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Spectral Response Computation of P23 boat in Bonny offshore

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Abstract
A detailed approach to ascertaining the behavior of a P23-boat basedon waves data measured in Bonny Offshore Nigeria is presented. The P23-boat is a personnel transport boat commonly used in Bonny Location. As a continuing research, wave spectra results of the Bonny Offshore location were extracted from previous studies and used as inputparameters in this work. Using Newton's second law of motion, the response equation involving complex wave amplitude was developed. The computations showed that the translations and moments (Surge, sway, heave, roll, pitch and yaw) motions peak for P23 boat happens at a frequency of 1.0rad/s. The zeroth moment of all the response spectra is noted to be less than 50% of the Bonny offshore wave spectra. However, it is found that the energy content in roll is somewhat large. This is attributed to the nature of the P23 bull. This approach can be useful in determining the response of other floating structures with much ease.

Keywords: *Wave spectra, Bonny offshore, Response amplitude, Frequency domain, P23 boat*

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1. Introduction

In the last two decades there have been great increases in offshore activities in the Bonnyregion. Some of such activities include crude exploration, maritime transportation, structures transportation, installation, maintenance among others. Most of these activities require the use of floating structures. Thus, for a successful project execution, an accurate prediction of the vessel's motion on site is vital.

Prior to this study, vessel motions were measured and recorded with the help of Motion Reference Unit (MRUs), also with the use of diffraction software by engaging the popular Response Amplitude Operators (RAOs) (Skandali,2013; Williams et al., 2012). RAO is an engineering statistic, or set of such statistics that are used to determine the likely behavior of a vessel when operating at sea. Usually, the RAO is obtained from models of proposed vessel designs and tested in a model basin, or from running a specialized CFD computer programs, often both (Adam and Bjorn, 1999). In a number of cases, the utilizers of computed motions have noticed that the calculated vessel motions do not fully match with the measured vessel motion on site (Skandali, 2013; Abam and Akaawase 2018). Such inaccuracies have been credited to the limited attention that is often paid to the wave headings by the response computation software available.

To eliminate the identified inaccuracies, the authors of the previous and present paper present a mathematical approach of computing any vessel's response putting into consideration the wave headings. The present approach will tackle the issue of viscous damping force on vessel motion when loaded rather than calculating the hydrodynamic damping matrix based on the ideal hydrostatics parameters of the vessel. Thus, it is assumed that the P23 boat is seating on the water facing the incoming waves without being anchored nor engine(s) engaged. As shown in Fig. 1.

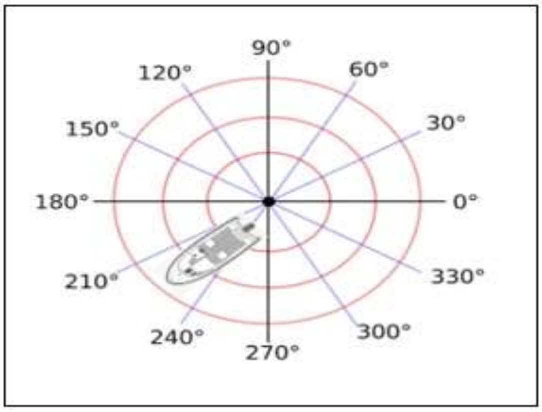

Fig. 1: Position of P23 at Bonny offshore.

2. Approach

To predict an accurate vessel's response spectrum, several equations of motions are engaged to determine the RAOs and wave spectrum. To actualize this, the RAOs is obtained with respect to the available vessel's hydrostatic andhydrodynamic database characteristics provided by the Centre for Maritime and Offshore Studies, FUPRE, Nigeria using MATLAB. The aim is to simplify the RAO computations thereby creating provisions for RAO elements adjustments for future predictions on other vessels. In addition to the element's adjustment consideration, the hydrodynamic added mass and damping matrices will be expressed in simple terms to help freshers better understand how the diffraction software works. The test cases will be based on the results of the wave spectral presented by Agbakwuru and Akaawase (2020) for the Bonny location. The extracted results from the work of Agbakwuru and Akaawase (2020) contained the wave spectrum (frequency, spectral density and wave directions). To derive the response spectra, a P23 vessel hydrodynamic properties supplied by the Centre for Maritime and Offshore Studies of the Federal University of Petroleum Resources, Effurun, Delta State, Nigeria is leveraged on.

