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Analysis of Vertical Motions of Bonga FPSO in Harsh Environmental Condition

Ezebuchi Akandu* and King Nyeche Wugha

Department of Marine Engineering, Rivers State University, Port Harcourt, Nigeria
*Corresponding author: akandu.ezebuchi@ust.edu.ng

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ABSTRACT

The analysis of the uncoupled vertical motions of the Bonga FPSO is performed for unrestricted service. The study made use of Airy's wave model and the strip theory, to determine the excitation forces and moments, hydrodynamic coefficients, and the RAOs. Spectral analysis was done on the basis of the above results with the Pierson-Moskowitz wave energy density spectrum using the 100-year return period storm data of the North Sea to predict the vessel responses in a realistic sea, as well as forecast the number of green water and slamming at the bow per hour. Furthermore, the (HaPMotA) computer programme written in MATLAB on the basis of the above theories was used for the analyses. As a result, the RAO diagrams, the response spectrum, force and moment diagrams, the responses for the modes of motion investigated, and the operability of the vessel in harsh environment were obtained. The result indicates that the freeboard needs to be increased to mitigate the effects of green water in the harsh environments.

KEY WORDS: *FPSO; Bonga; Heave; Pitch; Motion; Regular wave; Spectral analysis; Green water; Bow slamming.*

NOMENCLATURE

λ Wavelength
ω Circular wave frequency
k Wave number
Φ Velocity potential
$\hat{\xi}$ Amplitude of wave elevation
t Any time instant
g Acceleration due to gravity
ρ Density of sea water
$A_{33}^{(3D)}$ 3D Added mass
M_{jk} Elements of the generalized mass matrix
A_{jk} Elements of the added mass matrix.
D_{jk} Elements of the linear damping matrix.
C_{jk} Elements of the stiffness matrix.

F_j Wave excitation forces and moments.
j and k (as subscripts) are direction of fluid forces and modes of motion of vessel.
$\ddot{\eta}$, and $\dot{\eta}$, are acceleration and velocity terms
GM_L Distance of metercentric height from center of gravity
∇ Volume of vessel.
Other symbols are defined in the text

1.0 INTRODUCTION

The reliability and cost-effectiveness of ship-shaped and barge-shaped offshore units for oilfield applications in deep waters of more than 1,000m depth have seen the successful deployment of such vessels for more than 38 years in such harsh environments.

It is important that the vertical motions of a Floating, Production, Storage and Offloading units be researched due to the tremendous effect that vertical motions can have on exploration activities offshore, especially in the area of operational downtimes. As noted in Thu *et al.*, (2015), the study of wave-induced loads and motions of ships is important both in ship design and operational studies.

It has been reported in Chakrabati (1987) that on account of the minimal effect of the nonlinear drag force, the frequency domain method gives satisfactory results and the computation time is less compared to time domain method. Akandu *et al.*, (2014) investigated the susceptibility of FPSO to green water in extreme environment in the frequency domain.

Comparison between the coupled and uncoupled analysis for a moored FPSO in harsh environments was researched by (Heurtier *et al.*, 2001). It was recommended therein that the results of the uncoupled analysis can be used in the early design stage of the vessel and its mooring system.

In this research, the Bonga FPSO is modeled as a rectangular shaped vessel spread moored in the deep sea with head waves acting on it. The mooring lines are considered to be of negligible mass, such that the hydrodynamic loads on the mooring lines are negligible. Moreover, Airy's linear wave theory, the strip theory, and the spectral theory have been made use of in the analyses. The research thus first determined the motion behaviour of the vessel in regular waves and then on the basis of the principle of superposition of regular wave train of different amplitudes, directions and phases, carried out a spectral analysis to predict the responses of the vessel in a realistic irregular sea.

1.1 Aim and Objectives

The aim of this work is to analyze the heave and pitch motions of the Bonga FPSO for unrestricted service. The achievement of this however depends on the realization of the following objectives:

- Evaluate the heave and pitch response amplitude operators in regular head waves.
- Determine whether the most probable maximum heave and pitch responses of the vessel in harsh environment are within the acceptable limits for oil separators.
- Predict the operability of the vessel with respect to green water and bow slamming in harsh environment.

