NUMERICAL MODELLING OF CURRENT ON WAVE DRIFT LOAD OF A SHIP SHAPED OFFSHORE STRUCTURES (CASE STUDY – EXCRAVOS IN WEST AFRICAN OFFSHORE)

Abam, Tamunopekere Joshua[1,a*], Agbakwuru, Jasper Ahamefula[1,b]

Adeyemi, I. Olabisi[2,c]

[1]*Department of Marine Engineering, Federal University of Petroleum Resources Effurun, Delta State. Nigeria*

[2]*Department of Mechanical Engineering, Federal University of Petroleum Resources Effurun, Delta State. Nigeria*

[a]*abam.joshua@fupre.edu.ng*, [b]*agbakwuru.jasper@fupre.edu.ng*, [c]*adeyemi.olabisi@fupre.edu.ng*

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Abstract: On account of the piecemeal reduction of oil and gas resources onshore and shallow waters, oil exploration is gradually moving into deeper waters. One of the major means of exploration of these resources is by ship-shaped offshore structures. Owing to marginal field and the increment of depths of exploration, there comes the need for the reusable, re-locatable and field-independent ship-shaped offshore structures. They include FPSO, FLNG, FSO, drill ships etc. A usual phenomenon these structures face at their location is drifting i.e. losing its course. The research presents the numerical analysis of sea loads on these structures. It focuses more on waves and current effects. This work uses a theory developed by Faltenses 1990 and modified by Said in 2010 and extended the theory to verify the effects of current on 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. Data used for computation of the current forces were obtained from the Oil Companies International Marine Forum of 2014. Computations were carried out in irregular wave's conditions data prevalent in Escravos, Offshore Nigeria. Based on it, *steady drift motion responses and effect of the current forces* are examined. Environmental conditions, such as effect of current velocity, current forces and current angle of attack on wave drift load are analyses, which significantly affected the FSO motion in surge, sway and yaw moments. It is found that the effect of current forces is quite significant when the current velocity is increased. In this numerical analysis, while the current velocity is increased to 2.0 meter/seconds (3.90 knots), the impact on FSO motion is quite significant, which should be taken into consideration from the point of view of design, safety, failure of mooring systems, operating responses, production shut down and the positioning of the FPSO. The results of the discussion conform to facts about sea loads and its effects.

Introduction

Today, oil and gas are essential commodities in world trade. Exploration that initially started ashore has now moved offshore. These explorations were initially in shallow waters but now in deeper waters because of the increasingly reduced possibilities of new fields in shallow waters. Very recently, the need for development of offshore oil and gas resources in increasingly deep waters is becoming more realizable and important because of the high increase in demand for oil and gas energy [1]. Ship-shaped offshore units such as FPSOs have been recognized as the most reliable, economical solutions in developing offshore marginal oil and gas reserves in deep-water regions. The process of developing offshore oil and gas reserves is sub-divided into the following major steps, according to [2]; exploration, exploratory drilling, production drilling and completion, production, processing, Storage, offloading and transportation either via a tanker vessel or pipeline. Ships and ship-shaped offshore structures have been vital to these developments. In his book Chakrabarti [3], noted that the FPSO generally refers to a ship-shaped offshore structures moored to seabed, used for the sole aim of oil and gas production.

Applied loads from winds, waves (sea and swell), currents and tide results in the dynamic structural response of the FPSO. Waves and currents are major source of disturbance on ship-shaped offshore structures with which we are concerned. This paper is aimed at analyses and verifying the importance of the effect of surface current on the dynamic structural response of an FPSO being acted upon by wave drift load. Furthermore this research will address the effects of irregular seas in Nigeria offshore structure, described by the effect of current forces, current attack angle and current speed on the motion response of the ship-shaped floating structures subjected to waves. Effects of these phenomena could cause heave motion which is a limiting factor for drilling operation as a result of the motion of the risers. It can also results in rolling, pitching and related motion, which may also limit the processing operation onboard a FPSOs and resulting in the crew been uncomfortable onboard. In order to reduce the undesirable motion of marine vehicles under sea states, the reducing forces and moments are significant issues to be considered. An engineer can reduce the forces and moments by increasing the damping coefficient, reducing natural frequency, or even directly reducing the excitation forces and moments [4].

In offshore West Africa there is a relative high surface current in the upper water column. This high surface current is thought to be caused by wind driven water from the main rivers and may generate currents speeds in the range of 1.7 – 2.0 m/s in the upper few meters. In analysis of offshore structures 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 and the difficulty encounter during scaling results in model tests make numerical method a viable tool for calculating wave-induced motion and loads on ship-shaped offshore structures. This has given birth to the novelty of this paper.

Islam et al. [5], affirms that current loads have significant effects on FPSO positioning and under extreme circumstances which may lead to mooring line failure. Current impacts on FPSO, depends on current speeds, angles of attack and most significantly the water depth to ship draught ratios. Molland [6], in his work argue that this excessive amplitude of motion of the vessels is undesirable. They can make shipboard tasks hazardous or even impossible, and reduce crew efficiency and passenger comfort. Large motion amplitudes increase the power demands of such systems and may restrict the safe arcs of fire. Remery and Van-Oortmerssen [7], presented a method to predict current forces on moored tankers, based on several model tests conducted at the Netherlands Ship Model Basin (currently MARIN). The authors proposed that the ITTC 1957 frictional resistance formula be used to predict the longitudinal force. For transverse force and yaw moment coefficients, they calibrated a separate fifth order Fourier cosine series to the test results and proposed these to model the variation of each coefficient with a relative current heading. They suggested that the lateral current force and yaw moment coefficients should be independent of the Reynolds number. A curve was provided for adjusting the force coefficients for shallow water effects.

