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Comparative Spectral Motion Responses of P23 and W23 Passenger Boats in Bonny Offshore Water in Nigeria

Agbakwuru, J.A*, Akaawase, B.T and Abam, J
Department of Marine Engineering, Federal University of Petroleum Resources Effurun
*Corresponding author's email: agbakwuru.jasper@fupre.edu.ng

Abstract
A detailed approach to ascertaining relative behavior of P23 and W23 as passenger boats on wave data measured in Bonny Offshore Nigeria is considered. As a continuing research, wave spectra result of the Bonny Offshore location were extracted from previous studies and used as input in this work. Using Newton's second law of motion, the response equation involving complex wave amplitude was deduced and used to estimate the vessels' response. Zeroth moments of the spectra graph were calculated for both vessels in different motion modes and in average term, P23 showed high spectra zeroth moment values compared to W23. P23 experienced 39% of the surface wave energy content while W23 experienced only 28% in average term. The reduced spectra zeroth moment of W23 boat implies low Motion Sickness Index (MSI) which in-turn is an indicator of passenger's comfort. In line with the research goal, from the perspective of motion response of the P23 and W23 due to surface waves at Bonny Offshore, the best-performed boat, W23 is recommended for use at the location.

Keywords: *Wave spectra, Offshore, Response amplitude, Frequency domain, Boat, MATLAB*

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1. Introduction

Bonny offshore is located at 4.1902N and 7.233E in Nigeria, West Africa. The site consideration is 19.0m water depth. Activities such as crude exploration, maritime transportation, structures transportation, installation, maintenance among others are on the increase in the Bonny location. 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 (Agbakwuru et al., 2020). There are also incessant reports of passenger boat mishaps due to wave conditions and consequential loss of precious lives of men, women and children in Bonny waters. This work is intended to review common passenger boat hydrodynamic configuration with respect to response under wave conditions.

Agbakwuru and Akaawase (2021a) has previously studied the spectral response computation of a P23 boat in Bonny waters. Agbakwuru and Akaawase (2021a) also provided extensive review and report of literatures in the research area including the work of Skandali (2015), Williams et al. (2012), Adam and Bjorn (1999), and Abam and Akaawase (2018). In this work and as performed in Agbakwuru and Akaawase (2021a), inaccuracies are minimized by an approach of computing vessel's response putting into consideration the wave headings. As in Agbakwuru and Akaawase (2021a), it is assumed that the boats (W23 and P23) are seating on the water facing the incoming waves without been anchored nor engine(s) engaged as shown in Fig. 1.

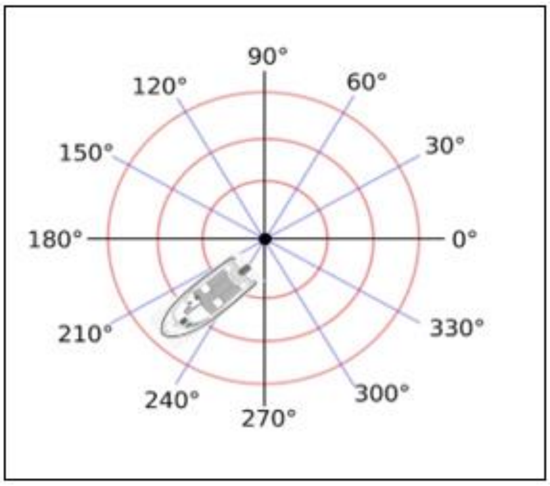

Fig. 1: Position of the boats (W23 and P23) at Bonny offshore

To predict an accurate vessel's response spectrum, several equations of motions are engaged to determine the Response Amplitude Operators (ROAs) and wave spectrum. To actualize this, the RAOs is obtained with respect to the available vessel's hydrostatic and hydrodynamic database characteristics provided by the Centre for Maritime and Offshore Studies, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria (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.

Similar to Agbakwuru and Akaawase (2021a), the test case will be based on the results of the wave spectral presented by Agbakwuru and Akaawase, (2021b) for the Bonny location. The extracted results from the work of Agbakwuru and Akaawase (2021b) contained the wave spectrum (frequency, spectral density and wave directions). To derive the response spectra, W23 and P23 vessels' hydrodynamic properties supplied by the Center for Maritime and Offshore Studies of the Federal University of Petroleum Resources, Effurun, Delta State, Nigeria is used.

As described in Agbakwuru and Akaawase (2021a), the motion is described mainly as linear and analysed in frequency domain. 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, 2015). 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.