2.1 Motion equations

To describe the motion, which mainly has a linear behavior, a frequency domain analysis is usually performed. In the analysis, the resulting motions of the vessels in irregular waves are calculated by adding together the vessel's response to regular harmonic waves of different amplitudes, frequencies and propagation directions (Skandali, 2013). Given the wave spectrum and the frequency characteristics of the vessel, the response spectra can be determined as shown in Fig. 2.

Fig. 2: Calculation of motion response spectra for a floating structure

2.1.1 Wave spectrum

For the surface elevation of an offshore environment to be described, the wave spectrum is determined. The spectral represents the irregular waves travelling across the water surface. Such irregular waves are represented as the sum of a large number of harmonic wave components with a varying periods, directions, phases and amplitudes. A detailed computation of Bonny Offshore wave spectral is detailed in Agbakwuru and Akaawase (2020) and it is adopted in this study as shown in Fig. 3. The 2D-wave spectrum of Fig. 3 considered both the wave frequencies and directions. These directions have a great influence on the final vessel response.

3. Materials and methods

3.1 Response amplitude operator (RAO)

To calculate the RAOs, an analysis involving the dynamic behavior of the vessel due to an incoming harmonic wave is carried out. Such dynamic behavior is derived from the hydromechanics of a single mass-spring system as described by the Newton's second law of motion (Journee and Massie, 2001). To obtain the dynamic equation for marine structures, one needs to get the forces and moments from the radiation and diffraction potentials. The motion of the structure in fluid based on the Newton's second law of motion becomes:

For translational motion (surge, sway, heave)

$$F = m\ddot{x} \quad (1)$$

For rotational motion (roll, pitch, yaw)

$$I\dot{\omega} = \mathrm{M} \quad (2)$$

In a more compact form, the equation becomes:

$$\sum_{j=1} M_{ij}\dot{V}_j = F_i \quad (3)$$

where F_i are the total hydrodynamic and hydrostatic forces generally expressed as the sum of hydrostatic, radiation and exciting forces.