Edward [8], found that, contrary to results by Remery and Van-Ootmerssen, the influence of Reynolds number on the lateral current force and yaw moment is significant, in particular due to changes in the nature of the vortex shedding from the bow and stern. Experimental results for steady current forces on tanker-based FPSO are given in [9]. The authors claimed that a longitudinal force near 180 and 90 degree angles of attack is strongly dependent on the details of the bow and stern configuration. These resulted in larger lateral force and yaw moments than those indicated by OCIMF in 1994. Inoue et al. [10], presented some numerical results for a moored FPSO and a parallel connected LNG carrier. The authors presented the effects of current, wind and drift forces on this multi-body floating system. They analyzed the interaction effect between the two vessels for one current heading angle and concluded that the effect of current on the motion of FPSO is significant.

Islam et al. [5], states that the steady wind, current and wave drift forces causes a shift of the neutral position of the moored object around which the oscillation due to waves occurs. Verhagen and Van-Sluijis [11], Hsu and Blenkarn [12] and Remery and Hermans [13], showed that the low frequency components of the wave drift forces in irregular waves could, even though relatively small in magnitude, excite large amplitude low frequency horizontal motions in moored vessels.

The equation of motion for a freely floating or moored ship-shaped offshore structure, the exciting force may include the first order wave excitation force, second order wave excitation force, current drag force, wind drag force, any other forces (specified forces and forces from station-keeping and coupling elements, etc.). The wave frequency (WF) motions are excited by the first order wave excitation force. The low-frequency (LF) motions are excited by the slowly varying part of the second order wave excitation force, the wind drag force and the current drag force. The high-frequency (HF) motions are excited by the sum-frequency second-order wave excitation force. DNV-RP-F205 [14] and Wishers [15], established that steady current when in combination with irregular wave; a tanker will not take up a steady position in the horizontal plane. Both full scale observations and model tests have shown that the behavior of a tanker moored to a single point mooring system is greatly determined by the slow motions of the tanker in the horizontal plane.

Remery and Van-Ootmerssen [7], expressed that the almost steady current and wave drift forces cause a shift of the neutral position of the moored structure around which the oscillation due to waves occurs. Generally the natural frequency of the horizontal motion of the anchored structure is considerably smaller than the wave frequency. The problem of determining the exciting forces acting on a rigid floating body due to uni-directional waves has been extensively studied. This is usually formulated in the frequency domain by assuming that the incident waves are sinusoidal and of fixed frequency with respect to time domain by superposition and Fourier analysis. Numerical techniques are developed for bodies of arbitrary shape. The solutions in the time domain and frequency domain are related through the use of Fourier transforms. [14]. Therefore it is very important to study the effect of the current and wave drift forces in the early stage of the design and periodically during service, to be sure that resonance at the wave frequency will be avoided.

General Description of Escravos LPG FSO and Associated Environment Conditions. The Escravos Liquefied Petroleum Gas FSO (LPG FSO) was initiated by Chevron Nigerian and its joint venture partner the Nigeria National Petroleum Cooperation (NNPC) to stop gas flaring and recover the gas and condensate from the company offshore oil production. The LPG FSO converts ethane, propane and butane components of the gas stream into liquid products as such it will chill depressurize. The liquid products are stored in tanks of the FSO hull prior to being offloaded to LPG tankers that are used to transport the LPG to the market. It serves as a solution to gas flaring in West Africa.

Environmental Phenomena. For ship-shaped offshore structures, a good knowledge of the environmental conditions in the areas where the structures will be installed is necessary for design and construction. Wave and current conditions in a sea state can be divided into two classes: wind seas and swell. Wind seas are generated by the local wind; while swell have no relationship with the local wind. Swells are waves that have travelled out of the areas where they were originally generated by wind.

Offshore West Africa. Environmental conditions around the world can be classified as either benign or harsh. Paik and Thayamballi [1], stated that offshore West Africa is characterized as benign. Similarly, Hansen, Duggal and Macmillian [18] joined in classified the environmental conditions found in offshore West Africa as benign since the relative wave magnitude is significantly lower when compared to what is found in other regions of the world such as North Sea, Brazil, Norway and Gulf of Mexico. However, there are certain unique design challenges encountered in this region that are caused by large period, persistent swells, squalls and high surface currents. Gbuyiro and Olaniyan [19], reported that swells of about 0.47 meters in height resulting from winds of about 10 knots grazed the coast frequently during the period. In this paper the offshore location is Escravos oil field of Nigeria coastal line 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 Longitudinal East as shown in Fig. 1.

Met-ocean Data. The environment data to be used for the analysis will be based on a 100-year storm for a typical ship- shaped FPSO novel design in Ukpokiti Field on Lat. North and East adjacent to Escravos Field. This was used as a result of the availability of data for the Escravos field. The design report for a 100-year storm from FMC Sofec and Chevron Nigeria Ltd. for the LPG FSO in the Escravos Field will also be used.

