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Surge Motion Response Evaluation due to Induced Wave Loads on a Drillship (Scorpio 300)

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ABSTRACT

Wave induced loads on offshore structures are very important factor that decides the performance rating of the response of the structure in question. These loads must be properly investigated during design or redesign stage to determine the response and structural integrity of the ship. A ship displaced from its horizontal position in translational surge motion cannot return to its original position without the necessary restoring force. However, for it to be returned, a suitable mooring system must be put in place to provide the required restoring force through its line stiffness. This work is on the investigation of the surge responses of the drillship to induced wave loads at different angles of attack. It is aimed at determining the most probable maximum surge amplitude for various angles of attack ranging from 0^o to 90^o. Froude-Krylov theory was used to determine the surge force model. Spectra analysis in frequency domain was then carried out to obtain the required responses due to the force. A MATLAB-based program was developed to carry out these analyses from start to finish. This is to statistically determine the most probable maximum amplitudes of the ship. The results obtained show that the highest maximum surge response amplitude is 0.2434m at 0^o, and it continued to decrease till 0m at 90^o angle of attack.

Keywords: Drill ship, Investigation, Most probable maximum surge amplitude, Wave induced loads.

1. INTRODUCTION

Man's quest to explore and exploit the ocean over time for marine and oil/gas activities, has made wave induced loads evaluation very important. To successfully carry out these activities, offshore structures must be designed to withstand all environmental induced loads, especially as the activities goes further into the ultra deep water areas with highly harsh environmental conditions. Floating vessels like FPSO, FSO, Drillship, Pipe laying barge etc. must at any given time be able to withstand any excitation force in a given geographical location for ease of operation.

Wave induced loads on offshore vessel is difficult to analyze. This is based on the fact that waves in real sea conditions are very much irregular. Design engineers rely mostly on the formulae provided by standard classification societies to ensure accuracy, reliability and safety. However, it is advisable for them to have adequate knowledge and understanding on the theory formulation used in the statistical wave loads determination.

Response of a ship to induced wave loads are usually determined using various approaches as may be considered fit for a particular ship type. In this context, spectra analysis will be used to determine the maximum responses in surge motion.

Surge Motion

This is the sideways motion of the ship in the longitudinal X-axis as the wave attacks the transverse Y-axis. The motion is translational in nature, and when it occurs, the ship cannot regain its initial position. Therefore, in order for the ship not to move beyond the acceptable limit, a mooring or dynamic positioning system is put in place to check mate this condition.

Scorpio 300 in Brief

Scorpio 300 is a Drillship designed to carry out drilling activities. This brief history about the Drill ship will help the reader appreciate the significance of this work as stated above.

It is worthy to know that this ship was acquired without any marine history, and other

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major functional equipment onboard, which made it impossible to operate; most of the equipments like the mooring system are not in place. The Marine Operating Manual (MOM), the model below and other deliverables which have been approved by standard regulatory body were developed. The model below was developed using inventor software.

Fig. 1: Scorpio 300 Model

Aim

- To determine for each case study the most probable maximum surge amplitude (responses of the ship) caused by the induced wave loads at different angles of attacks 0:15:90 degrees.

Objectives

- To determine the pressure forces acting on the transverse section of the ship capable of causing surge motion, by using Froude- Krylov theory.
- To determine the ship responses at different angles of attacks caused by the pressure forces induced by the wave loads, by using modified Pierson-Moskowitz spectrum.

Various methods have been adopted by different researchers to investigate ship responses; such as numerical method, using equation of motions, hybrid, and time history to carry out spectra analysis. All these gave good and satisfactory results after their estimations.

II. ANALYTICAL MODEL

In this research, an independent MATLAB-based program will be developed to carry out analysis for all the different angles of attacks on the ship. The Froude-Krylov force (Pressure force) developed and the Pierson-Moskowitz energy equation will be used to determine the ship most probable maximum surge amplitude by carrying out spectra analysis for angles 0^0:15^0:90^0. After which the angle with the highest response is obtained, and the determined results validated with results extracted from work done in a different soft ware to ascertain the accuracy of the method adopted in this research work.

III. METHODOLOGY

The materials used are the principal dimensions of the ship, the metocean data for typical Nigeria sea state from DNVGL. The dimensions are as given below in a tabular form.

