nabla \phi^{(1)} \cdot \vec{N}^{(1)}$, the fluid motion.

If the velocity potential ϕ is known, the fluid pressure at a point is determined using the Bernoulli equation,

$$p = -\rho g z - \rho \frac{\partial \phi}{\partial t} - \frac{1}{2} \rho (\nabla \phi)^2 \quad (7)$$

Pressure at mean position of a surface element yields,

$$p = p^{(0)} + \varepsilon p^{(1)} + \varepsilon^2 p^{(2)} \quad (8)$$

The Fluid force exerted on the body, relative to the body coordinate system follows,

$$\vec{F} = - \iint_S p \cdot \vec{N} \cdot dS \quad (9)$$

Where S is the instantaneous wetted surface which can be split into two parts, a constant part S_0 up to the static hull waterline and an oscillating part s , the splash zone between the static hull waterline and the wave profile along the body as shown in Fig. 1

Figure 1. Partition of Instantaneous Wetted Surface

Substituting equations 5 and 8 in equation 9 yields,

$$\vec{F} = - \iint_{S_0} (p^{(0)} + \varepsilon p^{(1)} + \varepsilon^2 p^{(2)}) \cdot (\vec{n} + \varepsilon \vec{N}^{(1)}) \cdot dS - \iint_s (p^{(0)} + \varepsilon p^{(1)} + \varepsilon^2 p^{(2)}) \cdot (\vec{n} + \varepsilon \vec{N}^{(1)}) \cdot dS \quad (10)$$

Where $\vec{F}$ can be written as follows,

$$\vec{F} = \vec{F}^{(0)} + \varepsilon \vec{F}^{(1)} + \varepsilon^2 \vec{F}^{(2)} \quad (11)$$

Where $\vec{F}^{(0)}$ is the hydrostatic fluid force, $\vec{F}^{(1)}$ is the first order oscillatory fluid force and $\vec{F}^{(2)}$ is the second order fluid force.

Taking second order fluid force alone in consideration $\vec{F}^{(2)}$ yields,

$$\vec{F}^{(2)} = - \iint_{S_0} (p^{(1)} \cdot \vec{N}^{(1)}) \cdot dS - \iint_{S_0} (p^{(2)} \cdot \vec{n}) \cdot dS - \iint_s (p^{(0)} \cdot \vec{N}^{(1)}) \cdot dS - \iint_s (p^{(1)} \cdot \vec{n}) \cdot dS \quad (12)$$

Which includes four integral terms,

- First part was the products of the first order pressures $p^{(1)}$ and the first order oscillatory components of the normal vector $\vec{N}^{(1)}$, give second order force contributions over the constant part S_0 , of the wetted surface.
- Second part was the Products of the second order pressures $p^{(2)}$ and the normal vector $\vec{n}$, also give second order force contributions over the constant part S_0 , of the wetted surface.
- Third part was the Products of the hydrostatic pressures $p^{(0)}$ and the first order oscillatory components of the normal vector $\vec{N}^{(1)}$, give (in principle) second order force contributions because of its integration over the oscillatory part s , of the wetted surface.
- Products of the first order pressures $p^{(1)}$ and the normal vector $\vec{n}$, give second order force contributions because of its integration over the oscillatory part s , of the wetted surface.

Summing up of all the above components together finally yields the Total second order force.

3. NUMERICAL MODELLING AND ANALYSIS OF SEMISUBMERSIBLE PLATFORM

A square pontoon semi-submersible platform was modelled using Multi surf and the hydrodynamic analysis of semisubmersible in its free floating condition has been carried out using commercial software program WAMIT. Analysis involves study on Mean or steady forces, calculation of difference frequency QTF matrix, second order forces/moments. Also with the help of spectrum analysis, second order responses characteristics are enlightened.

3.1 Geometric modelling of platform

The semisubmersible hull consists of a square pontoon (85×85×12m) and four columns (17.5×17.5×15.5m) with a total draft of 27.5m. The dimensions of the wetted hull surface is shown in Fig. 2.

Figure 2. 2D Representation of Semisubmersible Wetted Hull

Geometric Modelling of platform hull below design water line was built using modelling CAD software Multisurf. The model surface is subdivided into patches, each is a smooth continuous surface, and the ensemble of all patches represents the complete body surface. In order to provide the accuracy of each patch, a set of small elements are defined which are called panels.