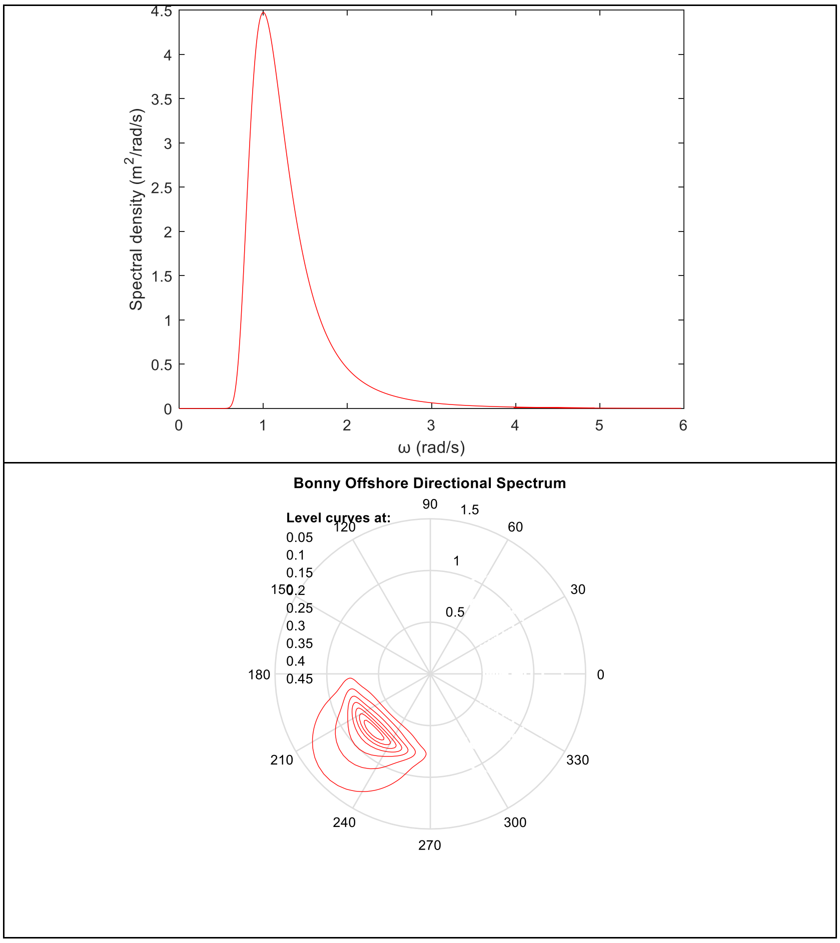

Fig. 3: Bonny wave spectral representation (Agbakwuru and Akaawase, 2020)

3.1.1 Hydrostatic forces

The hydrostatic forces are given as the net hydrostatic forces due to the structure motion away from the equilibrium state, expressed as:

$$F^s = -\sum_{j=1} c_{ij}\xi_j \quad (4)$$

where ξ_j is the motion amplitude of the structure and c_{ij} is the non-zero hydrostatic coefficients.

It should be noted that some of the non-zero hydrostatic coefficients will vanish if the structure is symmetric about some axes.

3.1.2 Radiation force (hydrodynamic)

The radiation forces are given as:

$$F^R = -\sum_{j=1}(\omega^2 a_{ij} - i\omega b_{ij})\xi_j \quad (5)$$

where a_{ij} is the added mass due to the wave radiation, and b_{ij} is the radiation damping due to the wave radiation. It should be noted that the subscript i indicates the motion modes while the main i is for the imaginary unit.

3.1.3 Exciting force (hydrodynamic)

This is expressed as:

$$F^{ex} = -i\omega\rho \iint \left(\varphi_0 \frac{\partial\varphi_i}{\partial n} - \varphi_i \frac{\partial\varphi_0}{\partial n}\right) dS \quad (6)$$

where$\varphi_i$andφ_o are potential of incoming wave and the potential of radiated waves respectively.

3.2 The domain

In a frequency domain, the motion of complex amplitude(ξ_j), the corresponding velocity and acceleration are given as:

Velocity: $V_j = i\omega\xi_j$ (7)

Acceleration: $\dot{V}_j = a_j = -\omega^2\xi_j$ (8)

These expressions show that velocity has a phase difference of 90^0 and acceleration has 180^0 phase difference with regards to the motion. If we substitute the hydrostatic forces and the hydrodynamic forces into the equation of the structure motion, the hydrodynamic equation of the 6-DOF motions of the vessel under the wave action in a frequency domain will be:

$$\sum_{j=1}\left[-\omega^2\left(M_{ij} + a_{ij}\right) + i\omega b_{ij} + c_{ij}\right]\xi_j = F_i \quad (9)$$

where $M_{ij}$is the mass matrix, a_{ij}, b_{ij} is the added mass and damping due to the radiation.$c_{ij}$is the hydrostatic restoring force coefficient.

Next, the potentials can be determined as explained in section 3.5.1. Once the relevant potentials and thus the hydrodynamic forces are computed, the motion amplitude can be solved by making the complex amplitude subject of the formula in Equation (9):

$$\xi_j = \frac{F_i}{\sum_{j=1}[-\omega^2(M_{ij}+a_{ij})+i\omega b_{ij}+c_{ij}]} \quad (10)$$

Then the response amplitude operator which is dependent on the wave frequency and wave incident angle is calculated as:

$$RAO_j(\omega, dir) = \frac{\xi_j}{A} \quad (11)$$

where A is the wave amplitude.