Table 1: Principal Ship Dimensions

Ship Dimensions	
Length overall L_{OA}	59.10 m
Beam B_s	16.46 m
Depth D_s	4.0 m
Draft d_s	1.7572 m
Mass displacement Δ	1,642.7 ton

The metocean data for the wave parameters are as given below for Nigeria sea state according to DNVGL (2018) position mooring guide.

Wave (Squall) condition

H_S = 2.5 m, T_P = 7.2 s, T_Z = 5.12 s, 100 years return period.

Definitions

H_S Significant wave height, T_P Peak period, and T_Z is the zero up crossing period.

Determination of the Surge Force model

The force is derived by taking an elemental part dz of the transverse section (y-y axis) from the aft of the ship as seen in figure 1 above, and integrating

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from the reference point 0 to the keel of the ship –ds. This is shown in the figure 2 below for clarity.

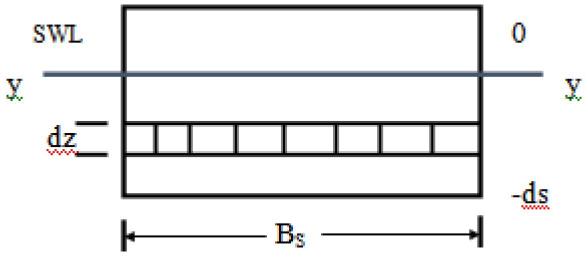

Fig.2: Elemental strip in the transverse section

The surge force acting on the ship is the sum of the force from the aft and the force countering it from the fore. This is expressed as;

$$dF_1 = dF_{1aft} + dF_{1fore} \tag{1}$$

The force acting on the aft of the ship is equal to the Froude-Krylov force plus the added mass force expressed as;

$$dF_{1aft} = (dF_k + A_{11}.a_1 dz)\cos\theta \tag{2}$$

The Froude-Krylov force is expressed as;

$$dF_k = P_D.dA \tag{3}$$

$$P_D = -\rho.\frac{\partial \emptyset}{\partial t} \tag{4}$$

From figure 2, the elemental area is gotten as;

$$dA = B_S.dz \tag{5}$$

The velocity potential equation for shallow water condition is given according to Akandu, (2018) as;

$$\emptyset = -\frac{g\zeta_\alpha}{\omega}\cdot\frac{\cosh\big(k(h+z)\big)}{\cosh(kh)}\cos(kx - \omega t) \tag{6}$$

The water particles acceleration in the longitudinal direction (x axis of the ship) is also expressed as;

$$\alpha_1 = \frac{\partial}{\partial t}\cdot\frac{\partial \emptyset}{\partial x}$$

Hence

$$\alpha_1 = kg\zeta_\alpha\left(\frac{\cosh\big(k(h+z)\big)}{\cosh(kh)}\right)\cos(kx - \omega t) \tag{7}$$

Substituting equations (4) and (5) into equation (3), will give the Froude-Krylov force as

$$dF_k = -\rho.\frac{\partial \emptyset}{\partial t}\cdot B_S dz \tag{8}$$

Substituting equations (7) and (8) into equation (2), and integrating from –ds to 0. Further substituting the direction of wave propagation x= $-L_S/2$ into the equation will give the surge force equation acting on the aft of the ship. Expressed as given below;

$$dF_{1aft} = \frac{g\zeta_\alpha}{k}(A\cdot B)C \tag{9}$$

Where

$$A = \rho B_S \sin\left(\frac{kl_s}{2} + \omega t\right) \tag{10}$$

$$B = -A_{11}k\cos\left(\frac{kl_s}{2} + \omega t\right) \tag{11}$$

$$C = \frac{\sinh(kh) + \sinh\big(k(d_s - h)\big)}{\cosh(kh)} \tag{12}$$

In a similar manner, the surge force in the opposite direction is the force acting at the fore of the ship. The same approach will be taken to achieve this force as given below;

$$dF_{1fore} = -\frac{g\zeta_\alpha}{k}(D\cdot E)C \tag{13}$$

$$D = \rho B_S \sin\left(\frac{kl_s}{2} - \omega t\right) \tag{14}$$

$$E = -A_{11}k\cos\left(\frac{kl_s}{2} - \omega t\right) \tag{15}$$

Putting equations (9) and (13) into equation (1), summing up like term and further simplification will give the Surge force acting on the ship as induced by the wave loads.