2.0 MATERIALS AND METHODS

2.1 Regular Wave Analysis

On the basis of Airy's linear wave model it is assumed that the vessel has a constant mass density with small amplitude of oscillation, it is acted upon by sinusoidal waves propagating along the negative x- axis, the wave motion is generally irrotational as the sea bottom is considered horizontal, and the viscosity and surface tension effects are negligible.

A right handed coordinate system fixed with respect to the mean position of the vessel, with z vertically upward through the centre of gravity of the vessel, x in the direction of forward motion, and then the origin in the plane of the undisturbed still water surface, has been adopted.

On the basis of the assumptions stated above, the velocity potential thus satisfies the value-boundary problem of the potential theory. The free-surface and sea bottom conditions are used together with the Laplace equation to derive the velocity potential for propagating head waves. The profile is thus represented as:

$$\Phi = \hat{\xi}\frac{g}{\omega}\, e^{kz} \cos(kx + \omega t) \qquad (1)$$

After applying the free surface conditions the wave elevation is given as:

$$\xi = \hat{\xi} \sin(kx + \omega t) \qquad (2)$$

The dispersion relationship in deep water has been deduced as:

$$k = \frac{\omega^2}{g} = \frac{2\pi}{\lambda} \qquad (3)$$

The velocity potential was also used to obtain expressions for the parameters of motion of water particles. Thus the vertical particle velocity U_z is:

$$U_z = \frac{\partial \Phi}{\partial z} = \hat{\xi}\omega e^{kz} \cos(kx + \omega t) \qquad (4)$$

The vertical particle acceleration is the time derivative of the vertical velocity. So,

$$\dot{U}_z = \frac{\partial U_z}{\partial t} = -\hat{\xi}\omega^2 e^{kz} \sin(kx + \omega t) \qquad (5)$$

The wave dynamic pressure is given as

$$P_d = -\rho\frac{\partial \Phi}{\partial t}$$
$$P_{d3} = \rho g \hat{\xi} e^{kz} \sin(kx + \omega t) \qquad (6)$$

The equation of motion for a six degree of freedom involving surge, sway, heave, roll, pitch, and yaw can be written as:

$$\sum_{k=1}^{6}(M_{jk} + A_{jk})\ddot{\eta} + D_{jk}\dot{\eta} + c_{jk}\eta = F_j \qquad (7)$$

The primary particulars of the vessel are: L (305m), B (58m), D (32m), and T (23.4m).

2.1.1 Hydrostatics

The stiffness in heave and pitch are as a result of the change in the displacement of the vessel. Thus, the buoyancy of the vessel per unit length of sinkage defines the coefficient of the restoring forces and moments. As such, the stiffness in heave and pitch are respectively:

$$c_{33} = \rho g A_{wp} = \rho g BL \qquad (8)$$

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$$c_{55} = \rho\nabla g\,.GM_L = \rho gBTL.\frac{L^2}{12T} = \rho gBL.\frac{L^2}{12} = \frac{L^2}{12}C_{33} \quad (9)$$

2.1.2 Heave Force and RAO

The total heave force is the integral of the sum of the pressure (Froude-Krylov) and added mass forces (dF_3) on each strip of the ship frame, across the length of the vessel. Thus,

$$dF_3 = P_{d3}dA + A_{33}{}^{(2D)}\dot{U}_z dx$$

$$dF_3 = P_{d3}Bdx + A_{33}{}^{(2D)}\dot{U}_z dx$$

The 2-D added mass in heave is given as:

$$A_{33}{}^{(2D)} = \rho.\frac{1}{2}\pi\left(\frac{B}{2}\right)^2.C_{A3} \quad (10)$$

For a rectangular vessel, Akandu (2015) derived the added mass coefficient as:

$$C_{A3} = 1.014\left(\frac{B}{T}\right)^{-0.2692} + 0.674 \quad (11)$$

$$F_3 = \left(\rho gB + A_{33}{}^{(2D)}kg\right) \times \hat{\xi}e^{kz}\int_{-\frac{L}{2}}^{\frac{L}{2}} sin(kx+\omega t)\,dx$$

$$F_3 = \hat{\xi}\rho g\left(B \; - A_{33}{}^{(3D)}\frac{k}{\rho L}\right)\left(\frac{1}{k}.e^{-\frac{2\pi T}{\lambda}}\right) \times 2\,sin\left(\frac{kL}{2}\right)sin(\omega t)$$