As in Agbakwuru and Akaawase (2021a), the surface wave elevation of Bonny offshore environment is described in a wave spectrum. The spectral represent the energies in the irregular waves traveling across the water surface. Such irregular waves are represented as the sum of a large number of harmonic wave components with varying periods, directions, phases, and amplitudes. A detailed computation of Bonny Offshore wave spectral is discussed in Agbakwuru and Akaawase (2021b) 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.

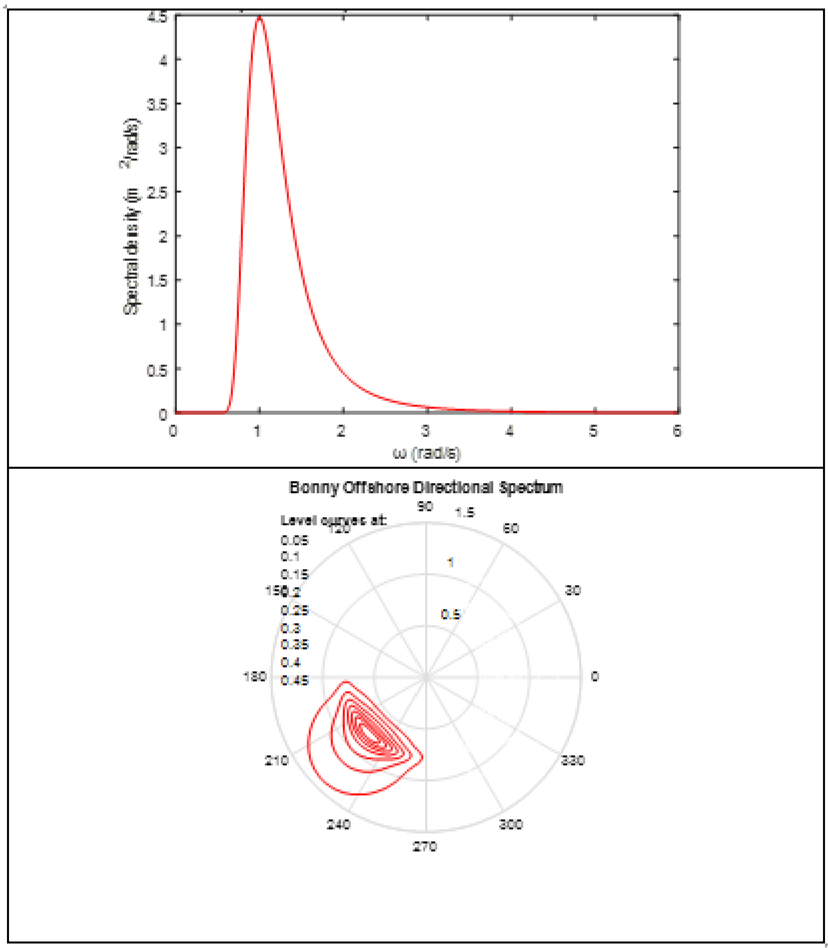

Fig. 3: Bonny wave spectral representation (Source: Agbakwuru and Akaawase, 2021b)

2. Materials and methods

The Spectra employed is developed using wave data from the location (Bonny Offshore location) presented in Agbakwuru and Akaawase (2021b). The hydrodynamic data for the P23 and W23 boats are generated and collected from the Center for Maritime and Offshore Studies of the Federal University of Petroleum Resources Effurun. The method used in this work is similar to the presentation made in Agbakwuru and Akaawase (2021a).

2.1 W23 parameters

The major parameters of the W23 Passenger boat are: Length: 7.0m, Beam: 2.35m, Depth: 0.80m. Other details required for response computation are presented in Table 1.

2.2 P23 parameters

The P23 Passenger boat records the following details: Length: 7.0m, Beam: 2.56m, Depth: 1.50m. Other hydrostatic parameters for the P23 are presented in Table 2. These values are useful at the matrix establishment stage.