It will be seen clearly that the added mass force is out of phase with the Froude-Krylov force. Neglecting the added mass force due to its insignificant effect, and dividing by the wave amplitude will give a surge force expressed as per unit amplitude as given below.

$$\frac{F_1}{\zeta_\alpha} = -2g\rho B_S J\sin\left(\frac{kl_s}{2}\right)\sin(\omega t) \tag{16}$$

Amplitude of the surge force becomes;

$$\frac{F_{1\alpha}}{\zeta_\alpha} = -\frac{2g\rho B_S}{k}J\sin\left(\frac{kl_s}{2}\right)\cos\theta \tag{17}$$

Where

$$J = \tanh(kh) + \frac{\sinh\big(k(ds - h)\big)}{\cosh(kh)} \tag{18}$$

Definition of terms

F_1 = surge force, F_{1a} = amplitude of the surge force, F_{1aft} = surge force acting on the aft of the ship, F_{1fore} = surge force acting on the fore of the ship, F_k = Froude-Krylov force, A_{11} = added mass in surge, a_1 = horizontal water particles acceleration dz = elemental strip in the vertical axis of the ship, P_D = dynamic pressure, dA = elemental area of the transverse section, ρ = water density, ϕ = velocity Potential, B_S = beam of the ship, $\boldsymbol{g}$ = acceleration due to gravity, K = wave number, $\boldsymbol{\omega}$ = wave frequency, h = water depth, $\boldsymbol{\zeta}_a$ = wave amplitude, z = vertical axis of the ship, x = direction of wave propagation, $\boldsymbol{\theta}$ = angle of wave attacks on the longitudinal axis of the ship. Other equations useful to the work are given below.

The shallow water dispersion relationship equation will be used to determine the wave frequency, and is given as. Equations (19) to (29) are according to Akandu, (2017).

$$\omega = \sqrt{kg\,tanh(kh)} \qquad (19)$$

The quasi static force will be used with the magnification factor to determine the response amplitude operator (RAO) of the ship.

It is given as;

$$\frac{F_q}{\zeta_\alpha} = \frac{F_\alpha}{C} \qquad (20)$$

It will be worthy to note that C is the restoring force, and the value is obtained from the mooring line stiffness.

The dynamic amplification or magnification factor for a non damped system is gotten from the equation shown.

$$\varphi = \frac{1}{\sqrt{(1 - R^2)}} \qquad (21)$$

R is the frequency ratio, and is expressed as;

$$R = \frac{\omega}{\omega_n} \qquad (22)$$

The natural frequency of the ship is then obtained with the equation given below.

$$\omega_n = \sqrt{\frac{C}{M + A}} \qquad (23)$$

The response amplitude operator (RAO) is used to measure the response of the ship exposed to first order wave loads.

$$RAO = F_q \cdot \varphi \qquad (24)$$

The Pierson-Moskowitz wave energy spectrum equation is used with the square of the RAO to determine the ship response in various angles of attacks. And it is given as;

$$S(\omega) = \frac{124}{T_z^4} H_s^2 \omega^{-5} \exp\left(-\frac{496}{T_z^4}\omega^{-4}\right) \qquad (25)$$

Hence, the ship responses will be achieved using the equation as given.

$$S_R = S(\omega) \cdot RAO^2 \qquad (26)$$

The variance or Zeroth Moment (M_0) is achieved by using the equation below

$$M_0 = \frac{0.001 * S_{RT}}{3} \qquad (27)$$

The significant surge amplitude (ξ_s) is expressed as given below.

Where S_{RT} is the sum of the responses, and 0.001 is the step size chosen during the wave number determination which will be seen in the results and discussions section of this work.

$$\xi_s = 2 \cdot \sqrt{M_0} \qquad (28)$$

Then the most probable maximum surge amplitude (ξ_{max}) will be obtained with the equation below.

$$\xi_{max} = 1.86 * \xi_s \qquad (29)$$

IV. RESULT AND ANALYSIS

Range of wave number 0.001:0.001:3.001 rad.m^2/s were used in equation (19) to determine the wave frequencies used for the analysis. This gave 3001 values of the wave frequencies; it implies that for each parameter analyzed, results obtained are within this range for more statistical accuracy. The maximum results for each angle of attack 0, 15, 30, 45, 60, 75 and 90 degrees are of focus. These results and sequential procedures to achieve them will be itemized below.