3.3 Time domain

Principally, the hydrodynamic equation in frequency domain is actually derived from the hydrodynamic equation in time domain. Since in linear dynamic system, we assume under the sinusoidal action, the motion will be sinusoidal accordingly, thus:

$$f_i(t) = F_i \cdot e^{i(\omega t)} \Longrightarrow x_i(t) = \xi_i \cdot e^{i(\omega t)} \quad (12)$$

And the corresponding motion velocity and acceleration of the structure are calculated as:

$$\dot{x}_j(t) = i\omega\xi_i e^{i(\omega t)} \quad (13)$$

$$\ddot{x}_j(t) = -\omega^2\xi_i e^{i(\omega t)} \quad (14)$$

Resulting to a time domain equation after applying the hydrostatic and hydrodynamic forces as:

$$F(t) = \big(m + a(\omega)\big)\ddot{x}(t) + b(w)\dot{x}(t) + cx(t) \quad (15)$$

So, substituting the sinusoidal force, velocity and acceleration in Equation (15), we have:

$$F_i e^{i(\omega t)} = [-\omega^2\big(m + a(\omega)\big)]\xi_i e^{i(\omega t)} + i\omega b(w)\xi_i e^{i(\omega t)} + c\xi_i e^{i(\omega t)} \quad (16)$$

If we cancel out the time factor in Equation (16), we can obtain the frequency domain equation shown in Equation (9). However, we must be careful when we transform the hydrodynamic equation in frequency domain to the equation in time domain since all the hydrodynamic parameters are frequency dependent.

Finally, the motion response spectra are obtained by multiplying the wave spectrum with the RAO squared and integrating over the wave directions.

$$S_r(\omega) = \int_{-\pi}^{\pi} s_\xi(\omega, dir) \cdot RAO_i(\omega, dir)^2 d(dir) \quad (17)$$

where i indicates the degree of freedom, S_r is the response spectrum, and $S_\zeta$is the wave spectrum.

In order to identify possible sources of inaccuracy of the RAOs, special attention should be given to the parameters that contribute to their calculation.

3.4 Further description of parameters

From the body mass of the vessels and their respective radius of gyration, a 6X6 is generated as:

$$M = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & r_{xx}{}^2m & 0 & 0 \\ 0 & 0 & 0 & 0 & r_{xx}{}^2m & 0 \\ 0 & 0 & 0 & 0 & 0 & r_{xx}{}^2m \end{bmatrix} \quad 18)$$

Where m is the mass of the vessel and r_{xx}, r_{yy}, r_{zz}, are the radii of gyration with respect to x, y and z axes respectively.

The radius of gyration is determined from the vessel hydrostatic parameters by solving:

$$r_{xx} = \sqrt{\left(\frac{I_{xx}}{m}\right)}, r_{yy} = \sqrt{\left(\frac{yy}{m}\right)}, \qquad r_{zz} = \sqrt{\left(\frac{I_{zz}}{m}\right)} \quad (19)$$

where I_{xx}, I_{yy}andI_{zz} are the moments of inertia about the x, y and z axes respectively.

The stiffness matrix contains the restoring spring terms which influence the heave, roll and pitch motions. A 6X6 spring matrix shown below is adopted for the P23.

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_{WL} & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho g \bar{V} GM_T & 0 & 0 \\ 0 & 0 & -\rho g A_{WL}(CoF - CoB) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (20)$$

where ρ is the fluid density,$\bar{V}$ is the submerged volume of the vessel, g is the acceleration of gravity, A_{WL} is the wetted plane area, *CoF* is the center of floatation, *CoB* is the center of buoyancy and GM_T, GM_L,are the transverse and longitudinal metacentric heights. All these values were gotten from the Centre for Maritime and Offshore Studies Catalogue of P23 boat.

The transverse and longitudinal metacentric heights are obtained using the following equations:

$$GM_T = KB + BM_T - KG \quad (21)$$

$$GM_L = KB + BM_L - KG \quad (22)$$

GM_T, GM_L should be given different equation numbers (i.e. Equation (20) and (21)).

where *KB* is the vertical distance from the *CoB* to the keel point of the ship and *KG* is the vertical distance from *CoG* to the keel.