Table 1: W23 parameters needed for response amplitude operator

S/N	Parameters	Value
1.	Weight displacement of the vessel at 0.215m draft.	2538.2268 kg
2.	Submerged volume of the vessel	2.4763188 m^3
3.	Moment of Inertia with respect to x, y, z axes (Iax)	I_{xx} = 30738.94 kg.m^2 I_{yy} = 3965.98 kg.m^2 I_{zz} = 38.08926 kg.m^2
4.	Water plane area	12.276305 m^2
5.	Wetted surface area	14.63 m^2
6.	Centre of flotation (COF)	2.6460769 m

7.	Longitudinal Centre of Buoyancy (COB)	2.5488596 m
8.	Transverse moment of inertia I_T	35.023903 m^4
9.	Longitudinal moment of inertia I_L	4.335084 m^4
10.	BM: Distance between Buoyancy and Metacenter	1.7506169 m
11	KB: Vertical distance from COB to the keel	0.1102231 m
12.	KG: vertical distance from COG to the keel	Varies based on loading.
13.	Acceleration due to gravity	9.80665 m/s^2
14.	Fluid density	1025 kg/m^3

Table 2: P23 parameters needed for response amplitude operator

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

2.3 Response amplitude operator (RAO)

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

For translational motion (surge, sway, heave)

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

where m is the mass of the single system in motion and $\ddot{x}$ is the accelerating motion

For rotational motion (roll, pitch, yaw)

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

where I is the moment of inertia and $\dot{\omega}$ is the angular velocity.

In a more compact form, the Equation (1) becomes:

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

where F_i is the total hydrodynamic and hydrostatic forces, M_{ij} is the mass matrix in relative i and j motion mode. Equation (3) is generally expressed as the sum of hydrostatic, radiation and exciting forces.

2.4 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 coefficient. Note that some of the non-zero hydrostatic coefficients would vanish, as the boats are symmetric about some axes.

2.5 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 in different motion modes and b_{ij} is the radiation damping due to the wave radiation in different motion modes. It should be noted that the subscript j indicates the motion modes while the main i is for the imaginary unit.

2.6 Exciting force (hydrodynamic)

This is expressed as:

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

where $\varphi_i$andφ_o are potential of incoming wave and the potential of radiated waves respectively and dS is the surface normal (n) to the wave pressure p.

2.7 The domain

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

$$\text{Velocity: } V_j = i\omega\xi_j \quad (7)$$

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

These expressions shows that velocity has a phase difference of 90^0 and acceleration has 180^0 phase difference about the motion. Substituting the hydrostatic forces and the hydrodynamic forces into the equation of the boats' 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} are the added mass and damping due to the radiation, and c_{ij} is the hydrostatic restoring force coefficient. With this, the potentials can be determined from the potential theory described in section 2.9. Once the relevant potentials and thus the hydrodynamic forces are computed, the motion amplitude can be solved by making the complex amplitude subject of Equation (9):

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

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

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

where, A is the wave amplitude. Principally, the hydrodynamic equation in frequency domain is derived from the hydrodynamic equation in time domain. Since in linear dynamic system, we assume the system is under sinusoidal, the motion will also be sinusoidal accordingly, thus:

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

And the corresponding motion velocity and acceleration of the structure were 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:

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

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

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

If we cancel out the time factor in Equation (16), we can obtain the frequency domain equation shown in Equation (9). Finally, the motion response spectra were 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_ζ 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.

2.8 Further description of parameters

From the body mass of the vessels and their respective radius of gyration, a 6x6 is generated as:

$$\mathbf{M} = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & r_{xx}{}^2 m & 0 & 0 \\ 0 & 0 & 0 & 0 & r_{yy}{}^2 m & 0 \\ 0 & 0 & 0 & 0 & 0 & r_{zz}{}^2 m \end{bmatrix}$$

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:

$$r_{xx} = \sqrt{\left(\frac{I_{xx}}{m}\right)}, r_{yy} = \sqrt{\left(\frac{Iyy}{m}\right)}, r_{zz} = \sqrt{\left(\frac{I_{zz}}{m}\right)} \quad (18)$$

where I_{xx}, I_{yy} and I_{zz} are the moments of inertia regarding 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 W23 and P23.