A. Amplitude of the Surge Forces

As seen in figure 3 below, the amplitude of the surge forces are expressed as per unit amplitude and it follows a sinusoidal pattern. The maximum impact of the wave will be felt within the low frequency range; it dies off as the frequency continued to increase. The maximum amplitude of the surge forces obtained for various cases (angle of attacks) are as follow; 0^0 = 507.4270kN/m, 15^0 = 490.1368kN/m, 30^0 = 439.4446kN/m, 45^0 = 358.8050kN/m, 60^0 = 253.7135kN/m, 75^0 = 131.3318kN/m, and 90^0 = 3.1071*10^{-14}kN/m.

From the results above, the highest value of the maximum amplitude of the surge forces for all the angles occurred at 0^0 angle of attack, and it continued to reduce until it got to 90^0. As the angle increases, the forces reduced to zero at angle 90^0. Clearly, at 0 degrees angle of attack, pure surge motion occurred and this gave the highest response of the ship.

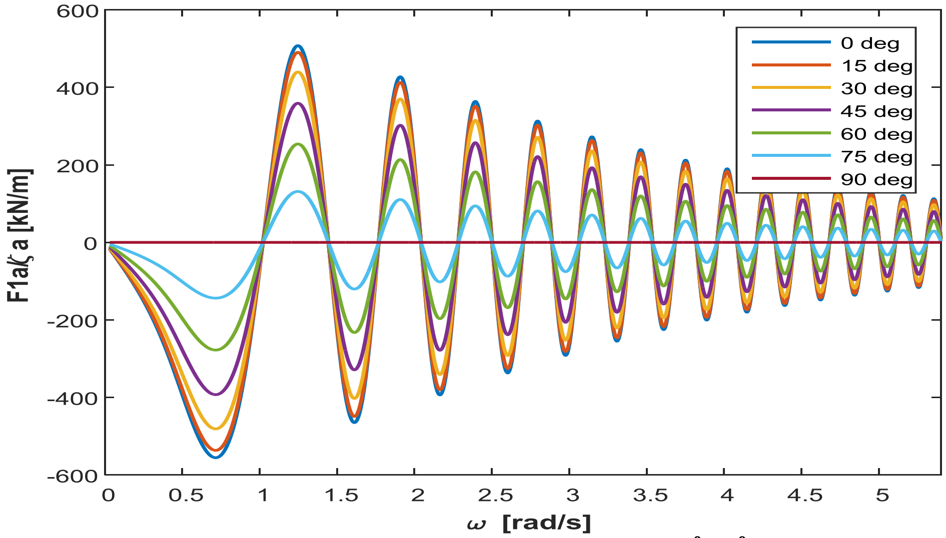

Fig. 3: Amplitude of the Surge Force (0^0-90^0)

B. Quasi-static Forces

The quasi-static forces are gotten by dividing the amplitude of the surge forces by the mooring line stiffness (Restoring force) for each angle. This reduced the magnitude of the surge forces. The value of the restoring force is 65.7248kN/m calculated from work done by the author. This also tells about the importance of the restoring force in the mooring arrangement of the ship in question. The results obtained are as follow; 0^0 = 7.7205, 15^0 = 7.4574, 30^0 = 6.6861, 45^0 = 5.4592, 60^0 = 3.8602, 75^0 = 1.9982, and 90^0 = $4.7274*10^{14}$. As seen, the forces reduced and this will lead to the determination of the response amplitude operator. The figure 4 represents the quasi-static behaviour of the ship. From all indications, the maximum value occurred within the low frequency range.