Water Depth. The water depth in this region to sea ranges from shallow water (~20 meters) to deep water (+ 1100 meters). FMC Sofec and Chevron Nigeria Ltd. recorded that a water depth of (28.5 – 30) m was used as design criteria for the FSO and its mooring system. Similarly from the Ukpokiti Field data, it reported the water depth to be 26.82m (88 ft). For the analysis, the water depth will be taken as 28.5m.

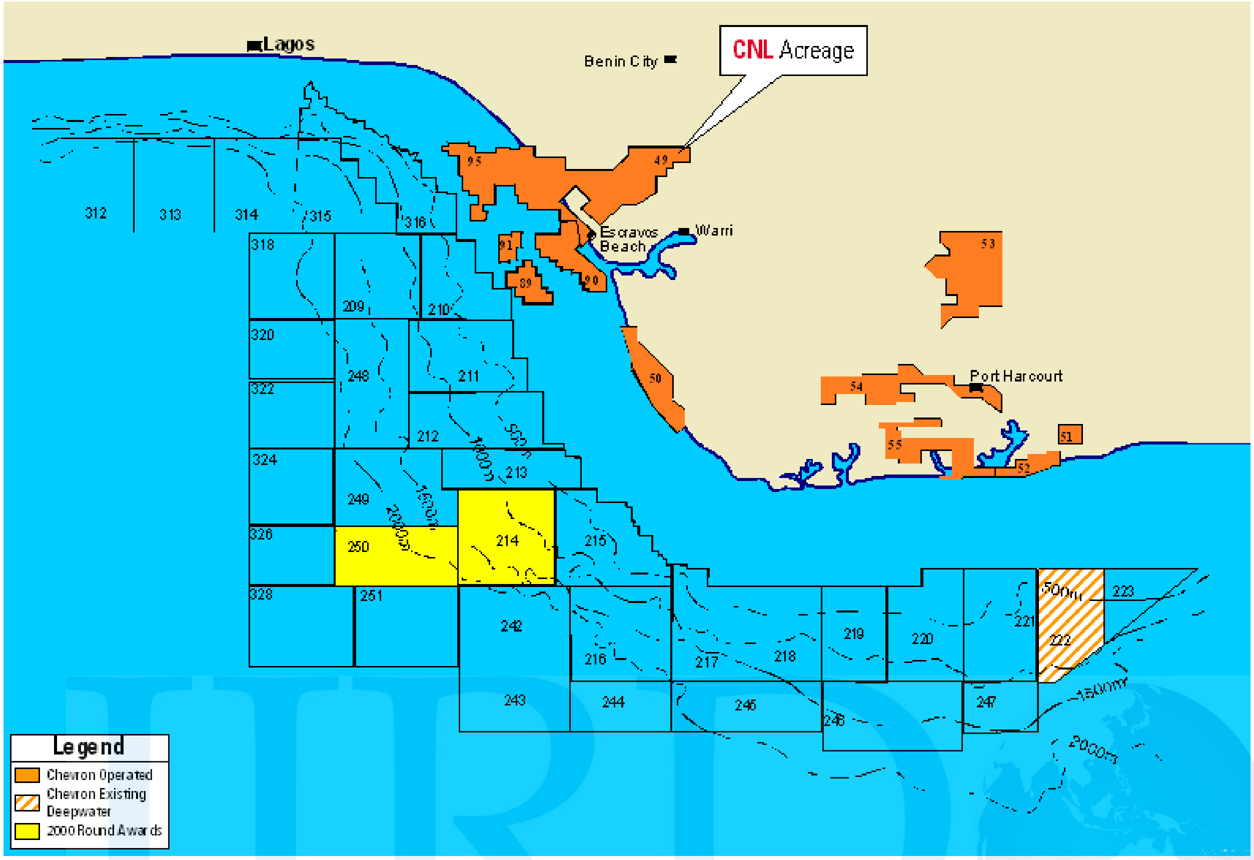

Fig. 1: Escravos River
Source: Chevron Nigeria

Wind. At 100-year storm for environmental conditions (wind, wave and current), FMC Sofec and Chevron Nigeria Ltd. has the value for the wind velocity as 30m/sec. while Ukpokiti Field data holds the one-hour sustained wind speed at 15m/s (29.16 knots). Hence, for Escravos Field a 100 year hourly wind speed design value of 30 m/s.

Current. For the design of the FSO and its mooring system, FMC Sofec and Chevron Nigeria Limited holds the current speed at 1.2m/s (2.2 Knots). Ukpokiti Field data account for a current speed of 1m/s (1.94 knots) at the surface. A conservative value of 1.2 m/s is chosen.

Waves. A significant wave height of 3.0m and wave period of (15-17 sec.) was used by FMC Sofec and Chevron Nigeria Ltd. for the environment criteria for the design of the FSO. Ukpokiti Field data holds the following about the waves in this region: wave height 3.2m, spectral peak period 15.5 sec., maximum wave height 5.6m, maximum wave period 13.8 sec. From physics of waves, Maximum wave height = approximately 2 × significant wave height. Significant wave height = 2.8m.