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_{WL} & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho g \bar{V} GM_T & 0 & 0 \\ 0 & 0 & -\rho g A_{WL}(CoF - CoB) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (19)$$

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 are extracted from the Centre for Maritime and Offshore Studies Catalogue of W23 and P23 boats, refer to section 4.0.

$$GM_T = KB + BM_T - KG$$
$$GM_L = KB + BM_L - KG \quad (20)$$

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:

$$BM_T = \frac{I_T}{V} \quad (21)$$

$$BM_L = \frac{I_L}{V} \quad (22)$$

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

2.9 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, wave forces and moments. Some of these parameters have been described earlier, for the hydrodynamic force, it can be computed with this expression:

$$F(\omega, dir) = F_a \cos(\omega t + \varepsilon_F) \quad (23)$$

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

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 Φw, the potential due to the diffraction of the undisturbed incoming wave, Φd, and the radiation potential Φd, and the radiation potential due to six body motions Φr (Williams et al., 2012).

$$\Phi = \Phi_r + \Phi_w + \Phi_d \quad (24)$$

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:

$$p = -\rho \frac{d\Phi}{dt} - \rho g z = -\rho\left(\frac{d\Phi_r}{dt} + \frac{d\Phi_w}{dt} + \frac{d\Phi_d}{dt}\right) - \rho g z \quad (25)$$

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 in Skandali (2015) as:

$$F_{total} = -\iint (p \times n)\cdot dS = \rho \iint \left(\frac{d\Phi_r}{dt} + \frac{d\Phi_w}{dt} + \frac{d\Phi_d}{dt}\right)\boldsymbol{n}\cdot dS \quad (26)$$

where $\boldsymbol{n}$ is the matrix of the direction cosines of the surface elements dS:

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

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

$$F_{total} = F_r + F_w + F_d + F_s \quad (27)$$

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

$$\varphi_w = \frac{g}{\omega^2} e^{kz} e^{i(kxcos(dir)+kysin(dir))} \quad (28)$$

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

$$\Phi_d = \{\varphi_d \cdot i\omega\zeta_a e^{i\omega t}\} \quad (29)$$

where φ_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:

$$p_w = -\rho \frac{d(\Phi_w + \Phi_d)}{dt} \quad (30)$$

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

$$\boldsymbol{F_w} + \boldsymbol{F_D} = -\iint (p * \boldsymbol{n}) \cdot dS = \rho\omega^2\zeta_a e^{i\omega t}\iint_S((\varphi_w + \varphi_d)\cdot \boldsymbol{n})\cdot dS \quad (31)$$

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.

3. Results

Using Equation (18) to (22), the parametric computed values of P23 and W23 are shown Tables 3 and 4. To precisely model the dynamics of the vessels, great attention is paid to the RAO values. Fig. 4 presents the amplitude of Heave RAO of P23. Based on the wave spectral results, attention has been given to the main angle of wave attack (225^0). Also, shown in Fig. 5 is the corresponding result of heave RAO of W23. Fig. 4 and 5 are derived from Equations (10) and (11).

Table 3: P23 hydrodynamic parameters

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

Table 4: W23 hydrodynamic parameters

R_{xx}^2	R_{yy}^2	R_{zz}^2	BM_L	BM_T	GM_T	GM_L
11.1	2.21	0.36	0.0367	0.029	1.53	1.18

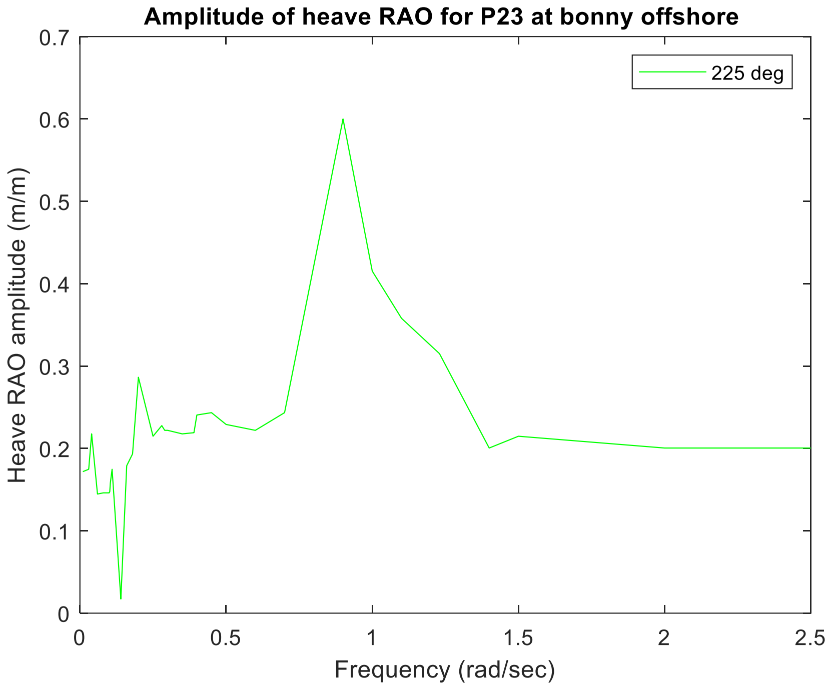

Fig. 4: Amplitude of P23 heave RAO.

