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Numerical Modelling Of Wave Drift Load On Ship Shaped Offshore Structures (Case Study – West Africa Offshore)

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***Abstract:** Today, oil and gas are essential commodities in world trade. Exploration that initially started ashore has now moved offshore. These explorations were initially in shallower waters and now into deeper waters because of the continue decline of new fields discovery in shallower and intermediate waters. Recently, the need for development of oil and gas resources in increasingly deeper waters has taken the center stage due to the difficulties associated with the processes involved. One of such challenges includes the influence of the environment around the field another of this challenge is the availability of the necessary host facility for the extraction of oil and gas in such regions of water depth and its ability to withstand the challenges posed by the peculiarity of the environment. A usual phenomenon these structures face at their location is drifting i.e. losing its course. The research presents the numerical analysis of wave loads on these structures. It focuses more on wave drift effects. This work modifies and use a theory developed by Said (2010) and extended the theory to analyses the effects of second-order wave force on an operational FSO LPG ESCRAVOS in West Africa, Nigeria. This FSO is co-owned by the Nigerian government and Chevron Nigeria limited. OCIMF (1994) data are used for computation of the current forces. It also includes the response of these loads on the FSO. Using Excel software, computations were carried out in irregular wave's conditions data prevalent in Escravos, offshore Nigeria. Based on it, steady drift motion responses are examined while altering the wave angle. Several environmental conditions, such as the wave angle of attack, wave frequencies and wave headings are considered, which may significantly affect FSO motion in surge, sway and yaw moments.*

***Keywords:** FPSO, Wave Drift Loads, Motion Response, Wave Angle,*

I. INTRODUCTION

Today, oil and gas are essential commodities in world trade. Exploration that initially started ashore has now moved offshore. Knowing that the ocean environment presents its own uniqueness conditions which dominate the design and construction methods. One of such challenges includes the influence of the environment, around the intending design structures. Offshore West African as other area predominately have its own challenges, one of such challenges includes long period swells, wave drift etc. Floating structures are the most used offshore structures in offshore West Africa this resulted in the numerical modeling of wave drift load on ship shaped offshore structures. In the family of ship shaped offshore structures the FPSOs have been recognized as one of the most reliable, economical solutions to develop marginal offshore oil and gas reserves in both shallow and deep-water areas. Note the process of developing offshore oil and gas reserves can be divided into the following major steps as in (Graff, 1981) which includes: Exploration, Exploratory drilling, Development drilling, Production, Storage and offloading, transportation. The ship shape offshore structures have been vital to these developments. It appears deceptively simple, being based on conventional ship-shaped hulls, with which there should be plenty of experience in design and construction. However, the reality is that the duty of the FPSO is completely different from that of the trading very large crude carriers (VLCC), and although the hull shape may be similar, an FPSO is in fact a very complex system.

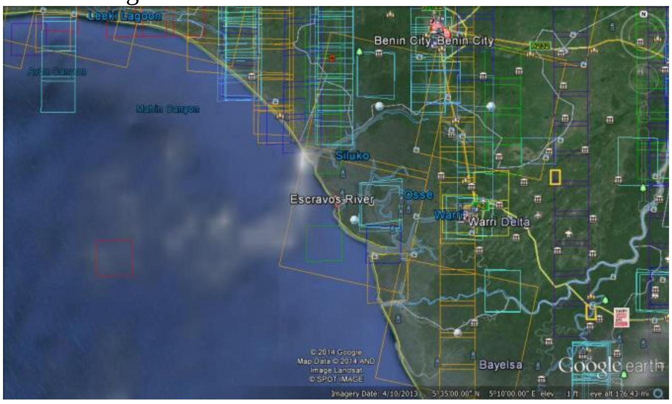
Various engineering tools can be used to assess the effects of these met-ocean conditions on ship-shaped offshore structures which include full-scale trials, model tests and numerical calculations. The cost and unrealistic extreme weather of full-scale trials, difficulty of scaling results in model tests makes numerical calculations a viable tool for calculating wave-induced motion and loads on ship-shaped offshore structures. The numerical tool is considered in this work.

This research work is centered on numerical modeling of Environmental loads. Environmental (sea) loads are attributed from the resultant motion of winds, waves, current, ice, tides etc. These loads posed a challenge to the existence, reliability and stability of these structures, in course of their design and construction. This research is aim at analyzing the effect of waves drift load on ship shaped offshore structures as its affects its motions. This is based on the fact that, wave plays a major role in the motions and stability of any floating structures. Another section of this research covers, analyzing the Effects of irregular seas described by second-order wave force on the design of ship-shaped offshore structures, and the corresponding motion response of the ship-shaped floating structures to wave drift load.

Part of preliminary findings suggest that effects of these loads could cause heave motion which is a limiting factor for drilling operation as a result of the motion of the risers. Also it can result in both rolling and pitching motion which may limit the processing operation onboard FPSOs. Uncomfortable sensation while onboard is also experienced as a result of these phenomena, as well as other impending motions. In order to reduce the undesirable motion of marine structures on sea, the resultant forces and moments are significant issues to be considered. This is done by reduce the forces and moments thru the increase of the damping coefficient, reduction of natural frequency, or even directly reducing the excitation forces and moments (Bhattacharyya, 1978). Floating structures on sea experiences a number of motions such as captured by faltinsen (1990) namely; wave-frequency motion which is mainly linearly-excited motion in the wave-frequency range of significant wave energy, another is the high-frequency motion is significant to TLPs which are excited by non-linear wave effects., slow-drift motion and mean drift motion are excited by non-linear effects of waves, wind and currents.

Offshore environment today can be either classified as harsh or benign as stated by Paik and Thayamballi (2007), they went further to classify offshore west African as benign and to buttress their point Hansen et al (2004) allotting its reason to the fact that the relative wave magnitude is significantly lower than found in other regions of the world such as North Sea or Gulf of Mexico. Its worthy to note that in area like offshore West Africa and Brazil both swells and seas (local wind or storm generated waves) exist and propagate in separate direction (Chuntian and Jer-Fang 2002), resulting in large period, persistent swells, squalls and high surface currents. Gbuyiro and Olaniyan (2003) reported that swells of about 0.47 meters in height resulting from winds of about 10 knots grazed the coast frequently.

In this work, the offshore location - Escravos field, Nigeria is taken as the case study. The Escravos oil field is located at approximately 33 kilometers offshore west of the mouth of Escravos River on Lat. North and Long. East as shown in Figure 1 below.



Source: Google earth

Figure 1: Escravos River

II. HYDRODYNAMIC THEORY

The Hydrodynamic theory which form the basis for computations of the mean and low frequency second order wave drift forces (mean and low frequency) on floating offshore structures. The theory is developed based on the assumption that the fluid surrounding the body is in-viscid, irrotational, homogeneous and incompressible. The fluid motions may then be described by a velocity potential as stated in equation (1):

$$\emptyset = \sum_{i=1}^{n} \epsilon_i \emptyset_i \qquad 1$$

Where ϵ_i is a small parameter (perturbation) and ϕ_i is the ith order velocity potential such that ϕ_2 denotes second order velocity potential.