For the analysis, a significant wave height of 3.0m is preferable.

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. Knowing that the fluid motions may be described by a velocity potential

$$\emptyset = \sum_{i=1}^{n} \epsilon_i \emptyset_i . \quad (1)$$

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.

Coordinate Systems. Three co-ordinate systems of axes are used as seen in Fig. 2, the first is a right-handed system of $G{-}X_1{-}X_2{-}X_3$ body axes with the center of gravity G as origin and with positive $G{-}X3$ axis vertically upwards in the mean position of the oscillating vessel. The surface of the hull is uniquely defined relative to this system of axes. A point on the surface has as position the vector x. The orientation of a surface element in this system of axes is defined by the outward pointing normal vector $\vec{n}$.

The second system of co-ordinate axes is a fixed $O{-}X_1{-}X_2{-}X_3$ system with axes parallel to the $G{-}X_1{-}X_2{-}X_3$ system of axes with the body in the mean position and origin O in the mean free surface.

The third system of co-ordinate axes is a $G - X_1' - X_2' - X_3'$system of axes with the center of gravity G, as origin of the body and axes which are at all times parallel to the axes of the fixed $O{-}X_1{-}X_2{-}X_3$ system.

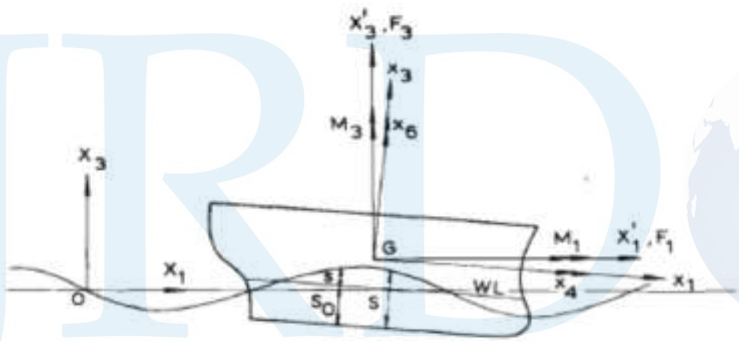

Fig. 2: Systems of co-ordinates. Source: (Pinkster, 1980)

Considering a system of fixed coordinate system the pressure in a point on the hull of the ship-shaped structure can be determined by writing down the Bernoulli's equation as:

$$p = p_0 - pgz - \frac{\partial \emptyset}{\partial t} - \frac{1}{2}\rho|\nabla\emptyset|^2 . \quad (2)$$

The quadratic term in Eq. (2) can be extended as

$$-\frac{1}{2}\rho|\nabla\emptyset|^2 = -\frac{1}{2}\rho|V_1^2 + V_2^2 + V_3^2| . \quad (3)$$

Knowing that V_i are the velocity terms as in-relation to the axis of the directions of coordinate system. This equation provides one of the non-linear effects. Other contributions may be equally important. Considering an idealized sea state consisting of two wave components of circular frequencies ω_1 and ω_2 consisting of sea waves and swell waves, an approximation for the x-component of the wave velocity can be written formally as

$$V_1 = A_1 \cos(\omega_1 t + \epsilon_1) + A_2 \cos(\omega_2 t + \epsilon_2) . \quad (4)$$

sea wave swell wave

Extending the first velocity terms of Eq. 3 for two wave components with different wave amplitudes A_1 and A_2 and different circular frequencies ω_1 and ω_2 propagating in an idealized sea state leads to:

$$-\frac{\rho}{2}V_1^2 = -\frac{\rho}{2}\left[\frac{A_1^2}{2}+\frac{A_2^2}{2}+\frac{A_1^2}{2}\cos(2\omega_i t+2\varepsilon_i)+\frac{A_2^2}{2}\cos(2\omega_2 t+2\varepsilon_2)+A_1A_2\cos\big((\omega_1-\omega_2)t\ +\varepsilon_1-\varepsilon_2\big)+A_1A_2\cos\big((\omega_1+\omega_2)t\ +\varepsilon_1+\varepsilon_2\big)\right]. \quad (5)$$

Eq. 5 shows that second order effects are generally those effects which are proportional to the square of the wave amplitude. It can be analyzed such that the presence of a constant term $-\frac{\rho}{2}\left[\frac{A_1^2}{2}+\frac{A_2^2}{2}\right]$ represents steady dynamic pressure.

Breaking Eq. 5 we have

$\left[\frac{\rho}{2}\frac{A_1^2}{2}\cos(2\omega_i t+2\varepsilon_i)-\frac{\rho}{2}\frac{A_2^2}{2}\cos(2\omega_2 t+2\varepsilon_2)+\frac{\rho}{2}A_1A_2\cos((\omega_1+\omega_2)t\ +\varepsilon_1+\varepsilon_2)\right]$ represents a dynamic pressure term which oscillates with the sum frequency $(\omega_1+\omega_2)$. This term shows the non-linear effects which can excite a vessel with frequency higher than the dominant frequency components in a wave spectrum.

Another term in Eq. 5, $\left(-\frac{\rho}{2}A_1A_2\cos((\omega_1-\omega_2)t\ +\varepsilon_1-\varepsilon_2)\right)$. Shows the non-linear effects can oscillate the vessel at a frequency difference of $(\omega_1-\omega_2)$.