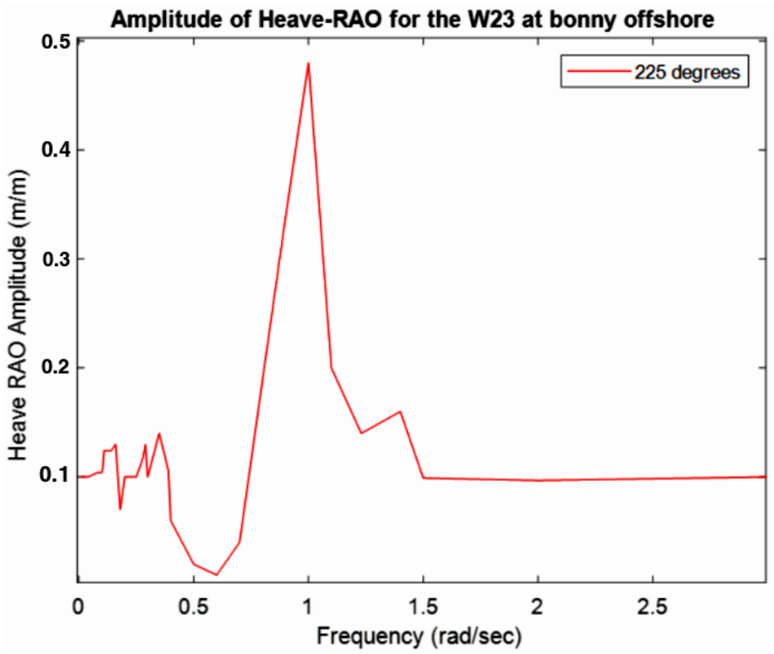

Fig. 5: Amplitude of W23 heave RAO

The results of the boat's response are presented in Fig. 6 to 11. The spectra zeroth moments for each of the different modes of spectral motion of P23 and P23 is tabulated in Table 5. The zeroth moment of the Bonny offshore wave spectra is presented in Table 6. The computations were made using Equation (17) for different *i*th motion mode.