The Multisurf model of the semisubmersible hull is given in Fig. 3, showing panel mesh grids and coordinate system with origin at centre of gravity of the platform. Radius of gyration of the model along X-axis and Y-axis is 35m and 36m respectively. Model displaces a volume of 78320.3m³ with Heave and Pitch natural time periods of 23.27s and 33.07s respectively. The coordinate defined in the Multisurf model will be used as body coordinate in WAMIT V6s analysis. Fig. 3.5 shows the wave heading with respect to body coordinate used in WAMIT.

Figure 3. Multisurf model of semisubmersible hull.

Figure 4. Directions of wave heading

3.2 Free floating hydrodynamic analysis

The problem was numerically modelled using WAMIT V6s, which is based on a three-dimensional panel method, designed to solve the boundary-value problem for the interaction of waves with prescribed bodies in finite and infinite water depth. The boundary value problem is recast into integral equations using the wave source potential as a Green function. The integral equation is then solved by a 'panel' method for the unknown velocity potential and/or the source strength on the body surface. Using the latter, the fluid velocity on the body surface is evaluated. The fluid velocity on the body surface and in the fluid domain is needed for computation of second order wave forces.

The 3D source distribution panel method is always sensitive to mesh near the resonance frequencies of the floating body. So, it is important to establish best practices and determine the mesh requirements for a given level of accuracy. For a second order wave force analysis, we need mesh independent study for the body surface and Free surface discretization around the body.

Body surface mesh indicates the total number of panels (NP) by which the surface is created. By varying NP, Heave QTF for difference frequency (dT) 23.27s with no free surface mesh was plotted in Fig.5. Results shows mesh independence above NP = 18322.

Figure 5. Heave QTFs for different number of panels

A circular free surface mesh with radius as 200m was created around the platform with two sub regions. The free surface discretization is represented by parameter called SCALE, which is a real number used as the scaling factor of the size of free surface panels relative to the average length of the waterline panels on the body. The total second order heave force was plotted for difference frequencies (dT) 23.27s against different SCALE values as shown in Fig.6.

Figure 6. Total SO heave force for different SCALE values.

The values are converging for SCALE ≥ 2 , which means the free surface mesh converges at SCALE=2. Final mesh configuration for free floating analysis in WAMIT was decided to 14832 numbers of panels with free surface mesh scale of 2.

3.3 Study on Mean or Steady Drift Force

The steady component of the second order wave force/moments are very important in case of moored structure to find out the peak mooring loads in a floating system. Steady drift forces are evaluated for 1m wave amplitude based on pressure integration method using WAMIT, which basically required only first order solution. The steady surge and yaw forces are plotted and shown in Fig. 7 and Fig. 8.

Figure 7. Steady Surge In 0° Wave Heading And 45° Wave Heading

Figure 8. Steady Sway and Yaw in 45° wave heading

The results shows that steady forces are predominant in the direction of wave propagation mainly and the magnitudes of steady forces are significantly high for high frequency waves and their magnitudes decreases as wave frequency decreases.

3.4 Second order wave forces and moments

The complete hydrodynamic analysis (linear and nonlinear) of freely floating platform has been done with numerical model having NP=14832 with a free surface mesh scale of 2. First and second order wave forces and moments are calculated using WAMIT second order version 6s. Complete difference frequency QTF matrix is calculated and total second order wave forces are evaluated by direct method in WAMIT for a wave frequency range of 0.3 to 1.97 rad/s with wave incidence angle of 0° . Complete difference frequency QTF matrix is represented as a surface plot with its top view representing exact location of the maximum and minimum values of QTFs.

Figure 9. Surge QTF for 0° wave heading

Fig.9 shows QTF of surge for 0° wave heading and its value spread around the diagonal. of 1.5 rad/s and 1.9 rad/s, which gives a difference frequency 0.4 rad/s or 16s. This observation is same for surge QTF in 0° wave heading. For 0° wave heading, we can observe two points of maximum QTF, for a frequency combination of 0.2 rad/s and 1.9 rad/s, which gives a difference frequency 0.7 rad/s or 9s and for a frequency combination of 1.5 rad/s and 1.9 rad/s, which gives a difference frequency 0.4 rad/s or 16s. So we can say that the maximum surge QTF values occur away from the surge natural frequency of the platform.

Figure 10. Heave QTF for 0° wave heading

Fig. 10 shows the Heave QTF for 0° wave heading. The maximum values are found to be concentrated and lies on the diagonal. Consider the case of Heave QTF for 0° wave heading and take any point near to maximum value to get a difference frequency combination. Any point selected will be lies between 0.6 rad/s to 0.9 rad/s, which gives a difference frequency 0.3 rad/s or 21s. So we can say the maximum surge QTF values occur very near to heave natural frequency of the platform, causing resonance.