The terms BM_L and BM_T are defined below:

$$BM_T = \frac{I_T}{V} \quad (23)$$

$$BM_L = \frac{I_L}{V} \quad (24)$$

where I_L is the longitudinal and I_T is the transverse moment of inertia of the wetted area, respectively.

3.5 Hydrodynamic properties

In practice, the hydrodynamic properties are calculated by diffraction software. However, in this work, an approach of getting the hydrodynamic properties from first principle through the engagement of potential theory and vessel design software is presented. Such parameters include added mass, wave damping and the wave forces and moments. Some of these parameters have been described earlier. For the hydrodynamic force, it can be computed with this expression;

$$F(\omega, dir) = F_a \cos(\omega t + \varepsilon_F) \quad (25)$$

where F_a and ε_F are the amplitude and the phase of the hydrodynamic forces, respectively.

3.5.1 Potential theory: added mass and damping

The added mass and damping coefficients as well as the wave forces are determined from the pressure distribution on the hull which is calculated from the velocity potentials. The potential of a floating body is expressed as the sum of the potential due to an undisturbed incoming wave Φ_w, the potential due to the diffraction of the undisturbed incoming wave, Φ_d, and the radiation potential Φ_d, and the radiation potential due to six body motions Φ_r(Williams et al., 2012).

$$\Phi = \Phi_r + \Phi_w + \Phi_d \quad (26)$$

Assuming the condition of an ideal fluid, the potential theory can then be developed for unidirectional regular waves.

Using the velocity potentials, the hydrodynamic pressures on the surface of the body can be obtained from the linearized Bernoulli equation:

$$p = -\rho \frac{d\Phi}{dt} - \rho g z = -\rho\left(\frac{d\Phi_r}{dt} + \frac{d\Phi_w}{dt} + \frac{d\Phi_d}{dt}\right) - \rho g z \quad (27)$$

where ρ is the water density and the term ρgz is the hydrostatic pressure.

The integration of this pressure over the submerged surface S of the body, provides the hydrodynamic force or moment expressed as; (Skandali, 2013).

$$F_{total} = -\iint (p \times n) \cdot dS = \rho \iint \left(\frac{d\Phi_r}{dt} + \frac{d\Phi_w}{dt} + \frac{d\Phi_d}{dt}\right) n \cdot dS \quad (28)$$

where n is thevectorof the direction cosines of the surface elements dS:

$$\boldsymbol{n} = \begin{bmatrix} cos(n,x) \\ cos(n,y) \\ cos(n,z) \\ ycos(n,z) - cos(n,z) \\ ycos(n,x) - cos(n,x) \\ ycos(n,y) - cos(n,y) \end{bmatrix} \quad (29)$$

Note: n is a vector of the direction cosine and not a matrix. It is an equation and should be numbered.

Then, the hydrodynamic forces and moments can be split into four parts:

$$F_{total} = F_r + F_w + F_d + F_s \quad (30)$$

where F_r is hydrodynamic forces and moments due to the waves radiating from the oscillating body, F_w is hydrodynamic forces and moments on the body due to the undisturbed approaching wave, F_d is hydrodynamic forces and moments due to the diffracted waves, and F_s is hydrodynamic forces and moments due to the hydrostatic buoyancy.

$$\varphi_w = \frac{g}{\omega^2} e^{kz} e^{i(kx\cos(dir) + ky\sin(dir))} \quad (31)$$

With respect to the diffraction potential, there is a linear relation with the undisturbed wave potential:

$$\Phi_d = \{\varphi_d \cdot i\omega\zeta_a e^{i\omega t}\} \quad (32)$$

where $\varphi_d$is the unknown space dependent term of the diffraction potential.