Thus the amplitude of the heave force is:

$$\hat{F}_3 = \rho g\hat{\xi}\left[\frac{2B}{k} - A_{33}{}^{(3D)}\left(\frac{2}{\rho L}\right)\right] \times \left(e^{\frac{-2\pi T}{\lambda}}\right)\sin\left(\frac{\pi L}{\lambda}\right) \quad (12)$$

Usually, a harmonic load produces a response of the same harmonic and type. Thus the heave response is given as:

$$\eta_3 = \hat{\eta}_3\sin(\omega t - \varepsilon) \quad (13)$$

The velocity and acceleration terms of the response are given below as:

$$\dot{\eta}_3 = \omega\hat{\eta}_3\,cos(\omega t - \varepsilon) \quad (14)$$

$$\ddot{\eta}_3 = -\omega^2\hat{\eta}_3\,sin(\omega t - \varepsilon) \quad (15)$$

The amplitude of the response of the vessel is the product of its static displacement ($\frac{\hat{F}_3}{C_{33}}$) and magnification factor (♀_3). Thus,

$$\hat{\eta}_3 = \frac{\hat{F}_3}{C_{33}}.\text{♀}_3 \quad (16)$$

Where the heave magnification factor is given as:

$$\text{♀}_3 = \left[\left(1-\Omega_3{}^2\right)^2 + (2D_3.\Omega_3)^2\right]^{-\frac{1}{2}} \quad (17)$$

Thus, the heave Response Amplitude Operator (RAO_3) defined as the amplitude of the heave response per wave amplitude is given as:

$$RAO_3 = \frac{\hat{\eta}_3}{\hat{\xi}} = \frac{\hat{F}_3}{\hat{\xi}.C_{33}}.\text{♀}_3 = \frac{\rho g\text{♀}_3}{C_{33}}\left[\frac{2B}{k} - A_{33}{}^{(3D)}\left(\frac{2}{\rho L}\right)\right]\left(e^{\frac{-2\pi T}{\lambda}}\right)\sin\left(\frac{\pi L}{\lambda}\right) \quad \ldots\ldots..(18)$$

Referring to equation 15 where we have the acceleration term of the response, the RAO of the linear acceleration is given as:

$$RAO_{3acl} = \frac{-\omega^2\hat{F}_3\text{♀}_3}{C_{33}\hat{\xi}} = -\omega^2.RAO_3 \quad (19)$$

2.1.3 Pitch Moment and RAO

The pitch moment is the integral sum of the products of the heave forces and their trimming arms across the length of the vessel. The pitch moment on the 2-D strips would be:

$$dF_5 = dF_3.x$$

$$F_5 = \int_{-\frac{L}{2}}^{\frac{L}{2}} x\,.dF_3$$

Upon expansion and simplification, the pitch moment is obtained as:

$$F_5 = \rho g\hat{\xi}\left[\frac{B\lambda}{\pi} - A_{33}{}^{(3D)}\left(\frac{2}{\rho L}\right)\right]\left(e^{\frac{-2\pi T}{\lambda}}\right) \times \frac{1}{k}\left[sin\left(\frac{kL}{2}\right) - \left(\frac{kL}{2}\right)cos\left(\frac{kL}{2}\right)\right]cos(\omega t)$$

$$F_5 = \rho g\hat{\xi}\left[\frac{2B}{k} - A_{33}{}^{(3D)}\left(\frac{2}{\rho L}\right)\right]\left(e^{\frac{-2\pi T}{\lambda}}\right) \times \frac{1}{k}\left[1 - \left(\frac{kL}{2}\right)cot\left(\frac{kL}{2}\right)\right]cos(\omega t) \quad (20)$$