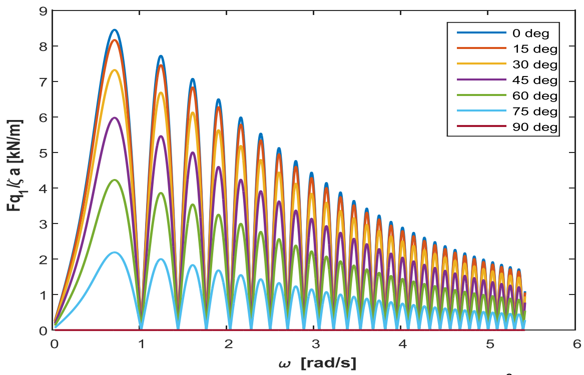

Fig. 4: Quasi-static surge forces (0-90^0)

C. Response Amplitude Operator (RAO)

The RAO evaluates the response of the ship to first order waves. It is obtained by multiplying the quasi-static forces by the magnification factor for all cases. The maximum results gotten for each case is 0^0 = 0.1822, 15^0 = 0.1760, 30^0 = 0.15779, 45^0 = 0.1288, 60^0 = 0.0911, 75^0 = 0.0472, and 90^0 = $1.1157*10\text{-}^{17}$.

The graphical results for all cases are shown below.

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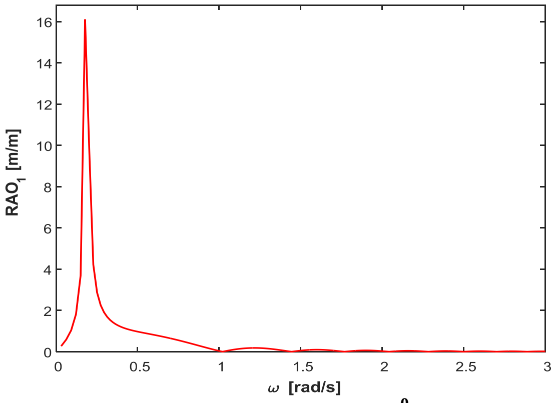

Fig. 5: Surge RAO 0^0

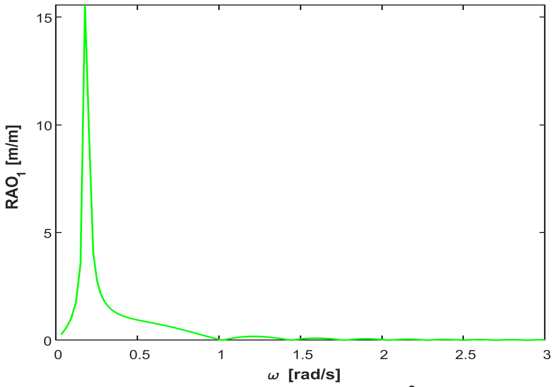

Fig. 6: Surge RAO 15^0

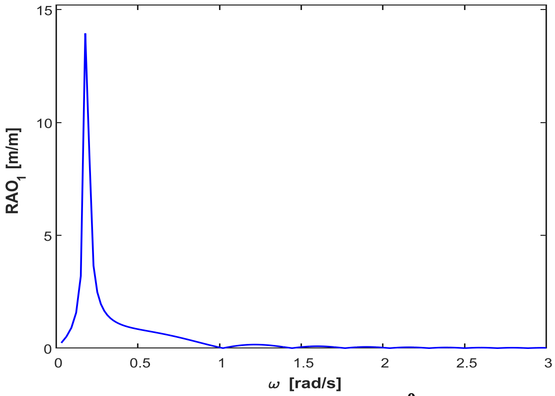

Fig. 7: Surge RAO 30^0

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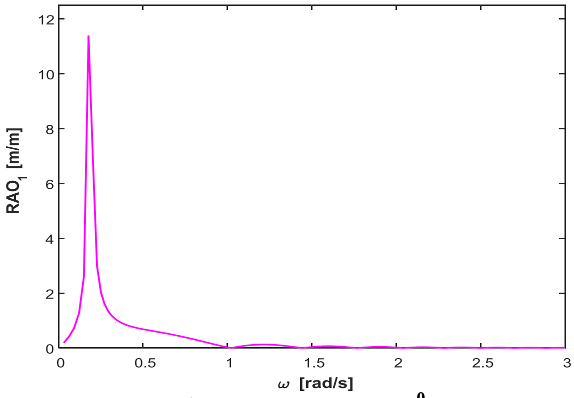