Therefore, according to Faltinsen [18] in his book, the presence of the constant term, dynamic pressure term oscillating with frequency difference and the terms with higher frequencies than dominant frequency components in a wave spectrum represents the effects of the second order wave loads and moments. These non-linear interaction terms produce slowly-varying excitation forces and moments which may cause resonance oscillations in the surge, sway and yaw motions of a moored structure. Typical resonance periods are 60 - 120 seconds.

Current Loads. The effect of current forces on the mean wave drift forces analysis on FSO in irregular waves will be found in the next section. This section has to do with the singular effects of current forces on the motion of FSO. DNV-RP-F205 [14], mentions the following effects of current on ship-shaped offshore structures. It includes:

i. Currents can cause large steady excursions and slow drift motions of moored platforms.
ii. Currents can give rise to vortex induced vibrations of slender structural elements and vortex induced motions of large volume structures.
iii. Interaction between strong currents and waves leads to change in wave height and wave period.

Steady current gives rise to a steady force in the horizontal plane and a yaw moment.

Empirical formulas are most often used to calculate steady current loads on offshore structures. The forces and moments are commonly a function of the square of the current velocity i.e. $F_c = C.V^2$. The basic theory about these forces can be found in OCIMF of 1994. They are given by:

$$\boldsymbol{F_{xc}} = \frac{1}{2}C_{xc}\,\rho\,L\,T\,V_{cr,}^2 \quad \boldsymbol{F_{yc}} = \frac{1}{2}C_{yc}\,\rho\,L\,T\,V_{cr,}^2 \quad \boldsymbol{M_{mc}} = \frac{1}{2}C_{mc}\,\rho\,L^2\,T\,V_{cr.}^2 \quad (6)$$

Where: $\boldsymbol{F_{xc}}$ is the longitudinal current force**,** $\boldsymbol{F_{yc}}$ is the lateral current force and $\boldsymbol{M_{mc}}$ is the current yaw moment.

The associated dimensionless force and moment coefficients are longitudinal current forces coefficient,$\boldsymbol{C_{xc}}$, lateral current forces coefficient, $\boldsymbol{C_{yc}}$ and current yaw moment coefficient, $\boldsymbol{C_{mc}}$. These current forces and moment coefficients are a function of the current angle, Froude and Reynolds numbers, hull form, and vessel draft and water depth to vessel draft ratio. These coefficients are obtained from the curves proposed by the Oil Companies International Marine Forum (OCIMF) [19] which are based on extensive tank tests on typical tests.

The values of coefficients$\boldsymbol{C_{xc}}$**,** $\boldsymbol{C_{yc}}$**,** $\boldsymbol{C_{mc}}$ are presented by the OCIMF for the following conditions:

- Current angle of attack: 180 degrees bow-on to 0 degrees on the stern.
- Water depth to draft ratio
- Bow-type configuration.

The remaining variables are the vessel draft, $\boldsymbol{T}$, length between perpendiculars, **L**, current velocity, $\boldsymbol{V_{cr}}$, and fluid density, $\boldsymbol{\rho}$.

Effects of Current on Wave Drift Loads. To consider the effects of current on the wave drift loads, the ship added resistance formula proposed by Faltinsen [20] will be modified to include current coefficient C_{cu}, this mile stone was achieved by Said [21]

$$\boldsymbol{F_i = \frac{1}{2}\rho g.\zeta_a{}^2 C_{cu}\int_{L_1}\sin^2(\theta+\beta).n_i.dl.} \tag{7}$$

The current coefficient $\boldsymbol{C_{cu}} = \left(\boldsymbol{1} + \frac{\boldsymbol{2\omega U_i}}{\boldsymbol{g}}\right)$ takes care of the effect of current on the wave drift force and moment. [21]

Therefore Eq.7 becomes:

$$\boldsymbol{F_i = \frac{1}{2}\rho g.\zeta_a{}^2\left(1+\frac{2\omega U_i}{g}\right)\int_{L_1}\sin^2(\theta+\beta).n_i.dl.} \tag{8}$$

Where $\boldsymbol{\omega}$ ***and*** $\boldsymbol{U_i}$ are oscillating wave and current speed respectively of circular frequency.

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. [14].

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:

$$\overline{X_1^S} = \frac{F_1^S}{c_x}\ ,\quad \overline{X_2^S} = \frac{F_2^S}{c_y}\ ,\quad \overline{X_6^S} = \frac{F_6^S}{c_\theta}. \tag{9}$$

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 = Rotational mooring stiffness which for a Turret moored floating structure is given by $c_\theta = L_m^2 c_x$; where $L_m =$ 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 of 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.

Validation - Hydrodynamic Analysis of FSO LPG Escravos. This section shows results from the computations of the theory analyzed. Mean wave drift force and current forces respectively. Various wave heading and current heading were calculated.