The amplitude of the pitch moment is thus:

$$\hat{F}_5 = \hat{F}_3.L_p \quad (21)$$

L_p , the virtual pitching lever is equal to:

$$L_p = \frac{1}{k}\left[1 - \left(\frac{kL}{2}\right)cot\left(\frac{kL}{2}\right)\right] \quad (22)$$

As in heave, the definition of the pitch response has been given as:

$$\hat{\eta}_5 = \frac{\hat{F}_5\text{♀}_5}{C_{55}} \quad (23)$$

The pitch Response Amplitude Operator (RAO_5) is thus given as:

$$RAO_5 = \frac{\hat{\eta}_5}{\hat{\xi}} = \left|\frac{\hat{F}_3.L_p.\text{♀}_5}{C_{55}\hat{\xi}}\right| \quad (24)$$

Where the pitch magnification factor has been obtained as:

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$$\varphi_5 = \left[\left(1 - \Omega_5{}^2\right)^2 + (2D_5.\Omega_5)^2\right]^{-\frac{1}{2}} \quad (25)$$

2.1.4 Relative motion

At any point *x*, along the length of the vessel, the relative displacement between the wave and the vessel can be given as:

$$\eta_{rd} = \eta_3 - x\eta_5 - \xi \quad (26)$$

At the bow where $x = +\frac{L}{2}$ from amidships, then:

$$\eta_{rd} = \eta_3 - \frac{L}{2}\eta_5 - \hat{\xi}\,sin\left(\omega t + \frac{kL}{2}\right)$$

$$\eta_{rd} = \hat{\eta}_3\,sin(\omega t) - \frac{L}{2}\hat{\eta}_5\,cos(\omega t) - \hat{\xi}\,sin\left(\omega t + \frac{kL}{2}\right) \quad (27)$$

Expanding $sin\left(\omega t + \frac{kL}{2}\right)$ and then substituting into equation (25) yields:

$$\eta_{rd} = \hat{\eta}_3\,sin(\omega t) - \frac{L}{2}\hat{\eta}_5\,cos(\omega t) - \hat{\xi}\left[sin(\omega t)\,cos\left(\frac{kL}{2}\right) + cos(\omega t)\,sin\left(\frac{kL}{2}\right)\right]$$

$$\eta_{rd} = \left[\hat{\eta}_3 - \hat{\xi}\,cos\left(\frac{kL}{2}\right)\right]sin(\omega t) - \left[\frac{L}{2}\hat{\eta}_5 + \hat{\xi}\,sin\left(\frac{kL}{2}\right)\right]cos(\omega t)$$

The magnitude of the amplitude of the relative motion displacement between the wave motion and the heave motion of the vessel at the bow will thus be:

$$\hat{\eta}_{rda} = \left\{\left[\hat{\eta}_3 - \hat{\xi}\,cos\left(\frac{kL}{2}\right)\right]^2 + \left[\frac{L}{2}\hat{\eta}_5 + \hat{\xi}\,sin\left(\frac{kL}{2}\right)\right]^2\right\}^{0.5} \quad (28)$$

Dividing by the amplitude of the wave profile yields the Response Amplitude Operator for the relative motion which is:

$$RAO_{rd} = \frac{\hat{\eta}_{rd}}{\hat{\xi}} = \left\{\left[RAO_3 - cos\left(\frac{kL}{2}\right)\right]^2 + \left[sin\left(\frac{kL}{2}\right) + \frac{L}{2}RAO_5\right]^2\right\}^{0.5} \quad (29)$$

The relative velocity between the wave and the vessel at any station x along the longitudinal direction of the vessel where slamming is to be analyzed, is defined as given by the relationship:

$$\dot{\eta}_{rd} = \dot{\eta}_3 - x\dot{\eta}_5 - \dot{\xi} \quad (30)$$

Thus, the relative velocity of the ship at the bow $(x = +\frac{L}{2})$ would be:

$$V_r = \dot{\eta}_{rd} = \omega\hat{\eta}_3\,cos\,\omega t + \frac{L}{2}\omega\hat{\eta}_5\,sin\,\omega t - \omega\hat{\xi}\,cos\left(\omega t + \frac{kL}{2}\right)$$