In order to determine the first order wave exciting forces and moments, the pressure due to the incoming and diffracted wave should be calculated:

$$p_w = -\rho \frac{d(\Phi_w + \Phi_d)}{dt} \quad (33)$$

Thus, the hydrodynamic forces and moments are determined by the following equation:

$$\boldsymbol{F_w} + \boldsymbol{F_D} = -\iint (p * \boldsymbol{n}) \cdot dS = \rho\omega^2\zeta_a e^{i\omega t} \iint_S ((\varphi_w + \varphi_d) \cdot \boldsymbol{n}) \cdot dS \quad (34)$$

As with the space dependent term of the radiation potential, the unknown term of the diffraction potential, φ_d, is determined by the panel method.

4. Data

The required data for these analyses is presented in this section.

Case 2 – P23.

Also, the P23 Passenger boat records the following details; Length: 7.0m, Beam: 2.56m, Depth: 1.50m.

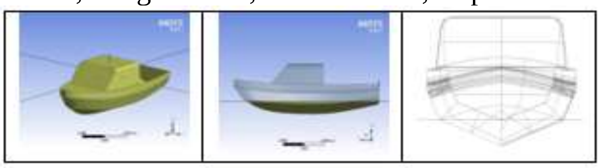

Fig. 4: P23 passenger boat

Other hydrostatic parameters for the P23 are presented in Table 1.0. These values are useful at the matrix establishment stage.

Table 1: The parameters needed for the response amplitude operator.

Parameters	Value
Weight displacement of the vessel at 0.6m draft.	3068.4240043 kg
Submerged Volume of the vessel	2.9935844 m^3
Moment of Inertia with respect to x, y, z axes (Iax)	I_{xx} = 36521.91671 kg.m^2 I_{yy} = 5185.636567 kg.m^2 I_{zz} = 1725.988502 kg.m^2
Water plane area	11.234378 m^2
wetted surface area	12.923 m^2
Centre of flotation (COF)	3.1736948 m
Longitudinal Centre of Buoyancy (COB)	3.280611 m
Longitudinal BM_L	9.4116354 m
Longitudinal moment of inertia I_L	28.174526 m^4
Transverse moment of inertia I_V	3.5872662 m^4
BM: Vertical Distance between Buoyancy and Metacenter	1.198318 m
KB: Vertical distance from COB to the keel	0.4258084m
KG: vertical distance from COG to the keel	Varies based on loading.
acceleration due to gravity	9.80665m/s^2
Fluid density	1025Kg/m^3

5. Results

It is important to obtain accurate values for the RAO amplitude and phase if the dynamics of the system are to be accurately modelled. These amplitude values vary for different types of vessels, and for a given vessel type they vary with draught, wave direction, forward speed and wave period/frequency. Figure 6 presents the amplitude of Heave –RAO of P23 at the bonny offshore location. Based on the wave spectral results, attention has been given to the main angle of wave attack (225^0). We can see that the resonance of heave motion happens at the frequency 1.0rad/s. At the resonance the RAO is about 0.6. So, in a short wave at high frequencies the response is very small. Which means that the P23 might not move in a very short wave. By implication, a heave RAO of 0.5 in a wave of height 4m (and hence wave amplitude 2m) means that the vessel heaves to and from -1m to +1m from its static position. Also, shown in figure 7 is corresponding result of heave RAO of the P23 described in Table 2 and Fig. 5.

Table 2: P23 further computed values

R_{xx}^2	R_{yy}^2	R_{zz}^2	BM_L	BM_T	GM_T	GM_L
12.1	1.56	0.02	0.0017	0.014	0.86	0.61

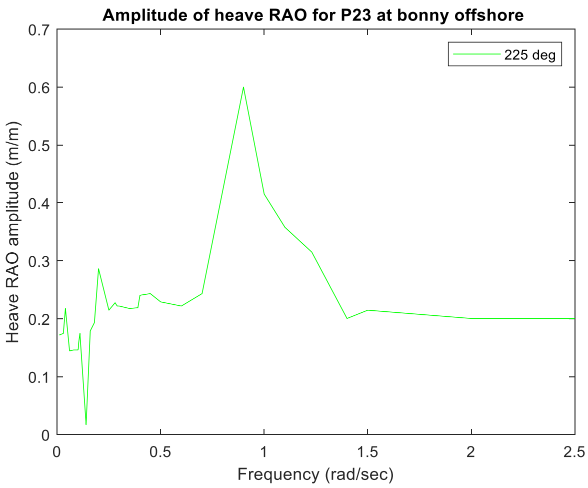

Fig. 5: Amplitude of P23 heave RAO

The results of the boat's response are presented in Figures 6 to 11.