A. WAVE LOADS

In the design of a ship shaped floating production storage and offloading system (FPSO) some chosen dominate loading parameters determine the existence, reliability and stability of the structures. The dominant design loading parameter includes wave, current, tide, ice, etc. Breakdowns of one of the dominant design loading parameter in this instance wave loading in irregular sea and the response of the structure due to the loading condition are captioned by Faltinsen (1990) and (Journée and Massie, 2001)

The mean wave drift force, drift force is caused by non-linear (second order) wave potential effects. Together with the mooring system, these loads determine the new equilibrium position - possibly both a translation and (influenced by the mooring system) a yaw angle - of the structure in the earth-bound coordinate system. This yaw is of importance for the determination of the wave attack angle. This wave drift force results in a mean displacement of the structure, resulting from a constant loading component on the structures and it derive its sources from both current and wind.

Oppenheim and Wilson (1982) also expressed that the second order hydrodynamic force (commonly called drift force) is proportional to the square of the wave amplitude and it has a mean level. This force is associated with occurrence of

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wave groups, with interactions between high-frequency vessel motions and the high-frequency excitation, and with wave diffraction. The "direct current" (dc) component of the low frequency force, together with almost steady wind and current forces causes slow oscillatory motions, since a moored vessel constitutes a mass-spring-damper oscillator. The damping and spring are typically small; consequently large resonant motions occur, larger in fact than the high- frequency ones.

a. WAVE DRIFT LOAD

It is generally accepted that the existence of wave drift forces was first reported by (Suyehiro, 1924). While experimenting with a model rolling in beam seas, he found that the waves exerted a steady horizontal force which he attributed to the reflection of the incoming waves by the model. The importance of the mean and low frequency wave drift forces from the point of view of motion behavior and mooring loads is generally recognized nowadays. (Wichers, 1982) also holds that SPM moored vessels are subjected in irregular waves to large, so-called first order wave forces and moments, which are linearly proportional to the wave height and contain the same frequencies as the waves. They are also subjected to small, so-called second order, mean and low frequency wave forces and moments, which are proportional to the square of the wave height. Low frequency second order wave forces have frequencies which correspond to the frequencies of wave groups present in irregular waves. These forces, which besides containing time-varying components also contain a non-zero mean component, are known as wave drift forces. This name is a consequence of the fact that a vessel, floating freely in waves, will tend to drift in the direction of propagation of the waves under influence of the mean second order forces.

(Chen and Duan, 2007) in their work defined the low-frequency quadratic transfer function (QTF) as the second-order wave loads occurring at the frequency ($\Delta\omega$) equal to the difference ($\omega 1 - \omega 2$) of two wave frequencies ($\omega 1$, $\omega 2$) in bi-chromatic waves. Similarly (Rouault et al, 2008) presented the numerical evaluation of the so-called QTFs: Quadratic Transfer Functions of the difference frequency wave induced second-order loads which they pointed out as an old problem which has been regaining interest in the past years, mostly due to the development of LNG related activity. The reference case was used in offloading terminal, in restricted water depth, with the LNG-carrier alongside a GBS or FSRU (Floating Storage Re-gasification Unit). It concluded that to design the mooring system, second-order wave loads acting on either structure are required. Yi-Shan et al (2007) also affirm that the low-frequency wave load is well known to be the main source of excitation to offshore or near shore moored FPSO systems. The accuracy of its evaluation is critically important in the time simulation of large slow-drift motions since the results of motion simulations determine the design of mooring systems.

High frequency second order forces contain frequencies corresponding to double the frequency of the waves (also known as sum frequencies). The horizontal motions response of moored structures to these forces is generally small. The fact that low frequency drift forces can cause large amplitude horizontal motion responses in moored vessels and that these motions are related to the wave group phenomenon was demonstrated by (Remery and Hermans, 1971).

Mean and Slow-drift wave loads (low-frequency or difference frequency loads) are important in ship-shaped offshore structures. They are the cause of drifting of ship-shaped and other floating structures in waves. Examples are in the mooring and thruster systems, analysis of slowly oscillating heave, pitch and roll of large-volume structures e.g. FPSOs with low water plane area, stabilization to avoid high-operational downtimes. (Hsu and Blenkarn, 1970) indicated that large amplitude low frequency horizontal motions of moored vessels could be induced by slowly varying wave drift forces in irregular waves.

(Remery and Hermans, 1971) indicated that for an accurate description of the low frequency motions not only the drift forces are important but also the accurate analysis of the damping coefficient near resonance. (Wichers, 1982) show that this damping coefficient is quadratic to the wave height, leading to the concept of wave drift damping coefficient. (Wichers, 1984) also showed that this damping coefficient is related or dependent on the forward speed of the wave drift force. Later (Hermans and Huijismans, 1996) restricted the speed to be low, due to the non-uniform character of the asymptotic expansion scheme. In their 1988 work, they explained how to construct a uniform expansion of the speed dependent wave potential as a superposition of the steady potential. This uniformly valid wave potential shall be used in the derivation of the speed dependent drift force.

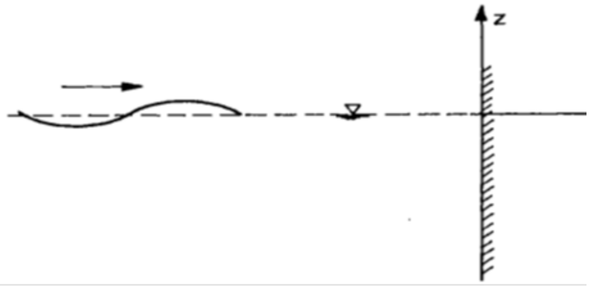
III. MODELLING OF MEAN WAVE (DRIFT) LOADS

The direct pressure integration method will be used here to obtain the mean wave forces and moment. This involves writing the Bernoulli's equation for the pressure on the hull correctly to second order in wave amplitude.

The following assumptions will be made in this work:

- ✓ The body motion as a result of the incident waves will be neglected i.e. the singular effect of the incident waves on the body will be considered.
- ✓ The diffracted wave effects will not be considered.

From a hydrodynamic point of view, it implies that the study of the incident waves on a vertical wall can be analyzed as shown in Figure 2. Journée and Massie (2001) shows that when the waves are not too long, this procedure can be used to estimate mean wave drift forces on a ship shaped structure in waves approaching from the side of the ship.