Fig. 8: Surge RAO 45^0

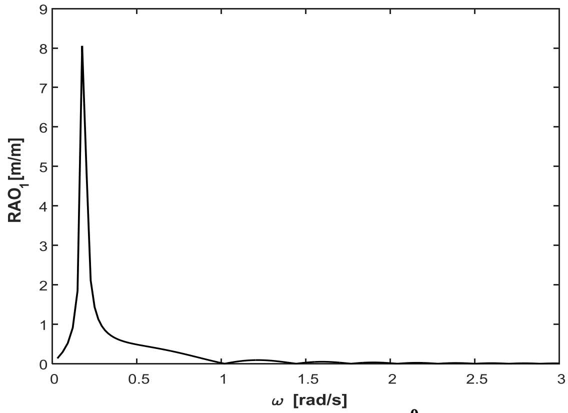

Fig. 9: Surge RAO 60^0

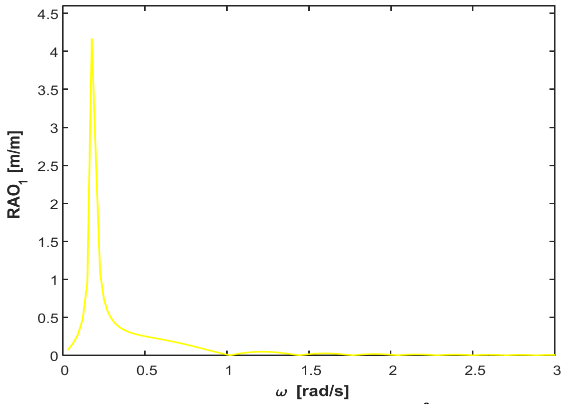

Fig. 10: Surge RAO 75^0

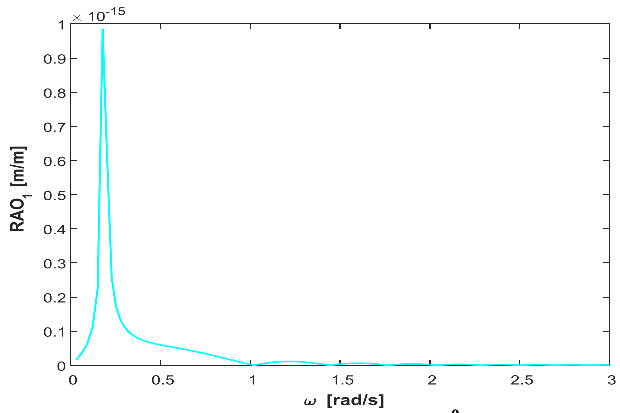

Fig. 11: Surge RAO 90^0

D. Ship Response Spectra

The response of the ship is obtained by making use of equation (26) for all the various angles of attacks. Plots of the responses against the frequencies form the response spectrum of the ship. The response is referred to as the area under the spectrum curve which will be seen in the figures below. The highest response result in each angle is as follows; 0^0 = 0.0105m^2s/rad, 15^0 = 0.0098 m^2s/rad, 30^0 = 0.0079 m^2s/rad, 45^0 = 0.0053 m^2s/rad, 60^0 = 0.0026 m^2s/rad, 75^0 = 0.0007 m^2s/rad, and 90^0 = 3.9435*10-^{35} m^2s/rad. As seen, this also followed similar pattern, as the angle increased from 0^0 to 90^0, the responses also decreased. Figures below show the plot of all the responses from 0^0 to 90^0, they showed clearly the behaviour and the pattern with which the ship is responding to the induced wave.