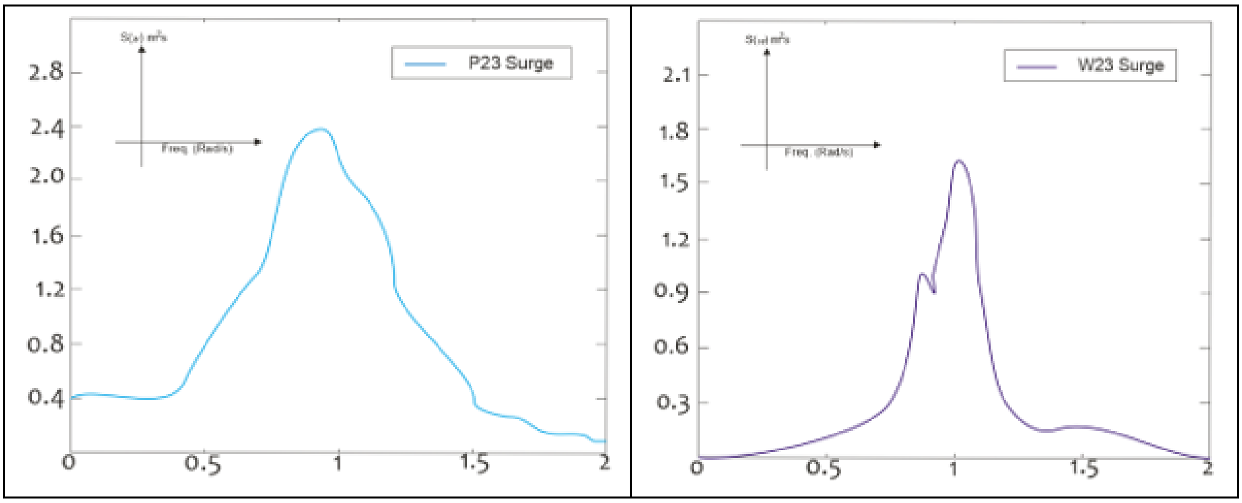

Fig. 6: Surge response

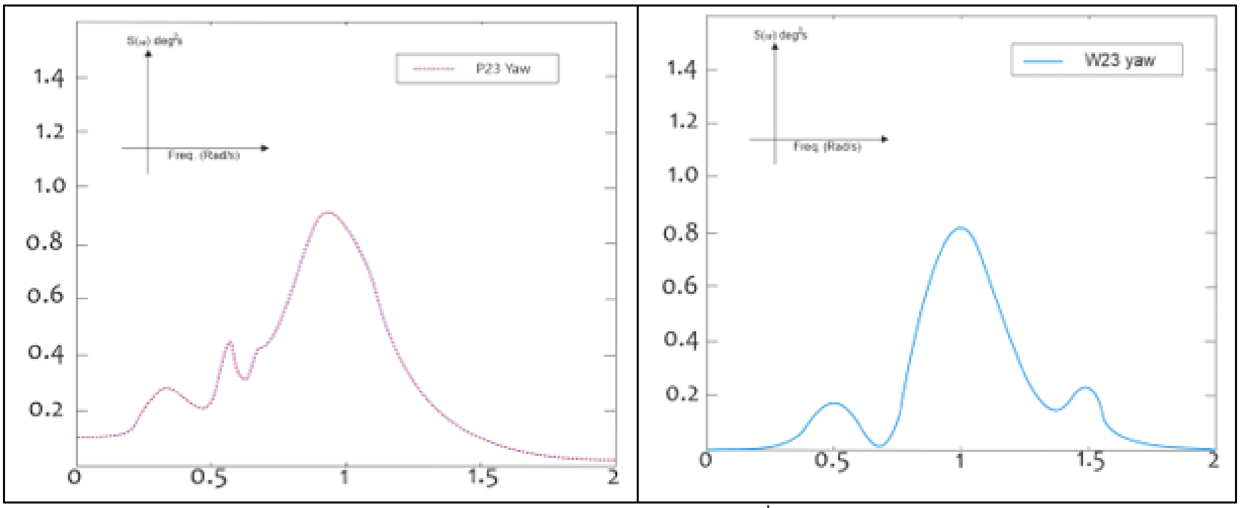

Fig. 7: Yaw response

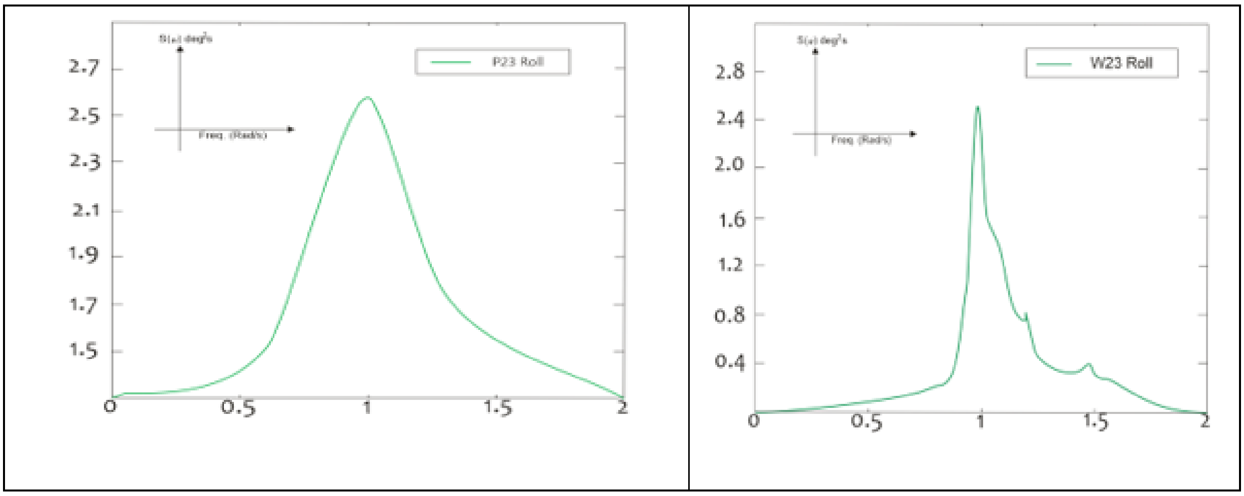

Fig. 8: Roll response

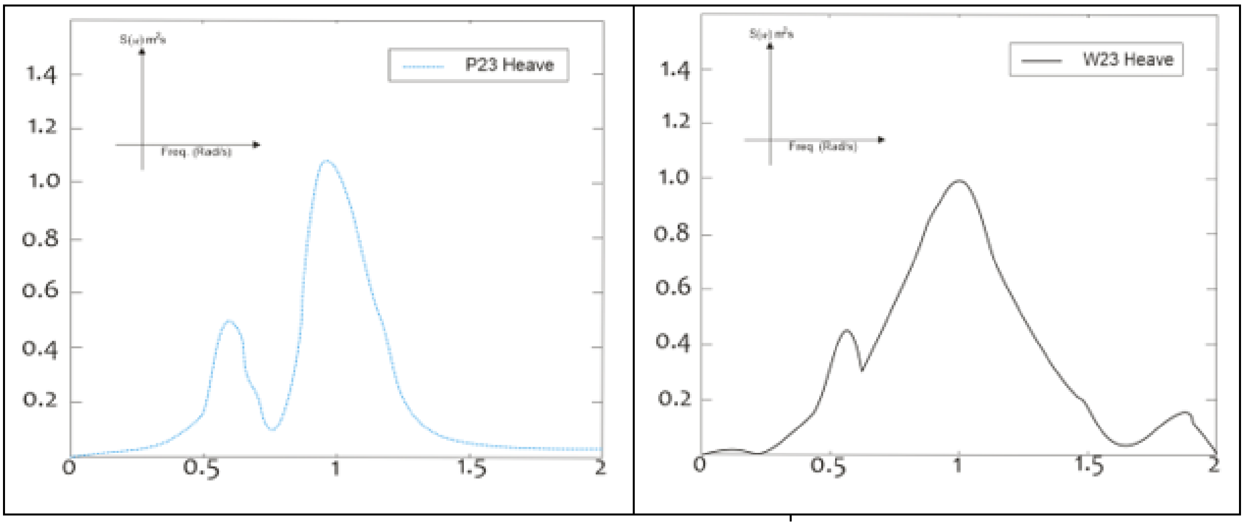

Fig. 9: Heave response

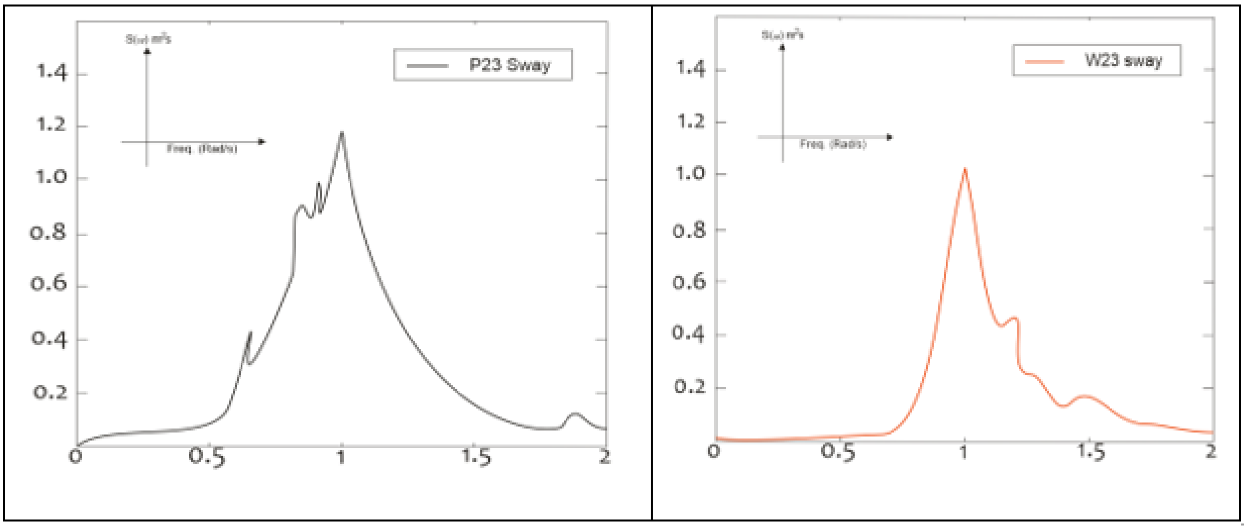

Fig. 10: Sway response spectra

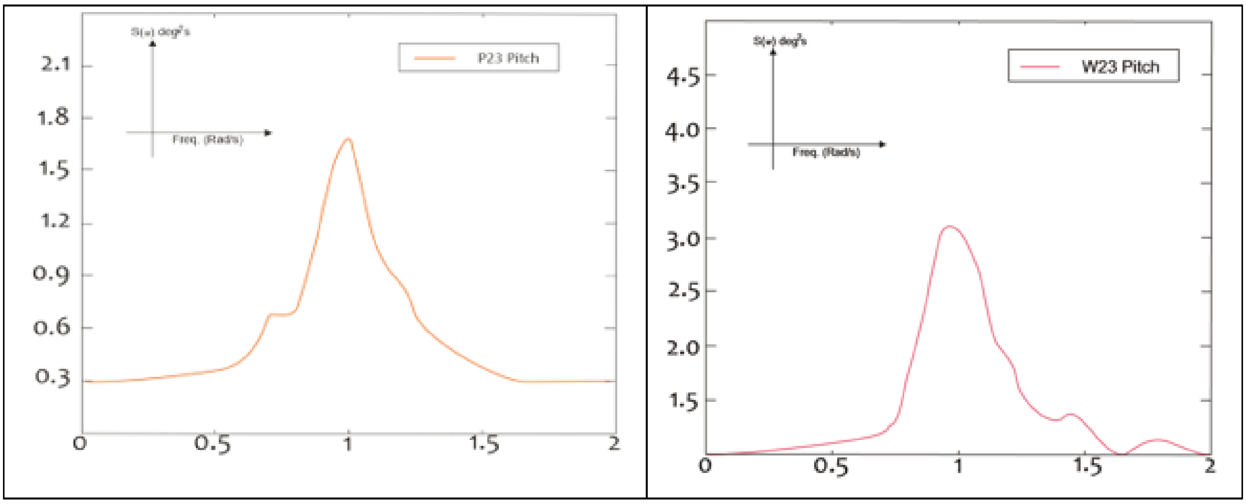

Fig. 11: Pitch response spectra

Table 5: The response spectra zero moment computations.

SN	Name of plot	Zeroth moment (P23)	Zeroth moment (W23)
1	Surge response curve	0.0454213	0.023
2	Heave response curve	0.0474265	0.051
3	Sway response curve	0.0300549	0.028
4	Roll response curve	0.0438435	0.024
5	Pitch response curve	0.0384621	0.017
6	Yaw response curve	0.0192354	0.018
	Mean	0.0374072	0.026833

Table 6: Bonny offshore wave spectra zero moment (sourced from Agbakwuru and Akaawase, 2020).

SN	Name of plot	Zeroth moment
1	Bonny offshore wave spectra	0.09615

4. Discussion