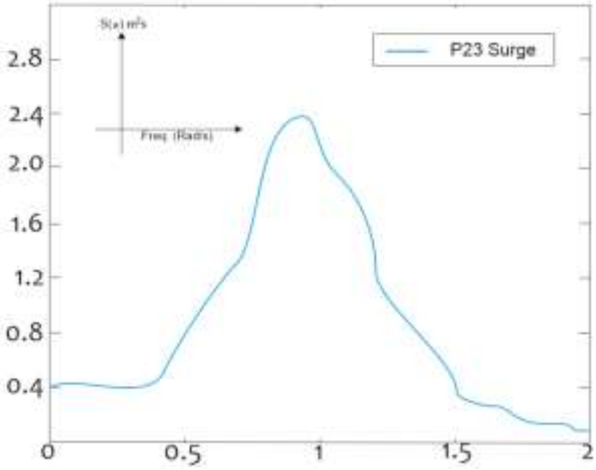

Fig. 6: Surge response

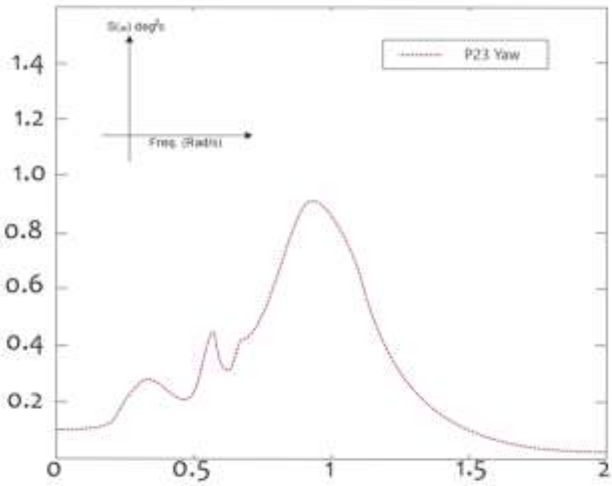

Fig. 7: Yaw response

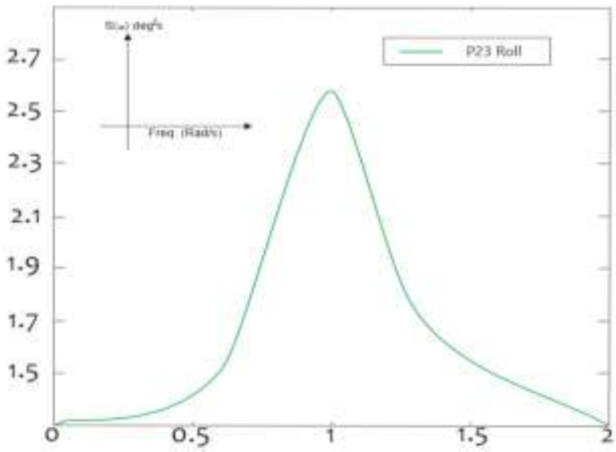

Fig. 8: Roll response

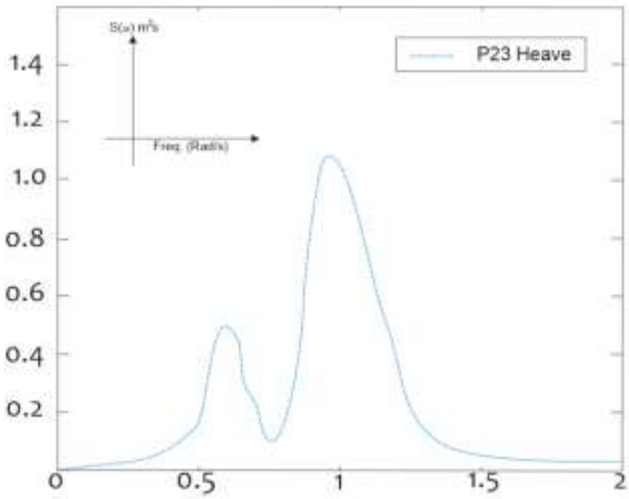

Fig. 9: Heave response

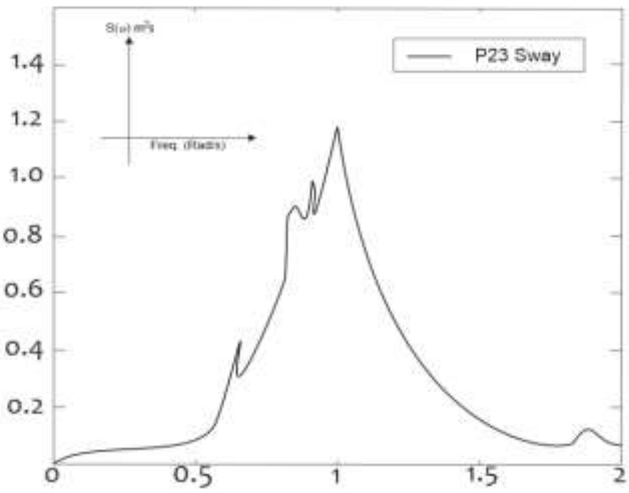

Fig. 10: Sway response spectra

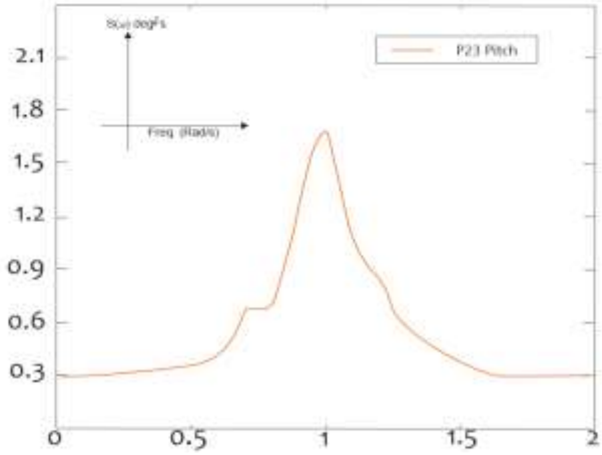

Fig. 11: P23 pitch response spectra

Table 3: The response spectra zero moment computations

Name of plot	Zeroth moment
Surge response curve	0.0454213
Heave response curve	0.0474265
Sway response curve	0.0300549
Roll response curve	0.0438435
Pitch response curve	0.0384621
Yaw response curve	0.0192354

Table 4: The wave spectra zero moment (Agbakwuru and Akaawase, 2020)

Name of plot	Zeroth moment
Bonny offshore wave spectra	0.09615

6. Discussion

Table 3 indicates the total energy experienced by P23 in different motion modes. Table 4 indicates the energy content of the Bonny offshore wave. It is evident that the vessel P23 experiences largest energy at heave and surge and lowest energy at yaw. This is expected because the wave is basically in one direction. From the various response spectra plots, it is observed that the major energy peaking occurred around the value of 1rad/s. Response spectra of in roll of P23 boat in Bonny offshore is somewhat large, with a value of 2.55 deg^2s roll recorded as highest response spectra value. The possible reason for this outcome is that the P23 hull-form is U-shaped.

7. Conclusions

P23 Boat response spectra in roll as found in the work is considered high due to consequence of rolls on angle of inclination of initial stability of a passenger boat. It is noted that this is attributed to the hull form of the P23 boat. Implying that a modification of the hull could be necessary to a more comfortable passenger transport in Bonny offshore using P23 boat.

Acknowledgements

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