Table 1: The principal particulars for the LPG FSO Escravos

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

Source: Maria, Gautam and Akinori (1997)

Other characteristics of the FSO include:

i. Ship-shaped Hull
ii. External Cantilevered Bow Turret (Single Point Mooring)
iii. Offloading to tanker
iv. Deck load capacity

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

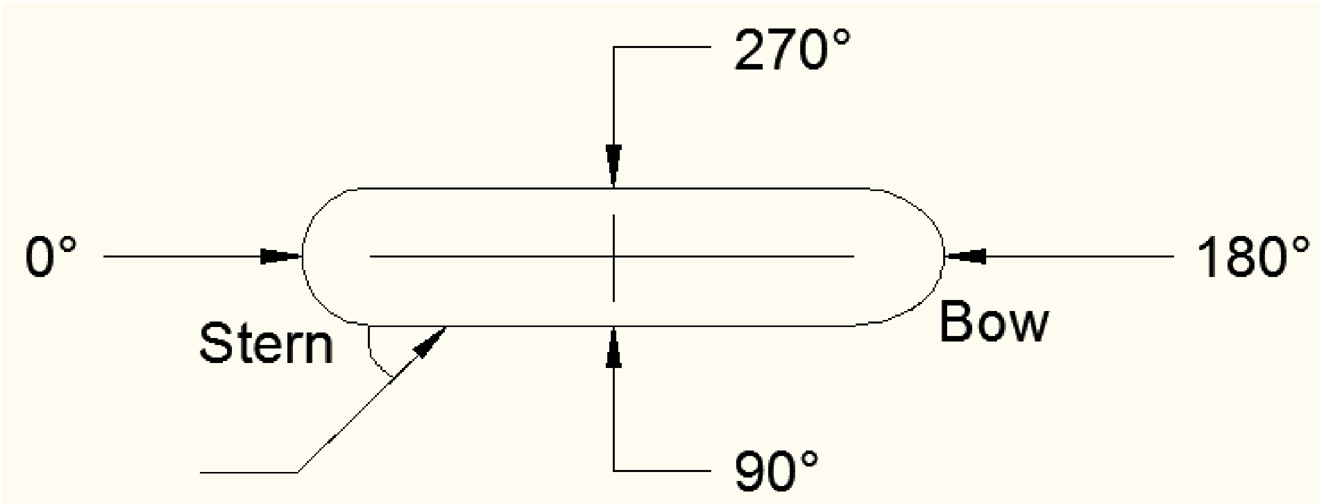

Fig. 3: Direction of wave heading/current attack angle

Response Curves. An analysis was carried out on the FSO having detail as given in Table 1 originally taken from [22, 23]. The computations for the FSO were carried out in irregular waves using the hydrodynamic theory described in section 3 and the met-ocean data in section 2.

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 and velocity as captioned in Table 2 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.

Table 2: Different current velocities considered

Case	Current velocity [m/s]	Current velocity [Knots]
1.	0.0	0
2.	0.8	1.56
3.	1.2	2.33
4.	*2.0*	*3.90*

Here, the current velocity of *2.0m/s (3.9 Knots)* is considered as an extreme case when compare to the value employ by [22, 23] where they both use a current velocity of 1.2m/s for the FSO design.

Result Discussion

This section presents the results of computations of current forces by Excel using the data from OCIMF of 1994. Computations were performed for different current velocities: 1.0, 1.2, 1.4, 1.6, 1.8, 2.0 m/s. ten current attack angles was considered. The longitudinal force, lateral force and yaw moment coefficients are tabulated below. See appendix A - E for full detailed results. While appendix A contains detail tabulated generated results, appendix E contains graphical representation of the results generated with excel.

Appendix A, Table A.1 – A.4, contains surge current coefficient at current velocity of 0, 0.8, 1.2 and 2.0m/s respectively, of which as earlier noted 2.0 m/s is considered an extreme case scenario. Appendix B, Table B.1 – B.4 contains sway current coefficient using this same range of current velocity. So also Appendix C Table C.1 – C.4 contains yaw current coefficient for the same range of current velocity. Appendix D Table D.1 – D.3 which rounded the tabulated results, in which, Table D.1 and D.2 contains the longitudinal and lateral current force coefficient respectively, while Table D.3 has in it current yaw moment coefficient.

Appendix E Fig E.1 – E.3 contains the graphical representation of the generated tabulated results of the longitudinal current force coefficient, lateral force coefficient and current yaw moment coefficient versus the current angle of attack respectively.

It is seen in Appendix E, Fig 1, that the higher the current velocity, the more significant impact on the amplitude of the FSO. The FSO cannot resist the impact from current forces, as the current velocity is *2 m/s (3.90 knots)* the force becomes 200 KN at about 100^o. The same is applicable for Fig. 1 and Fig. 2 respectively; the increase in velocity of current is direct proportional to force and moment on the FSO to a reasonable extent respectively. From the results it is shown that the impact of the current angle of attack on the FSO on the three (3) DOF respond differently two react differently with longitudinal and lateral forces experiencing maximum impact at am attack angle range of 90^o - 120^o.

The response is also presented as a function of the wave frequencies and wave headings.

Conclusions

As a result of the analysis the following conclusions may be drawn up: The effect of current forces is quite important for the FSO motion in surge, sway and yaw. It can also be understood that current angle and velocity influences FSO motion response and, in uttermost cases, at a current velocity of 2.0 m/s, the FSO is extremely affected by a huge impact, which should be given importance in the designing of mooring and dynamic positioning systems.