Source: Journée and Massie (2001)

Figure 2: Incident waves and drift forces on a vertical wall

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A. MEAN WAVE LOADS ON A WALL IN REGULAR WAVES

It can be calculated simply from the pressure in the fluid by using the more complete (not linearized) Bernoulli's equation. As shown in the Figure 3, an incident wave will be fully reflected so that a standing wave results at the wall (vessel)

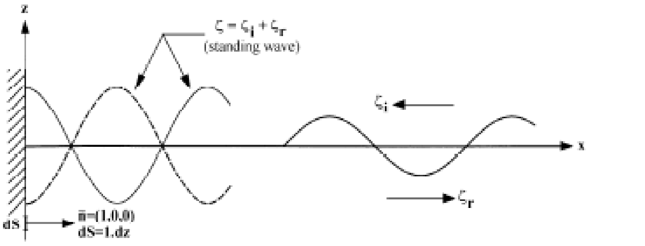


Figure 3: standing waves

The incident (undisturbed) wave is given by equation (2):

$\phi_i = -\frac{\zeta_a g}{\omega}.e^{kz}.\sin(+kx+\omega t)$;

Wave elevation $\zeta_i = \zeta_a.\cos(+kx+\omega t)$ 2

And the reflected wave will be represented with equation (3):

$\phi_r = -\frac{\zeta_a g}{\omega}.e^{kz}.\sin(+kx+\omega t)$

Wave elevation: $\zeta_r = \zeta_a.\cos(-kx+\omega t)$ 3

The standing wave is the addition of the incident and reflected wave which is given by:

$$\phi = \phi_i + \phi_r = -2.\frac{\zeta_a g}{\omega}.e^{kz}.\cos(kx).\sin(\omega t) \quad 4a$$

and wave elevation:

$$\zeta = \zeta_i + \zeta_r = 2.\zeta_a.\cos(kx).\cos(\omega t) \quad 4b$$

The derivatives of the potentials in the above equation with respect to x, z, t can be derived as follows:

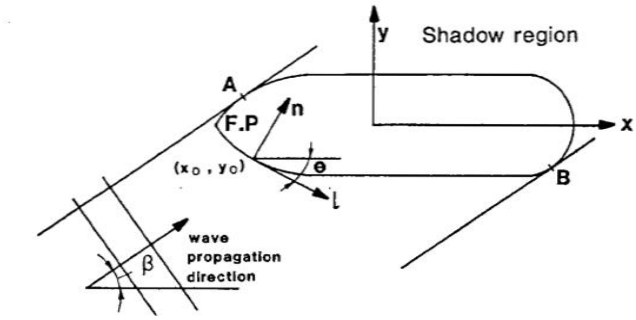
$$v = \frac{\partial\phi}{\partial t} = -2.\zeta_a.g.e^{kz}.\cos(kx).\cos(\omega t) \quad 5a$$

$$u = \frac{\partial\phi}{\partial x} = +2.\zeta_a.g.e^{kz}.\sin(kx).\sin(\omega t) \quad 5b$$

$$w = \frac{\partial\phi}{\partial z} = +2.\zeta_a.g.e^{kz}.\sin(kx).\sin(\omega t) \quad 5c$$

B. MEAN DRIFT FORCE FOR SHIP-SHAPED STRUCTURES

For ship-shaped structures subjected to an arbitrary wave. The mean wave drift force equation can be derived from the wave drift force equation 6 above can be corrected for the non-vertical side/curvature of the water-plane area.



Source: Faltinsen (1990)

Figure 4: The water plane area and the shadow region of a ship-shaped vessel subjected to an arbitrary wave

The mean drift forces and moments can be calculated through the following formula by Faltinsen (1990) as:

$$\boldsymbol{F_i} = \frac{1}{2}\rho g.\zeta_a^{\,2}\int_{L_1}\sin^2(\theta+\beta).n_i.dl \quad 6$$

C. MEAN (STEADY) DRIFT FORCES AND MOMENT FOR A SHIP-SHAPED STRUCTURE

The current coefficient for structures when Froude number $F_n \le 0.2$ can be written in form of Froude's number as:

$$C_{cu,i} = 1 + 2\omega F_{ni}\sqrt{\frac{D_i}{g}} \quad 7$$

$$where\ F_{ni} = \frac{U_i}{\sqrt{g D_i}}$$

Where the dimension of the vessel in the direction of current is , ω is the circular frequency of oscillation of the waves, U_i is the current speed.

The steady drift forces and moments for an FPSO subjected to arbitrary waves and current by considering the current coefficient C_{cu} from equation the equation directly above.

$$\boldsymbol{F_i} = \frac{1}{2}\rho g.\zeta_a^{\,2}\, C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{D_i}{g}}\right]\int_{L_1}\sin^2(\theta+\beta).n_i.dl \quad 8$$

Where: C_T = finite draft coefficient given by Kwon (1982) as $C_T = \left(1 - e^{-2kD}\right)$ k = wave number, D = draft of the vessel, circular frequency $\omega = \frac{2\pi}{T}$

So the steady ***surge*** and ***sway*** drift forces and ***yaw*** drift moment for a ship-shaped structure can be written *assuming* that both ends curvature parts are replaced by a semi-circle with a diameter equal to the beam of the rectangular section.

Surge Drift Force:

$$\boldsymbol{F_1} = \frac{2}{3}C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{D_i}{g}}\right]\rho g.\zeta_a^{\,2}\, r\cos\gamma \quad 8a$$

Sway Drift Force:

$$\boldsymbol{F_2} = C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{D_i}{g}}\right]\frac{\rho g.\zeta_a^{\,2}}{2}\left[L_2\sin\beta\ |\sin\beta| + r\frac{4}{3}\sin\beta\right] \quad 8b$$

Yaw Drift Moment:

$$\boldsymbol{F_6} = C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{D_i}{g}}\right]\frac{\rho g.\zeta_a^{\,2}}{2}$$

$$\left[\frac{1}{3}r(L_1' + L_2')\sin\gamma + \frac{[L_2'^2 - L_1'^2]}{2}\sin\gamma\,|\sin\gamma| + \frac{2}{3}(L_1' - L_2')r\sin\gamma\right] \quad 8c$$

IV. DRIFT WAVE LOADS IN IRREGULAR WAVES

The results of mean wave loads in regular waves can be used to easily obtain results in an irregular sea. Considering a long-crested seas described by a sea spectrum $S(\omega)$.

The velocity potential of the incident waves correctly to first order in wave amplitude as:

$$\phi^I = \sum_{j=1}^{N}\frac{gA_j}{\omega_j}e^{k_j z}\cos(\omega_j t - k_j x\cos\beta - k_j x\sin\beta + \epsilon_j) \quad 9$$

Studies has shown that the effect of using an idealized sea state with two wave components. The result from equation (4) shows clearly that we can linearly add together the mean force contribution from each wave components. The same principle would have happened if we had used N wave components.

Where $\bar{F}_i(\omega_j;\beta)$ is the ith mean wave load component in regular incident waves of circular frequency ω_j, wave amplitude A_j and wave propagation direction β. Further $\bar{F}_i(\omega_j,\beta)$ is divided by the wave amplitude square, i.e. ζ_a^2, so that $\bar{F}_i(\omega_j;\beta)/\zeta_a^2$ is independent of the wave amplitude.