$$V_r = \omega\hat{\eta}_3\,cos\,\omega t + \frac{L}{2}\omega\hat{\eta}_5\,sin\,\omega t - \omega\hat{\xi}\,cos\frac{kL}{2}cos\,\omega t + \omega\hat{\xi}\,sin\frac{kL}{2}sin\,\omega t$$

$$V_r = \omega\left[\left(\hat{\eta}_3 - \hat{\xi}\,cos\frac{kL}{2}\right)cos\,\omega t + \left(\frac{L}{2}\omega\hat{\eta}_5 + \omega\hat{\xi}\,sin\frac{kL}{2}\right)sin\,\omega t\right] \quad (31)$$

The amplitude of the relative velocity will therefore be:

$$V_{ra} = \omega\left[\left(\hat{\eta}_3 - \hat{\xi}\,cos\frac{kL}{2}\right)^2 + \left(\frac{L}{2}\omega\hat{\eta}_5 + \omega\hat{\xi}\,sin\frac{kL}{2}\right)^2\right]^{0.5} \quad (32)$$

The response amplitude operator would then be:

$$RAO_{rv} = \omega\left\{\left[RAO_3 - cos\left(\frac{kL}{2}\right)\right]^2 + \left[\frac{L}{2}RAO_5 + sin\left(\frac{kL}{2}\right)\right]^2\right\}^{0.5} = \omega.RAO_{rd} \quad (33)$$

2.2 Spectral Analysis

The wave environment is usually described in terms of the wave spectra and its 100 year return period storm given in terms of the significant wave height (H_s) and zero up-crossing period (T_z). The analysis is done to determine if the vessel can be operated in a harsh environment. As such, the North Sea of 100 year return period storm which is a typical harsh environment was chosen. The wave Parameters of this environment are: Hs=16.5m; Tz=17.5s. The modified Pierson-Moskowitz wave spectrum was adopted for the analysis. Expressed in terms of the significant wave height and zero up-crossing period, the modified P-M spectrum is given as:

$$S_w(\omega) = \frac{124}{T_z^4}H_s^2\omega^{-5}e^{\left(-\frac{496}{T_z^4}\omega^{-4}\right)} \quad (34)$$

Bergdahl (2009) gave the relationship between the wave and the ship response as:

$$S_{jr}(\omega) = S_w(\omega)\left[RAO_j\right]^2 \quad (35)$$

The nth moment of the response spectrum was also shown to be:

$$M_{nj} = \int_0^\infty \omega^n S_{jr}(\omega)\,d\omega \quad (36)$$

The most probable maximum response amplitude is thus:

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$$a_{jmax} = 3.72(M_{nj})^{\frac{1}{2}} \quad (37)$$

2.2.1 Heave spectrum and responses

From the relationship shown above, the heave response spectrum (j=3) is given as:

$$S_{3r}(\omega) = [RAO_3]^2.S_w(\omega) \quad (38)$$

The variance of the response spectrum (zeroth moment, n=0) which is the area under the heave response curve is given as:

$$M_{03} = \int_0^\infty S_{3r}(\omega)\, d\omega \quad (39)$$

Thus, the most probable heave response amplitude is:

$$a_{3max} = 3.72(M_{03})^{\frac{1}{2}} \quad (40)$$

2.2.2 Pitch Spectrum and Response

Similarly, the Pitch response spectrum is:

$$S_{5r}(\omega) = [RAO_5]^2.S_w(\omega) \quad (41)$$

Pitch zeroth moment is expressed as:

$$M_{05} = \int_0^\infty S_{5r}(\omega)\, d\omega \quad (42)$$

The most probable maximum pitch amplitude is thus:

$$a_{3max} = 3.72(M_{03})^{\frac{1}{2}} \quad (43)$$

2.2.3 Relative Motion and Response

The response spectrum of the relative motion displacement as a function of wave frequency would be:

$$S_{rd}(\omega) = (RAO_{rd})^2.S_w(\omega)d\omega \quad (44)$$

The zeroth moment is given as:

$$M_{0rd} = \int_0^\infty S_{rd}(\omega)\,.\,d\omega \quad (45)$$

Thus, the most probable maximum response amplitude of the relative motion is:

$$a_{rdmx} = 3.72(M_{0rd})^{\frac{1}{2}} \quad (46)$$

To predict the probability of occurrence of slamming of the vessel at the bow, the relative velocity between the wave and the vessel at the bow would be estimated. The most probable maximum amplitude of the relative velocity between the wave and the vessel at the bow must be greater than a certain predefined threshold or critical velocity (V_{cr}) for slamming to occur (Journée and Massie, 2001). Thus, the response spectrum of the relative velocity as a function of wave frequency is:

$$S_{rv}(\omega) = (RAO_{rv})^2.S_w(\omega)d\omega \quad (47)$$

The zeroth moment will thus be:

$$M_{0rv} = \int_0^\infty (RAO_{rv})^2.S_w(\omega)\, d\omega \quad (48)$$

Thus, the most probable maximum response amplitude of the relative velocity is:

$$V_{ramx} = 3.72(M_{0rv})^{\frac{1}{2}} \quad (49)$$

2.3 Probability of Freeboard Exceedance

The freeboard exceedance is the difference between the maximum amplitude of the relative motion between the wave and the vessel at a station x along the longitudinal direction of the vessel, and the freeboard. in order to prevent green water on deck of vessel with its attendant effects, it is expected that the freeboard exceedance is less than or equal to zero ($E_f \leq 0$). The freeboard is given as:

$$F_b = D - T \quad (50)$$

The probability that the amplitude a_{rdmax} would exceed a threshold value, F_b (in this case) will be:

$$\mathrm{P}(\eta_{ramx} > F_b) = exp\left\{\frac{-(F_b)^2}{2M_{0r}}\right\} \quad (51)$$

Journée and Massie (2001) further postulated that the average number of times per hour that the above probability occurs is:

$$N_{gw/hour} = \frac{3600}{T_z}.P(a_{rdamx} > F_b) \quad (52)$$

2.4 Probability of Bow Slamming

For slamming to occur, two conditions postulated by Ochi and highlighted in Journée and Massie (2001), must be met. There must be an emergence of the ship's bow which happens when the vertical relative motion amplitude, at 90 percent of the length of the ship is larger than the ship's draft at this location, and the exceedance of a threshold vertical relative velocity (V_{cr}), without forward speed effect, between the wave surface and the bow of the ship at the instance of impact. Having modeled the vessel as a rectangular box, then the draught is the same

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everywhere and given as T. Thus the probability that the bow of the vessel will emerge out of the water approximately follows from:

$$P(a_{rdamx} > T) = exp\left(-\frac{(T)^2}{2M_{0r}}\right) \qquad (53)$$

A certain threshold velocity (V_{cr}) that must be exceeded by the relative velocity between the wave and the vessel at the point where the slamming is investigated as postulated by Ochi is:

$$V_{cr} = 0.093(gL)^{0.5} \qquad (54)$$

The probability of exceedance of this critical value is expressed as:

$$P(V_{ramx} > V_{cr}) = exp\left(-\frac{(V_{cr})^2}{2M_{0r}}\right) \quad (55)$$

The occurrence of the above mentioned conditions are not statistically dependent and so must occur at the same time for slamming to occur.

It thus follows from the above formulae that the probability of slamming occurring is estimated as:

$$P(slam) = exp\left[-\left(\frac{(V_{cr})^2}{2M_{rv}} + \frac{(T)^2}{2M_{0r}}\right)\right] \quad (56)$$

The number of times per hour that slamming occurs can thus be estimated as:

$$N_{\frac{slam}{hr}} = \frac{3600}{T_z} \times$$

$$exp\left[-\left(\frac{(V_{cr})^2}{2M_{0rv}} + \frac{(T)^2}{2M_{0r}}\right)\right] \quad (57)$$

On the basis of the general operability limiting criteria for merchant vessels, the probability of slamming and deck wetness according to Journée and Massie (2001) has been given as:

P(slam)= 0.01 for ship length $\geq$ 300m

P(green water) = 0.05.