It is found that the magnitude of singular effects of the current forces can introduce drifting of the vessel from its moored position or resonance in the motion amplitude of the FSO. The current coefficient are dependent on the Froude’s no which ranges from 0~0.2. Hence, the low - velocity dependent second order wave drift forces have to be taken into account.

It is noted that the presence of current can increase the mean wave drift force for a particular range of wave frequencies in which the increase depend on the structure. The magnitude of the mean wave drift forces on the FSO can be in the range of 17.0 KNm, 240.0 KNm, and 2700 Nm for surge, sway and yaw moment respectively. Finally it’s worthy to note that the current angle of attack results in immense influence of the FSO motion response.

Appendix A: Surge Current Coefficients

Table A.1 Surge current coefficients at 0.0 m/s current velocity

w [rad/s]	Current velocity U = 0.0 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1.00	1.00	1.00	1.00	1.00	1	1	1	1
0.2	1.00	1.00	1.00	1.00	1.00	1	1	1	1
0.4	1.00	1.00	1.00	1.00	1.00	1	1	1	1
0.6	1.00	1.00	1.00	1.00	1.00	1	1	1	1
0.8	1.00	1.00	1.00	1.00	1.00	1	1	1	1
1.0	1.00	1.00	1.00	1.00	1.00	1	1	1	1

Table A.2 Surge current coefficients at 0.8 m/s current velocity

w [rad/s]	Current velocity U = 0.8 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1.00	1.00	1.00	1.00	1.00	1	1	1	1
0.2	1.03	1.02	1.00	0.98	0.97	0.976807	0.976807	1.023193	1.0328
0.4	1.07	1.05	1.00	0.95	0.93	0.953614	0.953614	1.046386	1.0656
0.6	1.10	1.07	1.00	0.93	0.90	0.930421	0.930421	1.069579	1.0984
0.8	1.13	1.09	1.00	0.91	0.87	0.907228	0.907228	1.092772	1.1312
1.0	1.16	1.12	1.00	0.88	0.84	0.884034	0.884034	1.115966	1.164

Table A.3: Surge current coefficient at 1.2 m/s current velocity

w [rad/s]	Current velocity U = 1.2 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1.00	1.00	1.00	1.00	1.00	1	1	1	1
0.2	1.05	1.03	1.00	0.97	0.95	0.96521	1	1.03479	1.0492
0.4	1.10	1.07	1.00	0.93	0.90	0.930421	1	1.069579	1.0984
0.6	1.15	1.10	1.00	0.90	0.85	0.895631	1	1.104369	1.1476
0.8	1.20	1.14	1.00	0.86	0.80	0.860841	1	1.139159	1.1968
1.0	1.25	1.17	1.00	0.83	0.75	0.826052	1	1.173948	1.246

w [rad/s]	Current velocity U = 2.0 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1.00	1.00	1.00	1.00	1.00	1	1	1	1
0.2	1.08	1.06	1.00	0.94	0.92	0.942017	1	1.057983	1.082
0.4	1.16	1.12	1.00	0.88	0.84	0.884034	1	1.115966	1.164
0.6	1.25	1.17	1.00	0.83	0.75	0.826052	1	1.173948	1.246
0.8	1.33	1.23	1.00	0.77	0.67	0.768069	1	1.231931	1.328
1.0	1.41	1.29	1.00	0.71	0.59	0.710086	1	1.289914	1.41

Table A.4 Surge current coefficients at 2.0 [m/s] current velocity

Appendix B: Sway Current Coefficients

Table B.1: Sway current coefficients at 0.0 m/s current velocity

w [rad/s]	Current velocity U = 0 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1
0.2	1	1	1	1	1	1	1	1	1
0.4	1	1	1	1	1	1	1	1	1
0.6	1	1	1	1	1	1	1	1	1
0.8	1	1	1	1	1	1	1	1	1
1.0	1	1	1	1	1	1	1	1	1

Table B.2: Sway current coefficients at 0.8 m/s current velocity

w [rad/s]	Current velocity U = 0.8 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1
0.2	1	1.007637	1.0108	1.007637	1	0.992363	0.9892	0.992363	1
0.4	1	1.015274	1.0216	1.015274	1	0.984726	0.9784	0.984726	1
0.6	1	1.02291	1.0324	1.02291	1	0.97709	0.9676	0.97709	1
0.8	1	1.030547	1.0432	1.030547	1	0.969453	0.9568	0.969453	1
1.0	1	1.038184	1.054	1.038184	1	0.961816	0.946	0.961816	1

Table B.3: Sway current coefficients at 1.2 m/s current velocity

w [rad/s]	Current velocity U = 1.2 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1
0.2	1	1.011455	1.0162	1.011455	1	0.988545	0.9838	0.988545	1
0.4	1	1.02291	1.0324	1.02291	1	0.97709	0.9676	0.97709	1
0.6	1	1.034365	1.0486	1.034365	1	0.965635	0.9514	0.965635	1
0.8	1	1.045821	1.0648	1.045821	1	0.954179	0.9352	0.954179	1
1.0	1	1.057276	1.081	1.057276	1	0.942724	0.919	0.942724	1

Table B.4: Sway current coefficients at 2.0 m/s current velocity

w [rad/s]	Current velocity U = 2.0 [m/s]								
	Current attack angle [deg]								
	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1
0.2	1	1.019092	1.027	1.019092	1	0.980908	0.973	0.980908	1