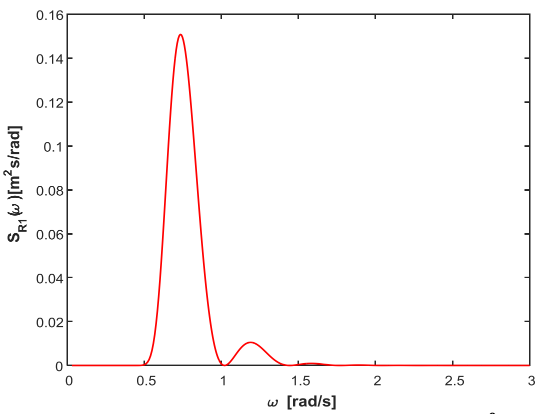

Fig. 12: Surge Response Spectrum 0^0

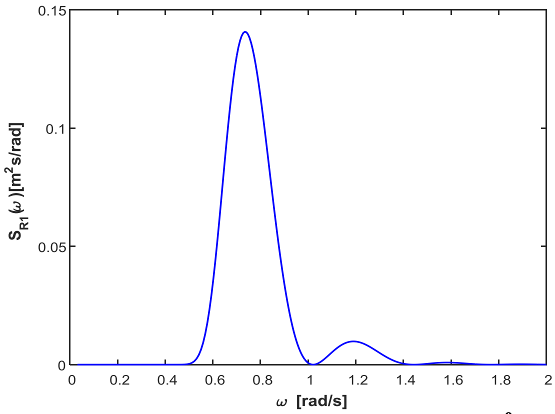

Fig. 13: Surge Response Spectrum 15^0

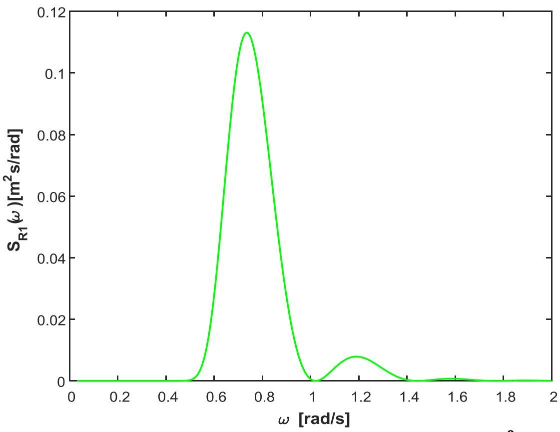

Fig. 14: Surge Response Spectrum 30^0

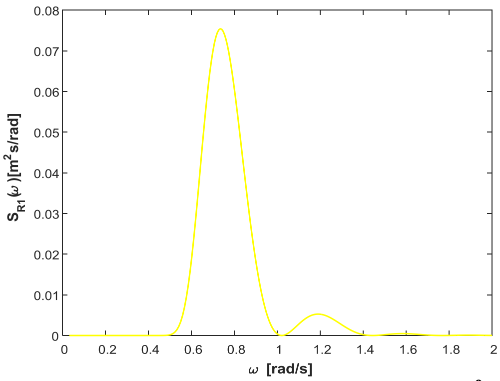

Fig. 15: Surge Response Spectrum 45^0

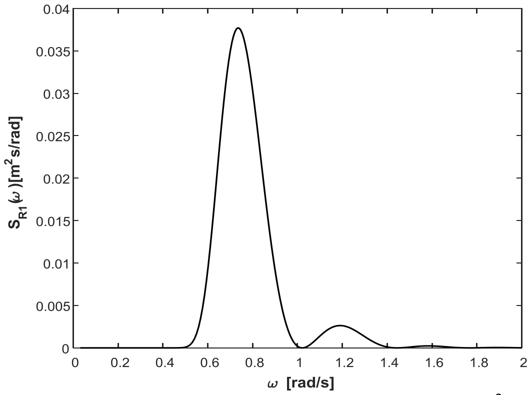

Fig. 16: Surge Response Spectrum 60^0

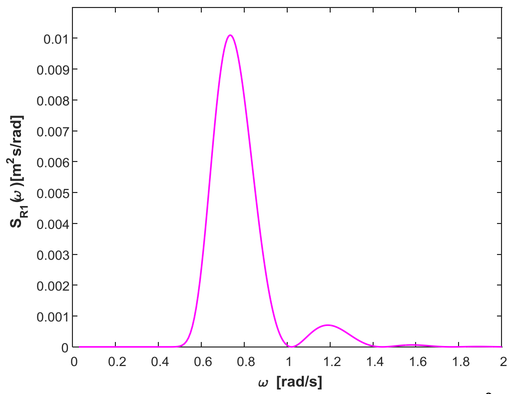

Fig. 17: Surge Response Spectrum 75^0

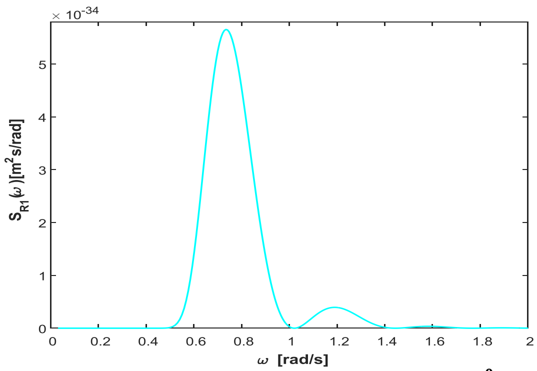

Fig. 18: Surge Response Spectrum 90^0

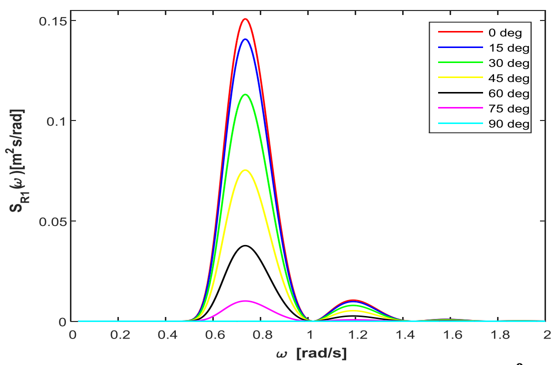

Fig. 19: Surge Response Spectrum 0-90^0

As seen in the figures above, the graphs are similar as expected for all the angles of attacks. Figure 19 is a superimposition of all the responses.

E. Most Probable Maximum Surge Amplitude (**ξ_{max}**)

This is the highest response of the ship statistically determined. For this to be obtained, the variance (Zeroth Moment) will be obtained using Simpson's first rule, after which the significant surge amplitude will also be gotten. Then the most probable maximum surge amplitude will then be achieved for all the various angles of attacks.using equations (27), (28) and (29) respectively.

The final results are tabulated for the various angles of attacks. These results represent the ship final responses. As said earlier, major interest is on the determination of the most probable maximum surge amplitude, which has achieved with all these procedures in Table 2 below.

Table 2: Ship Response Results 0-90^0

Angle (deg)	M_{01} (m^2)	ξ_s (m)	ξ_{max} (m)
0	0.0057	0.1511	0.2810
15	0.0053	0.1459	0.2714
30	0.0043	0.1308	0.2434
45	0.0029	0.1068	0.1987
60	0.0014	0.0755	0.1405
75	3.8229e-04	0.0391	0.0727
90	2.1397e-33	9.2514e-18	1.7208e-17

V. CONCLUSION