$S(\omega)$ = sea spectrum. $\bar{F}_i(\omega_j,\beta,\gamma)$ is the ith mean wave load component in regular incident waves of circular frequency ω_j and arbitrary direction of γ in the presence of arbitrary current with angle of β. The mean force components in ***irregular waves*** for surge, sway and yaw modes can be obtained as presented in equation (10), (11) and (12) respectively:

Surge drift force in irregular waves

$$\overline{F_1^s} = \frac{4}{3}\, C_T\, \rho g\, r \cos\gamma \left[\frac{H_{\frac{1}{3}}^{\,2}}{16}\right]\left[1 + 2\omega F_{ni}\sqrt{\frac{L}{g}}\right] \qquad 10$$

Similarly

Sway drift force in irregular waves

$$\overline{F_2^s} = \rho g\left[\frac{H_{\frac{1}{3}}^{\,2}}{16}\right] C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{B}{g}}\right]\left[L_2 \sin\beta\,|\sin\beta| + r\frac{4}{3}\sin\beta\right] \qquad 11$$

Yaw drift moment in irregular waves

$$\overline{F_6^s} = \rho g\left[\frac{H_{\frac{1}{3}}^{\,2}}{16}\right] C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{B}{g}}\right]$$

$$\left[\frac{1}{3} r(L_1' + L_2')\sin\gamma \;+\; \frac{[L_2'^{\,2} - L_1'^{\,2}]}{2}\sin\gamma\,|\sin\gamma| \;+\; \frac{2}{3}(L_1' - L_2') r\sin\gamma\right] \qquad 12$$

V. MODIFICATION FOR WEST AFRICA

Chakrabarti (2005) recommended the Pierson-Moskowitz (P-M) spectrum for operational activities offshore West Africa while Faltinsen (1990) holds that the modified P-M and the sea spectra from International Towing tank Conference (ITTC) and International Ship and Offshore Structures Congress (ISSC) are equivalent. The modified P-M/ISSC spectrum will be used to calculate $S(\omega)$ as presented in equation (15).

$$\frac{S(\omega)}{H_{\frac{1}{3}}^2 T_1} = \frac{0.11}{2\pi}\left(\frac{\omega T_1}{2\pi}\right)^{-5} \exp\left[-0.44\left(\frac{\omega T_1}{2\pi}\right)^{-4}\right] \qquad 13$$

where $H_{\frac{1}{3}}$ is the significant wave height defined as the mean of one third highest waves and T_1 is a mean wave period defines as $T_1 = 2\pi m_0/m_1$ where

$$m_k = \int_0^\infty \omega^k S(\omega)\, d\omega \qquad 14a$$

i.e.

$$m_0 = \int_0^\infty S(\omega)\, d\omega \qquad 14b$$

or

$$m_1 = \int_0^\infty \omega\, S(\omega)\, d\omega \qquad 14c$$

When input the solution of equation (13) into (10), (11) and (12) respectively, the resultant equation for surge sway and yaw will be presented in equation (15), (16) and (17)

Surge drift force in irregular waves

$$\overline{F_1^s} = \frac{4}{3}\, C_T\, \rho g\, r \cos\gamma \left[\frac{H_{\frac{1}{3}}^{\,2}}{16}\right]\left[1 + 2\omega F_{ni}\sqrt{\frac{L}{g}}\right] \qquad 15$$

Similarly

Sway drift force in irregular waves

$$\overline{F_2^s} = \rho g\left[\frac{H_{\frac{1}{3}}^{\,2}}{16}\right] C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{B}{g}}\right]\left[L_2 \sin\beta\,|\sin\beta| + r\frac{4}{3}\sin\beta\right] \qquad 16$$

Yaw drift moment in irregular waves

$$\overline{F_6^s} = \rho g\left[\frac{H_{\frac{1}{3}}^{\,2}}{16}\right] C_T\left[1 + 2\omega F_{ni}\sqrt{\frac{B}{g}}\right]$$

$$\left[\frac{1}{3} r(L_1' + L_2')\sin\gamma \;+\; \frac{[L_2'^{\,2} - L_1'^{\,2}]}{2}\sin\gamma\,|\sin\gamma| \;+\; \frac{2}{3}(L_1' - L_2') r\sin\gamma\right] \qquad 17$$

VI. RESULTS

The first task in a global response analysis is to identify the steady response, or the static position of the structure. The mean wave, wind and current forces/moments determine the static position. (DNV-RP-F205, 2010)

A. STEADY DRIFT MOTIONS

The motion response of structures subjected to steady drift force is characterized by Large Amplitude Horizontal Motions. The steady drift motions of a moored floating structure can be obtained as:

$$\overline{X_1^s} = \frac{F_1^s}{c_x}\;, \quad \overline{X_2^s} = \frac{F_2^s}{c_y}\;, \quad \overline{X_6^s} = \frac{F_6^s}{c_\theta}$$

X_1^s, X_2^s, X_6^s are the mean displacement of the ship-shaped structure in surge, sway and yaw modes respectively. F_1^s, F_2^s, F_6^s are the mean (steady) drift loads in irregular waves in surge, sway and yaw modes. c_x, c_y are the mooring stiffness coefficients in the x and y directions respectively. c_θ is the rotational mooring stiffness which for a turret moored floating structure is given by $c_\theta = L_m^2 c_x$; L_m = distance between the turret mooring point and FPSO's centre of gravity.

The motions of a moored offshore structure (e.g. FPSO) in irregular waves consist of small amplitude high frequency surge, heave and pitch motions and large amplitude low frequency surge motions. The high frequency motions are related to the individual wave frequency components the wave train. The low frequency -surge-motion is concentrated around the natural frequency of the moored vessel.

The response of a moored offshore structure in irregular seas is greatly dominated by large amplitude longitudinal and lateral motions with frequencies significantly lower than the frequency range of the individual waves.

B. VALIDATION - HYDRODYNAMIC ANALYSIS OF FSO LPG ESCRAVOS

This section shows results computed from the hydrodynamic theory analyzed for mean wave drift force and current forces respectively. Various wave heading and current heading was used for the computation.