Figure 11. Pitch QTF for 0° wave heading

Fig.11 shows the Pitch QTF for 0° wave heading. The maximum QTF value lies between 0.6 rad/s to 0.8 rad/s, which gives a difference frequency 0.2 rad/s or 31s. So we can say the maximum pitch QTF values occur very near to heave natural frequency of the platform, causing resonance.

3.5 Spectrum Analysis

The resonant motion of the platform can be verified by spectral analysis. The second order response spectral density can be calculated by crossing second order RAO with wave spectrum as follows by Pinkster [1],

$$S^{(-)}(\mu) = 8 \int_0^\infty S(\omega) S(\omega + \mu) |RAO^{(-2)}(\omega, \omega + \mu)|^2 d\omega \quad (11)$$

where $S(\omega)$ is the wave spectrum, $RAO^{(-2)}$ is the second order RAO. Second order response spectral density was evaluated for Pitch and Heave. Second order RAOs are evaluated using WAMIT and Jonswap Spectrum with $H_s = 7.3m$, $T_p = 10s$ and $\gamma = 2.4$ and Angle of Incidence = 0 degree is used. Spectral density calculation by crossing second order RAO with wave spectrum is done by Matlab coding.

From the second order response spectral density curves shown in Fig. 12, the peaks for Heave spectrum is found to be at 23.7s and that of Pitch is found to be at 33s, which are values very much closer to the Natural time period of Platform in heave and pitch motion. This proves the presence of resonant motion of platform in Heave and Pitch due to second order wave forces.

Figure 12. Second Order Response Spectral density curve for Heave and Pitch

The results from WAMIT analysis on the free floating platform can be summarised as follows,

- The difference frequency QTFs has maximum values near and around the diagonal. The diagonal values of QTFs intern represent the steady force.
- The maximum values of Heave and Pitch QTFs are present near to difference frequency combination, which gives frequency of excitation near to natural frequency of platform in Heave and Pitch, which may cause resonance. But in case of Surge, the maximum values are at difference frequency combination away from natural frequency in surge.
- Spectral analysis clearly shows the presence of resonant Heave and Pitch motions at 23.7s and 33s.

4.0 DYNAMIC ANALYSIS OF SEMISUBMERSIBLE PLATFORM

Numerical simulation and dynamic analysis of the fully configured, moored platform with risers, is completed with the help of commercial software program OrcaFlex. The output of hydrodynamic analysis through WAMIT is used as the input for OrcaFlex time domain analysis. The low frequency surge, heave and pitch responses of the platform are evaluated and uses spectrum analysis for studying resonance behaviours.

4.1 Mooring and Riser Configuration

A Taut leg mooring configuration with 16 mooring lines, a group of four mooring lines from each four bottom corners of the square pontoon was designed considering a water depth of 1500m. Mooring line basic design criteria was based on API recommendation, saying maximum offset of the platform allowed should be 2.5% of water depth with intact mooring lines and 5% of water depth with one mooring line broken. Each line consists of alternate chain and polyester rope segments. This combination will help in reducing mooring line weight considerably. TABLE 1 represents specifications of each segment. Each mooring line has a pretension of 600kN and 5 degree azimuth angle between the lines. Total Length of each mooring line was 2950m. Horizontal range and top angle of each mooring line was designed to be 2500m and 50 degree.

Table 1. Mooring line specifications

Section	Material	Length	Properties
Fair lead segment	K4 Studless Chain	75 m	Mass per unit length=352.01 kg/m Submerged weight per unit length=305.8 kg/m Longitudinal stiffness = 1.51 E6 kN
Intermediate segment	Polyester Rope	2850 m	Mass per unit length = 17.06 kg/m Submerged weight per unit length=4.31 kg/m Longitudinal stiffness = 23.23 E3 kN
Anchor Segment	K4 Studless Chain	25 m	Mass per unit length=352.01 kg/m Submerged weight per unit length=305.8 kg/m Longitudinal stiffness = 1.51 E6 kN

Deep water systems generally employ steel catenary risers for production, gas lift and water injection. Considering 36 risers including production, gas lift, water injection riser, for the ease of analysis, we took a common steel catenary riser with equal lengths and pretensions and are equally distributed around the semisubmersible platform. Riser specifications are shown in TABLE 2.