The most probable maximum surge amplitude represents the maximum responses of the ship in surge motion as a result of the induced wave loads. From the statistical results in the Table 2 above, the 0^0 angle of attack gave the highest response of the ship. Response in this context implies the horizontal displacement from the mean longitudinal position. These responses are considered as the area under the spectra multiplied by Simpson's multipliers and the step size, as shown in figures 12 to 19 above. From all evaluations done, it is clear that a ship cannot return to its original position after being perturbed by wave loads in surge motion condition. For it to return, the restoring force from the mooring lines must be in place.

The response amplitude operator (RAO) reviewed that the dynamic resonance of the ship occurred around the first order wave frequencies. From the RAO graphs, resonance occurred where the natural frequency of the ship is equal to the wave frequency. This effect can be dangerous to the operation of the ship, and can be mitigated by shifting the wave frequency away from the ship natural frequency during design. This is due to the fact that the natural frequency of a ship is used to dictate the behaviour of that ship in wave.

The shallow water dispersion characteristics equation used in a reversed manner (that is to estimate a range of wave numbers to be able to determine the wave frequencies) used in this work has proven to be a good approach which can be adopted for project of this kind.

The surge force model developed above using Froude-Krylov hypothesis proved to be a good method to evaluate the pressure force acting on the ship. After all the analyses and validation made in course of this research, the results have shown that the model developed is suitable for offshore structures of similar shape and characteristics. And also, the software developed is simple and easy to understand, and can be used for analysis of similar ships.

Based on the results and findings in this research, the highest most probable maximum surge amplitude occurred at 0^0 angle of attack, and it was minimum at angle 90^0. One can say that as the angle of attacks increased, the ship response reduces, and the added mass force in surge motion is insignificant and was neglected.

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