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LOA	163.8 m
Beam	36.0 m
Depth, Molded	23.4 m
Design Draft	10.85 m
Deadweight	37, 100 dwt
Gross Tonnage	40, 000 t
Design Life	30 years

Source: Edwards and Jones (1996)

Table 1: The principal particulars for the LPG FSO Escravos

Other characteristics of the FSO include:

- ✓ Ship-shaped Hull
- ✓ External Cantilevered Bow Turret (Single Point Mooring)
- ✓ Offloading to tanker
- ✓ Deck load capacity

The input for the analysis (significant wave height, wave period etc…) will be based on data from Environmental phenomena and assumptions. Various wave and current will be analyzed for. For the mooring stiffness coefficients, $c_x = 6.8\,\frac{N}{m}$, $c_y = 6.0\,\frac{N}{m}$ was applied. Therefore $c_\theta = 6.8 \times 6.0^2 = 244.8\,Nm$

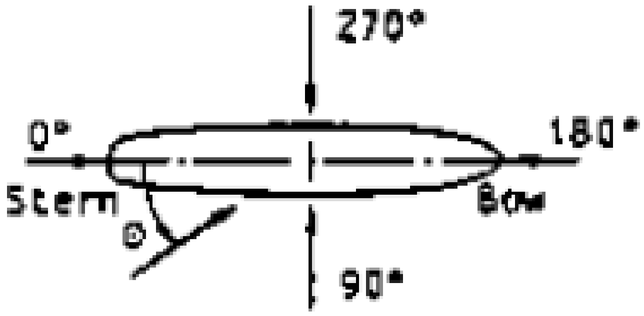

Figure 5: direction of wave heading/current attack angle

C. RESPONSE TABLES

An analysis was carried out on the FSO having a detail has given in Table 1 originally taken from (Edwards and Jones, 1996). The computations for the FSO were carried out in irregular waves using the hydrodynamic theory and met-ocean data from West Africa.

The current coefficients, mean wave drift coefficients for surge, sway and yaw moment coefficients are presented in appendix A, B, C and D respectively.

The resulting data consists of the motion of the FPSO in surge, sway and yaw motion at different wave frequency. The current angles of attack to the hull of the FSO are considered for 0, 45, 90, 135, and 180 degrees, respectively. The conditions that are considered in each of the current angles of attack are with and without current, different current velocities, and different wave propagation angles.

Case	Current velocities
1.	0.0 m/s (0 Knots)
2.	0.8 m/s (1.56 Knots)
3.	1.2 m/s (2.33 Knots)
4.	**2.0 m/s (3.90 Knots)**

Table 2: Different current velocities considered

Here, the current velocity of 2.0m/s (3.9 Knots) is considered as an extreme case because in (Edwards, B. and Jones, T., 1996) the current velocity 1.2m/s used to design the FSO.

VII. CONCLUSIONS

The mean wave (drift) force coefficients are generated from the wave excitation in the hydrodynamic analysis. The theory was modified such that it considered Faltinsen (1990) and Chakarbarti (2005) suggested wave spectrum for design and operation of ship-shaped offshore structures in the West Africa region. The second order wave forces are described as the mean wave (drift) forces with respect to all 3 DOF (surge, sway, and yaw) also as a function of the wave frequencies and wave headings. Further, these results are presented as the response of the FSO (i.e. steady drift motions) using the principle of mass-spring system also with respect to 3 DOF (surge, sway, and yaw). The response is also presented as a function of the wave frequencies and wave headings.

Beside the mean wave (drift) force coefficients and motion response, the non-linear damping effects are not considered in this analysis due to some constraints. Hence the need for future works so as to quantify the low frequency damping from an expansion of the mean drift force. It is important to analyze and speculate the non-linear damping effects in the design because the mean drift forces can generate large amplitude resonant motions.

As a result of the analysis it was observed that the magnitude of the Mean Wave Drift Forces Coefficients on the FSO can be as large as 17.0 KN, 240.0 KN, and 2700 Nm for Surge, Sway and for Yaw moment respectively. The effect of different wave heading and current attack angles influence the motion response of the FSO.

Mean Wave Drift Forces Computation

	Surge Force F1 (KN)								
U = 0m/s									
Gamma = 0			beta						
w rad/s	0	45	90	135	180	225	270	315	360
0	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
0.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
0.4	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
0.6	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
0.8	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
1	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
U = 0.0m/s									
Gamma = 45									
w rad/s	0	45	90	135	180	225	270	315	360
0	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
0.2	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
0.4	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
0.6	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
0.8	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
1	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
U= 0.0 m/s									
Gamma = 90									
w rad/s	0	45	90	135	180	225	270	315	360
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gamma = 135									
w rad/s	0	45	90	135	180	225	270	315	360
0	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
0.2	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
0.4	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
0.6	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
0.8	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
1	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
Gamma =180									
w rad/s	0	45	90	135	180	225	270	315	360
0	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2
0.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2
0.4	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2
0.6	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2
0.8	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2
1	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2

International Journal of Innovative Research and Advanced Studies (IJIRAS)
Volume 3 Issue 9, August 2016

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		Surge Force F1 (KN)						
U = 0.8 m/s								
Gamma =0		beta						
w rad/s	0	45	90	135	180	225	270	315	360
0	16.20	16.20	16.20	16.20	16.20	16.20	16.20	16.20	16.20
0.2	16.73	16.58	16.20	15.82	15.67	15.82	15.82	16.58	16.73
0.4	17.26	16.95	16.20	15.45	15.14	15.45	15.45	16.95	17.26
0.6	17.79	17.33	16.20	15.07	14.61	15.07	15.07	17.33	17.79
0.8	18.33	17.70	16.20	14.70	14.07	14.70	14.70	17.70	18.33
1	18.86	18.08	16.20	14.32	13.54	14.32	14.32	18.08	18.86
Gamma = 45									
w rad/s	0	45	90	135	180	225	270	315	360
0	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
0.2	11.83	11.72	11.46	11.19	11.08	11.19	11.19	11.72	11.83
0.4	12.21	11.99	11.46	10.92	10.70	10.92	10.92	11.99	12.21
0.6	12.58	12.25	11.46	10.66	10.33	10.66	10.66	12.25	12.58
0.8	12.96	12.52	11.46	10.39	9.95	10.39	10.39	12.52	12.96
1	13.33	12.78	11.46	10.13	9.58	10.13	10.13	12.78	13.33
Gamma = 90									
w rad/s	0	45	90	135	180	225	270	315	360
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gamma = 135									
w rad/s	0	45	90	135	180	225	270	315	360
0	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
0.2	-11.83	-11.72	-11.46	-11.19	-11.08	-11.19	-11.19	-11.72	-11.83
0.4	-12.21	-11.99	-11.46	-10.92	-10.70	-10.92	-10.92	-11.99	-12.21
0.6	-12.58	-12.25	-11.46	-10.66	-10.33	-10.66	-10.66	-12.25	-12.58
0.8	-12.96	-12.52	-11.46	-10.39	-9.95	-10.39	-10.39	-12.52	-12.96
1	-13.33	-12.78	-11.46	-10.13	-9.58	-10.13	-10.13	-12.78	-13.33
Gamma =180									
w rad/s	0	45	90	135	180	225	270	315	360
0	-16.20	-16.20	-16.20	-16.20	-16.20	-16.20	-16.20	-16.20	-16.20
0.2	-16.73	-16.58	-16.20	-15.82	-15.67	-15.82	-15.82	-16.58	-16.73
0.4	-17.26	-16.95	-16.20	-15.45	-15.14	-15.45	-15.45	-16.95	-17.26
0.6	-17.79	-17.33	-16.20	-15.07	-14.61	-15.07	-15.07	-17.33	-17.79
0.8	-18.33	-17.70	-16.20	-14.70	-14.07	-14.70	-14.70	-17.70	-18.33
1	-18.86	-18.08	-16.20	-14.32	-13.54	-14.32	-14.32	-18.08	-18.86