Table 2. Riser specifications

Outside diameter	0.219 m
Wall Thickness	0.011m
Mass per unit length	56.42 kg/m
Submerged weight per unit length	17.82 kg/m
Longitudinal stiffness	1.52 E6 kN
Azimuth angle between risers	6.5 degree
Riser length	3000 m
Horizontal range	2000 m
Pre-tension	400 kN

Figure 13. Semi-submersible platform with Mooring lines and Risers

Time domain analysis of fully configured, moored platform with risers is completed using OrcaFlex. The output of hydrodynamic analysis through WAMIT is used as the input loads, RAOs, added mass and damping matrices for OrcaFlex simulation with sea state as defined in chapter 3, section 3.8. The simulation runs for 600s, to make sure that system gets stabilized. The fully configured model is shown in Fig. 13.

First order, second order and combined motion analysis of the platform in Surge, Heave and Pitch directions are evaluated and plotted. The resonant behaviors are studied through spectral analysis which can be directly obtained from OrcaFlex. Fig. 14 shows first order response in time domain and Fig. 15 shows its corresponding response spectral density curves. From this response spectrum, we can see that the peak values present inside the wave frequency range itself and away from platform natural frequencies.

Figure 14. First order response in Surge, Heave and Pitch

Figure 15. First order response Spectrum for surge, Heave and Pitch

Figure 16. Second order response in Surge, Heave and Pitch

The second order response in time domain are extracted separately and shown in Fig. 16. The surge response graph itself clearly shows the slow drift or low frequency motion of the platform. Also the mean value of response has a shift of around 9m from X-axis, which is due to the steady surge force acting. In reality, it gives an offset of 9m for the platform and increases mooring line tension. Similar slow drift motions can be seen for heave and pitch, when comparing it with first order responses. Analysis also shows significant increase in Mooring line and Riser tension

The second order response spectrum is shown in Fig. 17, which clearly shows the presence of resonance motion. The peak values for Heave and Pitch response spectrum occurs at 25s and 33.3s respectively, both are very near to the natural heave and pitch frequencies of the platform.

Figure 17. Second Order Response Spectrum for Surge, Heave and Pitch

Combined first order and second order responses are shown in Fig. 18. It represents the resultant or actual motion of the platform due to first and second order wave forces. Fig 19 shows combined response spectral density of Surge, Heave and Pitch. It is actually a joined representation of first and second order response spectrums.

The results from time domain analysis can be summarized as follows,

- Spectral analysis of second order response shows slow drift motions near to natural frequencies of the vessel in Heave and Pitch causing Resonance.
- Presence of slow drift motion and steady forces affects vessels station keeping. Surge offset is found to be increased by 9m. Each Mooring line tension increased by 50kN and each Riser tension increased by 20kN.

Figure 18. Combined Response in Surge, Heave and Pitch

Figure 19. Combined Response Spectrum for Surge, Heave and Pitch

5. CONCLUSION

Numerical investigation on effects of second order wave force/moments on a semisubmersible platform in free floating and moored conditions are completed. Mesh convergence studies are found to be inevitable in case of second order wave force analysis to get an accurate numeric model. In case of a deep draft semisubmersible platform, the station keeping and heave and pitch motions are significantly affected by second order wave forces which sometimes cause resonance.

Hydrodynamic analysis was done using WAMIT second order version and time domain analysis with mooring lines and risers are completed using OrcaFlex. Maximum values of second order forces are found to be comparable with that of first order wave forces in horizontal motions. The spectral analysis clearly shows the presence of resonant motion of the platform in Heave and Pitch even though the second order wave force/moments are small compared to first order forces. The time domain analysis indicates the criticality in case of mooring and riser tension and platform offset due to second order wave force effects. Each section of analysis and its results shows that second order wave force effects are highly significant in case of deep draft semisubmersible.

The salient conclusions and observations from the entire study are as follows,

- Steady or mean forces are predominant in the direction of wave propagation and its magnitudes are significantly high for high frequency waves and decreases as wave frequency decreases.
- Maximum second order forces and moments have significant magnitudes which are comparable with maximum values of first order wave forces for 1m wave amplitude. Its magnitude and significance become critical as wave amplitude increases since second order wave forces and moments are proportional to square of wave amplitude compared to first order wave force and moments which is linearly varying with wave amplitude.
- Difference frequency QTFs has maximum values near and around the diagonal of QTF matrix. The maximum values of Heave and Pitch QTFs were found to be present near to difference frequency combination, near to natural frequency of platform in Heave and Pitch, which may cause resonance. But in case of Surge, the maximum values are found to be present at difference frequency combination away from natural frequency in surge.
- Spectral analysis of the free floating and constrained or moored platform clearly shows the presence of resonant Heave and Pitch motions.
- Presence of slow drift motion and steady forces affects station keeping characteristics of the platform. There was a significant increase in Surge offset Mooring line tension and Riser tension, shows the criticality of second order wave force effects in a constrained or moored deep draft semisubmersible platform.

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