For the operability of the vessel in any sea state, the limiting criteria probabilities above should not be exceeded. Moreover, a good motion performance requires that the linear and angular motions of the vessel do not exceed the motion levels at which oil separators can still function properly. The design levels of motion for conventional separators are: 0 to 0.25g for the linear motions; 0 to 7.5^0 for the angular motions; and 3 to 15s for the periods.

3.0 RESULTS AND DISCUSSIONS

The results of the analysis indicate that RAO_3 and RAO_5 are zero when $\left[\frac{2B}{k} - A_{33}^{(3D)}\left(\frac{2}{\rho L}\right)\right]$ and $\sin\left(\frac{\pi L}{\lambda}\right)$ equals zero. Furthermore, RAO_5 is also zero when $L_p = \frac{1}{k}\left[1 - \left(\frac{kL}{2}\right) cot\left(\frac{kL}{2}\right)\right]$ is zero. Figures 2 and 3 also give the points the RAOs are zero. Furthermore Figure 2 shows that the maximum heave response occurred at very short wave frequencies and decreased as the frequency increased until within the vicinity of resonance where it sharply declines due to damping.

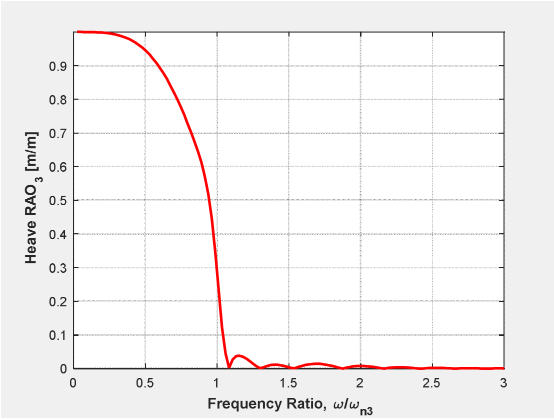

Figure 1: Heave response varying with wave frequency

Figure 3 on the other hand indicates that the pitch motion is greatest within the vicinity of resonance as it increases sharply from zero at short wave frequencies and then sharply declines as frequency of wave increased to resonance due to damping.

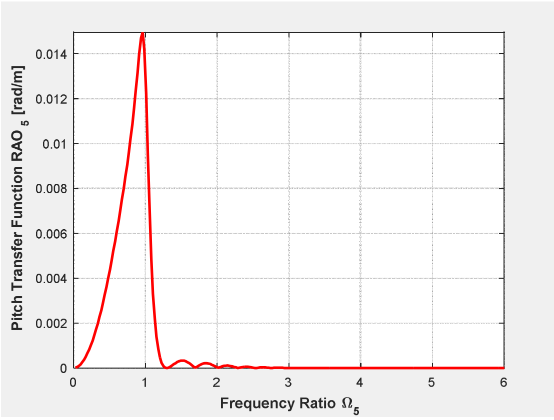

Figure 2: Pitch response varying with wave frequency

The responses of the vessel obtained for the heave and pitch motions are as follows: the most probable maximum heave response is 11.5075m, the most probable maximum linear acceleration is 0.91822ms^{-2} or 0.09g; the maximum pitch response is 0.12484rad or 7.15°.

The maximum amplitudes of the relative motion displacement and velocity are 32.43m and 10.89m/s. Note that the amplitude of the relative motion displacement is greater than

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the draught. The probability of green water and bow slamming are thus 0.61467 and 0.006017 respectively. The number of green water and slamming per hour were thus estimated as 125.7287 and 1.2307 per hour respectively.

4.0 CONCLUSIONS

- Damping affects the vertical motion of the vessel as it reduces the induced motion.
- The responses obtained indicates that the heave and pitch motions of the FPSO are within the safe levels for the smooth operation of oil-separators in the North Sea.
- The probability of green water obtained from the analysis showed that it was way beyond the operability limit for merchant vessels and thus gave a very high number of green water per hour. However, the probability of slamming obtained indicates that it is within the safe limits of operability.
- In view of the foregoing, the vessel has high likelihood of green water incidence in the harsh environment of the North Sea.

It is thus recommended that the process deck of the FPSO be raised to make the freeboard exceedance equal to or less than zero so that the probability of green water occurrence would be within the safe operability limits for merchant vessels.

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