				Surge Force F 1(KN)					
		U = 2.0 m/s							
Gamma = 0									
w rad/s	0	45	90	135	180	225	270	315	360
0	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
0.2	17.5	17.1	16.2	15.3	14.9	15.3	16.2	17.1	17.5
0.4	18.9	18.1	16.2	14.3	13.5	14.3	16.2	18.1	18.9
0.6	20.2	19.0	16.2	13.4	12.2	13.4	16.2	19.0	20.2
0.8	21.5	20.0	16.2	12.4	10.9	12.4	16.2	20.0	21.5
1	22.8	20.9	16.2	11.5	9.6	11.5	16.2	20.9	22.8
		Gamma = 45							
w rad/s	0	45	90	135	180	225	270	315	360
0	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
0.2	12.39	12.12	11.46	10.79	10.52	10.79	11.46	12.12	12.39
0.4	13.33	12.78	11.46	10.13	9.58	10.13	11.46	12.78	13.33
0.6	14.27	13.45	11.46	9.46	8.64	9.46	11.46	13.45	14.27
0.8	15.21	14.11	11.46	8.80	7.70	8.80	11.46	14.11	15.21
1	16.15	14.78	11.46	8.13	6.76	8.13	11.46	14.78	16.15
		Gamma =90							
w rad/s	0	45	90	135	180	225	270	315	360
0	9.92E-16	9.92E-16	9.92E-16	9.92E-16	9.92E-16	9.92E-16	9.92E-16	9.92E-16	9.92E-16
0.2	1.07E-15	1.05E-15	9.92E-16	9.35E-16	9.11E-16	9.35E-16	9.92E-16	1.05E-15	1.07E-15
0.4	1.16E-15	1.11E-15	9.92E-16	8.77E-16	8.30E-16	8.77E-16	9.92E-16	1.11E-15	1.16E-15
0.6	1.24E-15	1.16E-15	9.92E-16	8.20E-16	7.48E-16	8.20E-16	9.92E-16	1.16E-15	1.24E-15
0.8	1.32E-15	1.22E-15	9.92E-16	7.62E-16	6.67E-16	7.62E-16	9.92E-16	1.22E-15	1.32E-15
1	1.40E-15	1.28E-15	9.92E-16	7.05E-16	5.85E-16	7.05E-16	9.92E-16	1.28E-15	1.40E-15
		Gamma =135							
w rad/s	0	45	90	135	180	225	270	315	360
0	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
0.2	-12.39	-12.12	-11.46	-10.79	-10.52	-10.79	-11.46	-12.12	-12.39
0.4	-13.33	-12.78	-11.46	-10.13	-9.58	-10.13	-11.46	-12.78	-13.33
0.6	-14.27	-13.45	-11.46	-9.46	-8.64	-9.46	-11.46	-13.45	-14.27
0.8	-15.21	-14.11	-11.46	-8.80	-7.70	-8.80	-11.46	-14.11	-15.21
1	-16.15	-14.78	-11.46	-8.13	-6.76	-8.13	-11.46	-14.78	-16.15
		Gamma =180							
w rad/s	0	45	90	135	180	225	270	315	360
0	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2
0.2	-17.5	-17.1	-16.2	-15.3	-14.9	-15.3	-16.2	-17.1	-17.5
0.4	-18.9	-18.1	-16.2	-14.3	-13.5	-14.3	-16.2	-18.1	-18.9
0.6	-20.2	-19.0	-16.2	-13.4	-12.2	-13.4	-16.2	-19.0	-20.2
0.8	-21.5	-20.0	-16.2	-12.4	-10.9	-12.4	-16.2	-20.0	-21.5
1	-22.8	-20.9	-16.2	-11.5	-9.6	-11.5	-16.2	-20.9	-22.8

			Surge Force F1 (KN)						
U = 1.2 m/s					Gamma = 0				
w rad/s	0	45	90	135	180	225	270	315	360
0	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
0.2	17.0	16.8	16.2	15.6	15.4	15.6	16.2	16.8	17.0
0.4	17.8	17.3	16.2	15.1	14.6	15.1	16.2	17.3	17.8
0.6	18.6	17.9	16.2	14.5	13.8	14.5	16.2	17.9	18.6
0.8	19.4	18.5	16.2	13.9	13.0	13.9	16.2	18.5	19.4
1	20.2	19.0	16.2	13.4	12.2	13.4	16.2	19.0	20.2
					Gamma = 45				
w rad/s	0	45	90	135	180				
0	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46	11.46
0.2	12.02	11.85	11.46	11.06	10.89	11.06	11.46	11.85	12.02
0.4	12.58	12.25	11.46	10.66	10.33	10.66	11.46	12.25	12.58
0.6	13.15	12.65	11.46	10.26	9.76	10.26	11.46	12.65	13.15
0.8	13.71	13.05	11.46	9.86	9.20	9.86	11.46	13.05	13.71
1	14.27	13.45	11.46	9.46	8.64	9.46	11.46	13.45	14.27
					Gamma =90				
w rad/s	0	45	90	135	180	225	270	315	360
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Gamma = 135				
w rad/s	0	45	90	135	180	225	270	315	360
0	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46	-11.46
0.2	-12.02	-11.85	-11.46	-11.06	-10.89	-11.06	-11.46	-11.85	-12.02
0.4	-12.58	-12.25	-11.46	-10.66	-10.33	-10.66	-11.46	-12.25	-12.58
0.6	-13.15	-12.65	-11.46	-10.26	-9.76	-10.26	-11.46	-12.65	-13.15
0.8	-13.71	-13.05	-11.46	-9.86	-9.20	-9.86	-11.46	-13.05	-13.71
1	-14.27	-13.45	-11.46	-9.46	-8.64	-9.46	-11.46	-13.45	-14.27
					Gamma =180				
w rad/s	0	45	90	135	180	225	270	315	360
0	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2	-16.2
0.2	-16.997	-16.7636	-16.2	-15.6364	-15.403	-15.6364	-16.2	-16.7636	-16.997
0.4	-17.7941	-17.3272	-16.2	-15.0728	-14.6059	-15.0728	-16.2	-17.3272	-17.7941
0.6	-18.5911	-17.8908	-16.2	-14.5092	-13.8089	-14.5092	-16.2	-17.8908	-18.5911
0.8	-19.3882	-18.4544	-16.2	-13.9456	-13.0118	-13.9456	-16.2	-18.4544	-19.3882
1	-20.1852	-19.018	-16.2	-13.382	-12.2148	-13.382	-16.2	-19.018	-20.1852