Table 5 indicates the total energy experienced by W23 and P23 in different motion modes. The zeroth moment indicates the amount of energy contained in a motion mode. From operational point of view, it is desired that the energy content of the vessels' motion modes should be very less compared to that of the surface wave. W23 in Table 5 has mean spectra zeroth moment of 0.026833 compared to P23 that has mean spectra zeroth moment of 0.0374072. From the Bonny offshore wave spectra zeroth moment shown in Table 6, namely 0.09615, W23 experiences 28% energy of the surface wave at Bonny Offshore. For P23, the boat experiences about 39%. In a layman's term, a passenger onboard P23 will experience more motion effect (39% of the surface wave energy) than another passenger onboard W23. In general, comparing Table 5 with Table 6, it is evident that P23 experiences the largest energies at most motion mode. This is even when P23 has displacement weight of 0.5T larger than W23. P23 experiences large roll at spectral range of 0.8Hz - 1.2Hz (see Fig. 8, left-hand -side). The W23 is relatively stable in roll except at 1.1Hz (see Fig. 8 right-hand-side). This is an interesting result considering that P23 has larger beam than W23 and P23 has relatively low GM_T and GM_L (0.86m and 0.61m respectively) compared to W23 (1.58m and 1.18m respectively). The possible reason for this outcome is that the P23 hull-form is U-shaped. Comparing the two vessels, W23 will function best at the location.

4. Conclusion

The consequence of large mean energy content, especially roll in P23 is increase in Motion Sickness Index compared to W23. This implies that in terms of personnel comfort, W23 will be best as passenger transport boat in the location under consideration. The response spectral motion performance of W23 over P23 under Bonny Offshore wave condition also means that W23 will be safer to operate, especially as passenger boat compared to P23. As noted, the hull-form of the boats is perhaps responsible for the different characteristics of the two boats under consideration. Thus, W23 is recommended for usage at the location.

5. Acknowledgement

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