Excel Computations - Mean Wave Drift Forces Coefficients - Sway Force

				Sway Force F2 (KN)					
U = 0 m/s									
Gamma=0					beta (wave headings)				
w rad/s	0	45	90	135	180	225	270	315	360
0	0	115.859074	214.52	115.859074	5.0868E-15	-115.85907	-214.52	-115.8590736	-1.01736E-14
0.2	0	115.859074	214.52	115.859074	5.0868E-15	-115.85907	-214.52	-115.8590736	-1.01736E-14
0.4	0	115.859074	214.52	115.859074	5.0868E-15	-115.85907	-214.52	-115.8590736	-1.01736E-14
0.6	0	115.859074	214.52	115.859074	5.0868E-15	-115.85907	-214.52	-115.8590736	-1.01736E-14
0.8	0	115.859074	214.52	115.859074	5.0868E-15	-115.85907	-214.52	-115.8590736	-1.01736E-14
1	0	115.859074	214.52	115.859074	5.0868E-15	-115.85907	-214.52	-115.8590736	-1.01736E-14
				the same values are equal for current angles 0 - 180 deg.					
U = 0.8 m/s									
Gamma=0									
w rad/s	0	45	90	135	180	225	270	315	360
0	0	115.8591	214.52	115.8591	5.08682E-15	-115.8590736	-214.52	-115.859	-1.01736E-14
0.2	0	116.7439	216.8368	116.7439	5.08682E-15	-114.9742864	-212.203	-114.974	-1.01736E-14
0.4	0	117.6286	219.1536	117.6286	5.08682E-15	-114.0894992	-209.886	-114.089	-1.01736E-14
0.6	0	118.5134	221.4704	118.5134	5.08682E-15	-113.2047121	-207.57	-113.205	-1.01736E-14
0.8	0	119.3982	223.7873	119.3982	5.08682E-15	-112.3199249	-205.253	-112.32	-1.01736E-14
1	0	120.283	226.1041	120.283	5.08682E-15	-111.4351378	-202.936	-111.435	-1.01736E-14
				the same values are equal for current angles 0 - 180 deg.					
U = 1.2m/s									
Gamma=0									
w rad/s	0	45	90	135	180	225	270	315	360
0	0	115.8591	214.52	115.8591	5.08682E-15	-115.859	-214.52	-115.859	-1.01736E-14
0.2	0	117.1863	217.9952	117.1863	5.08682E-15	-114.532	-211.045	-114.532	-1.01736E-14
0.4	0	118.5134	221.4704	118.5134	5.08682E-15	-113.205	-207.57	-113.205	-1.01736E-14
0.6	0	119.8406	224.9457	119.8406	5.08682E-15	-111.878	-204.094	-111.878	-1.01736E-14
0.8	0	121.1678	228.4209	121.1678	5.08682E-15	-110.55	-200.619	-110.55	-1.01736E-14
1	0	122.495	231.8961	122.495	5.08682E-15	-109.223	-197.144	-109.223	-1.01736E-14
				the same values are equal for current angles 0 - 180 deg.					
U =2.0 m/s									
Gamma=0									
w rad/s	0	45	90	135	180	225	270	315	360
0	0	115.8590736	214.52	115.8590736	5.08682E-15	-115.859	-214.52	-115.859	-1.01736E-14
0.2	0	118.0710414	220.31204	118.0710414	5.08682E-15	-113.647	-208.728	-113.647	-1.01736E-14
0.4	0	120.2830093	226.10408	120.2830093	5.08682E-15	-111.435	-202.936	-111.435	-1.01736E-14
0.6	0	122.4949772	231.89612	122.4949772	5.08682E-15	-109.223	-197.144	-109.223	-1.01736E-14
0.8	0	124.7069451	237.68816	124.7069451	5.08682E-15	-107.011	-191.352	-107.011	-1.01736E-14
1	0	126.918913	243.4802	126.918913	5.08682E-15	-104.799	-185.56	-104.799	-1.01736E-14
			the same values are equal for current angles 0 - 180 deg.						

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			Yaw moment F6 (KN)						
Gamma = 0									
U = 0 m/s									
			beta (wave headings)						
w rad/s	0	45	90	135	180	225	270	315	360
0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0	0
0.8	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0
Gamma = 45									
U = 0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.2	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.4	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.6	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.8	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
1	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
Gamma = 90									
U = 0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
0.2	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
0.4	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
0.6	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
0.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
1	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
Gamma = 135									
U = 0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.2	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.4	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.6	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
0.8	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
1	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386103
Gamma = 180									
U = 0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63022E-14
0.2	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63022E-14
0.4	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63022E-14
0.6	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63022E-14
0.8	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63022E-14
1	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63022E-14

Gamma = 0									
U = 1.2 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0	0
0.8	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0
Gamma = 45									
U = 1.2 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386
0.2	1305.386	1320.339	1326.533	1320.339	1305.386	1290.433	1284.239	1290.433	1305.386
0.4	1305.386	1335.293	1347.681	1335.293	1305.386	1275.479	1263.092	1275.479	1305.386
0.6	1305.386	1350.246	1368.828	1350.246	1305.386	1260.526	1241.944	1260.526	1305.386
0.8	1305.386	1365.2	1389.975	1365.2	1305.386	1245.573	1220.797	1245.573	1305.386
1	1305.386	1380.153	1411.122	1380.153	1305.386	1230.619	1199.65	1230.619	1305.386
Gamma = 90									
U = 1.2 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
0.2	2352.8	2379.752	2390.915	2379.752	2352.8	2325.848	2314.685	2325.848	2352.8
0.4	2352.8	2406.703	2429.031	2406.703	2352.8	2298.897	2276.569	2298.897	2352.8
0.6	2352.8	2433.655	2467.146	2433.655	2352.8	2271.945	2238.454	2271.945	2352.8
0.8	2352.8	2460.607	2505.261	2460.607	2352.8	2244.993	2200.339	2244.993	2352.8
1	2352.8	2487.558	2543.377	2487.558	2352.8	2218.042	2162.223	2218.042	2352.8
Gamma = 135									
U = 1.2 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386
0.2	1305.386	1320.339	1326.533	1320.339	1305.386	1290.433	1284.239	1290.433	1305.386
0.4	1305.386	1335.293	1347.681	1335.293	1305.386	1275.479	1263.092	1275.479	1305.386
0.6	1305.386	1350.246	1368.828	1350.246	1305.386	1260.526	1241.944	1260.526	1305.386
0.8	1305.386	1365.2	1389.975	1365.2	1305.386	1245.573	1220.797	1245.573	1305.386
1	1305.386	1380.153	1411.122	1380.153	1305.386	1230.619	1199.65	1230.619	1305.386
Gamma = 180									
U = 1.2 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14
0.2	7.63E-14	7.72E-14	7.75E-14	7.72E-14	7.63E-14	7.54E-14	7.51E-14	7.54E-14	7.63E-14
0.4	7.63E-14	7.81E-14	7.88E-14	7.81E-14	7.63E-14	7.46E-14	7.38E-14	7.46E-14	7.63E-14
0.6	7.63E-14	7.89E-14	8E-14	7.89E-14	7.63E-14	7.37E-14	7.26E-14	7.37E-14	7.63E-14
0.8	7.63E-14	7.98E-14	8.12E-14	7.98E-14	7.63E-14	7.28E-14	7.14E-14	7.28E-14	7.63E-14
1	7.63E-14	8.07E-14	8.25E-14	8.07E-14	7.63E-14	7.19E-14	7.01E-14	7.19E-14	7.63E-14

Gamma = 0									
U = 0.8 m/s									
				beta (wave headings)					
w rad/s	0	45	90	135	180	225	270	315	360
0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0	0
0.8	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0
Gamma = 45									
U = 0.8 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386
0.2	1305.386	1315.355	1319.484	1315.355	1305.386	1295.417	1291.288	1295.417	1305.386
0.4	1305.386	1325.324	1333.582	1325.324	1305.386	1285.448	1277.19	1285.448	1305.386
0.6	1305.386	1335.293	1347.681	1335.293	1305.386	1275.479	1263.092	1275.479	1305.386
0.8	1305.386	1345.262	1361.779	1345.262	1305.386	1265.51	1248.993	1265.51	1305.386
1	1305.386	1355.231	1375.877	1355.231	1305.386	1255.542	1234.895	1255.542	1305.386
Gamma = 90									
U = 0.8 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
0.2	2352.8	2370.768	2378.21	2370.768	2352.8	2334.832	2327.39	2334.832	2352.8
0.4	2352.8	2388.736	2403.62	2388.736	2352.8	2316.864	2301.98	2316.864	2352.8
0.6	2352.8	2406.703	2429.031	2406.703	2352.8	2298.897	2276.569	2298.897	2352.8
0.8	2352.8	2424.671	2454.441	2424.671	2352.8	2280.929	2251.159	2280.929	2352.8
1	2352.8	2442.639	2479.851	2442.639	2352.8	2262.961	2225.749	2262.961	2352.8
Gamma = 135									
U = 0.8 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386
0.2	1305.386	1315.355	1319.484	1315.355	1305.386	1295.417	1291.288	1295.417	1305.386
0.4	1305.386	1325.324	1333.582	1325.324	1305.386	1285.448	1277.19	1285.448	1305.386
0.6	1305.386	1335.293	1347.681	1335.293	1305.386	1275.479	1263.092	1275.479	1305.386
0.8	1305.386	1345.262	1361.779	1345.262	1305.386	1265.51	1248.993	1265.51	1305.386
1	1305.386	1355.231	1375.877	1355.231	1305.386	1255.542	1234.895	1255.542	1305.386
Gamma = 180									
U = 0.8 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14
0.2	7.63E-14	7.69E-14	7.71E-14	7.69E-14	7.63E-14	7.57E-14	7.55E-14	7.57E-14	7.63E-14
0.4	7.63E-14	7.75E-14	7.8E-14	7.75E-14	7.63E-14	7.51E-14	7.47E-14	7.51E-14	7.63E-14
0.6	7.63E-14	7.81E-14	7.88E-14	7.81E-14	7.63E-14	7.46E-14	7.38E-14	7.46E-14	7.63E-14
0.8	7.63E-14	7.86E-14	7.96E-14	7.86E-14	7.63E-14	7.4E-14	7.3E-14	7.4E-14	7.63E-14
1	7.63E-14	7.92E-14	8.04E-14	7.92E-14	7.63E-14	7.34E-14	7.22E-14	7.34E-14	7.63E-14

Gamma = 0									
U = 2.0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0	0
0.8	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0
Gamma = 45									
U = 2.0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386
0.2	1305.386	1330.308	1340.632	1330.308	1305.386	1280.464	1270.141	1280.464	1305.386
0.4	1305.386	1355.231	1375.877	1355.231	1305.386	1255.542	1234.895	1255.542	1305.386
0.6	1305.386	1380.153	1411.122	1380.153	1305.386	1230.619	1199.65	1230.619	1305.386
0.8	1305.386	1405.075	1446.368	1405.075	1305.386	1205.697	1164.404	1205.697	1305.386
1	1305.386	1429.997	1481.613	1429.997	1305.386	1180.775	1129.159	1180.775	1305.386
Gamma = 90									
U = 2.0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8	2352.8
0.2	2352.8	2397.719	2416.326	2397.719	2352.8	2307.881	2289.274	2307.881	2352.8
0.4	2352.8	2442.639	2479.851	2442.639	2352.8	2262.961	2225.749	2262.961	2352.8
0.6	2352.8	2487.558	2543.377	2487.558	2352.8	2218.042	2162.223	2218.042	2352.8
0.8	2352.8	2532.478	2606.902	2532.478	2352.8	2173.122	2098.698	2173.122	2352.8
1	2352.8	2577.397	2670.428	2577.397	2352.8	2128.203	2035.172	2128.203	2352.8
Gamma = 135									
U = 2.0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386	1305.386
0.2	1305.386	1330.308	1340.632	1330.308	1305.386	1280.464	1270.141	1280.464	1305.386
0.4	1305.386	1355.231	1375.877	1355.231	1305.386	1255.542	1234.895	1255.542	1305.386
0.6	1305.386	1380.153	1411.122	1380.153	1305.386	1230.619	1199.65	1230.619	1305.386
0.8	1305.386	1405.075	1446.368	1405.075	1305.386	1205.697	1164.404	1205.697	1305.386
1	1305.386	1429.997	1481.613	1429.997	1305.386	1180.775	1129.159	1180.775	1305.386
Gamma = 180									
U = 2.0 m/s									
w rad/s	0	45	90	135	180	225	270	315	360
0	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14	7.63E-14
0.2	7.63E-14	7.78E-14	7.84E-14	7.78E-14	7.63E-14	7.48E-14	7.42E-14	7.48E-14	7.63E-14
0.4	7.63E-14	7.92E-14	8.04E-14	7.92E-14	7.63E-14	7.34E-14	7.22E-14	7.34E-14	7.63E-14
0.6	7.63E-14	8.07E-14	8.25E-14	8.07E-14	7.63E-14	7.19E-14	7.01E-14	7.19E-14	7.63E-14
0.8	7.63E-14	8.21E-14	8.45E-14	8.21E-14	7.63E-14	7.05E-14	6.81E-14	7.05E-14	7.63E-14
1	7.63E-14	8.36E-14	8.66E-14	8.36E-14	7.63E-14	6.9E-14	6.6E-14	6.9E-14	7.63E-14

Table 3: Surge Force @ U = 0 m/s at Different Angle of Attack

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