0.4	1	1.038184	1.054	1.038184	1	0.961816	0.946	0.961816	1
0.6	1	1.057276	1.081	1.057276	1	0.942724	0.919	0.942724	1
0.8	1	1.076368	1.108	1.076368	1	0.923632	0.892	0.923632	1
1.0	1	1.095459	1.135	1.095459	1	0.904541	0.865	0.904541	1

Appendix C: Yaw Current Coefficients

Table C.1: Yaw current coefficients at 0.0 m/s current velocity

	Cu 6								
w rad/s	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1
0.2	1	1	1	1	1	1	1	1	1
0.4	1	1	1	1	1	1	1	1	1
0.6	1	1	1	1	1	1	1	1	1
0.8	1	1	1	1	1	1	1	1	1
1.0	1	1	1	1	1	1	1	1	1

Table C.2: Yaw current coefficients at 0.8 m/s current velocity

U = 0.8 m/s									
	Cu 6								
w rad/s	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1
0.2	1	1.007637	1.0108	1.007637	1	0.992363	0.9892	0.992363	1
0.4	1	1.015274	1.0216	1.015274	1	0.984726	0.9784	0.984726	1
0.6	1	1.02291	1.0324	1.02291	1	0.97709	0.9676	0.97709	1
0.8	1	1.030547	1.0432	1.030547	1	0.969453	0.9568	0.969453	1
1	1	1.038184	1.054	1.038184	1	0.961816	0.946	0.961816	1

Table C.3: Yaw current coefficients at 1.2 m/s current velocity

U = 1.2 m/s									
	Cu 6								
w rad/s	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1
0.2	1	1.011455	1.0162	1.011455	1	0.988545	0.9838	0.988545	1
0.4	1	1.02291	1.0324	1.02291	1	0.97709	0.9676	0.97709	1
0.6	1	1.034365	1.0486	1.034365	1	0.965635	0.9514	0.965635	1
0.8	1	1.045821	1.0648	1.045821	1	0.954179	0.9352	0.954179	1
1	1	1.057276	1.081	1.057276	1	0.942724	0.919	0.942724	1

Table C.4: Yaw current coefficients at 2.0 m/s current velocity

U = 2.0 m/s									
	Cu 6								
w rad/s	0	45	90	135	180	225	270	315	360
0	1	1	1	1	1	1	1	1	1

0.2	1	1.019092	1.027	1.019092	1	0.980908	0.973	0.980908	1
0.4	1	1.038184	1.054	1.038184	1	0.961816	0.946	0.961816	1
0.6	1	1.057276	1.081	1.057276	1	0.942724	0.919	0.942724	1
0.8	1	1.076368	1.108	1.076368	1	0.923632	0.892	0.923632	1
1	1	1.095459	1.135	1.095459	1	0.904541	0.865	0.904541	1

Appendix D: Longitudinal Current Force Coefficient, Lateral Current Force Coefficients and Current Yaw Moment Coefficient

Table D.1: Longitudinal Current Force Coefficients (N)

Current Angles ϑ (deg.)	Force Coefficients (N)					
	Current Velocity (m/s)					
	1.0	1.2	1.4	1.6	1.8	2.0
0	36433.22	52463.83	71409.1	93269.03	118043.6	145732.9
20	1092996	45905.85	62482.96	81610.4	103288.2	127516.3
40	2185993	0	0	0	0	0
60	2987524	-13116	-17852.3	-23317.3	-29510.9	-36433.2
80	3570455	10492.77	14281.82	18653.81	23608.72	29146.57
100	3570455	72137.77	98187.51	128244.9	162310	200382.7
120	2914657	53775.43	73194.33	95600.76	120994.7	149376.2
140	2003827	-12853.6	-17495.2	-22850.9	-28920.7	-35704.6
160	1092996	-39347.9	-53556.8	-69951.8	-88532.7	-109300
180	0	-45905.9	-62483	-81610.4	-103288	-127516

Table D.2: Lateral Current Force Coefficients (N)

Current Angles ϑ (deg.)	Force Coefficients (N)					
	Current Velocity (m/s)					
	1.0	1.2	1.4	1.6	1.8	2.0
0	0	0	0	0	0	0
20	273249.1	393478.7	5568.3	699517.7	885327.1	1092996
40	546498.2	786957.4	1071137	1399035	1770654	2185993
60	746880.9	1075509	1463887	1912015	2419894	2987524
80	892613.8	1285364	1749523	2285091	2892069	3570455
100	892613.8	1285364	1749523	2285091	2892069	3570455
120	728664.3	1049277	1428182	1865381	2360872	2914657
140	500956.7	721377.7	981875.1	1282449	1623100	2003827
160	273249.1	393478.7	535568.3	699517.7	885327.1	1092996
180	0	0	0	0	0	0

Table D.3: Current Yaw Moment Coefficients [Nm]

Current Angles **ϑ**	Current Velocity (m/s)					
	1.0	1.2	1.4	1.6	1.8	2.0
0	0	0	0	0	0	0
20	-1.5E+07	-21483938	-2.9E+07	-3.8E+07	-4.8E+07	-6E+07
40	-2.1E+07	-30077514	-4.1E+07	-5.3E+07	-6.8E+07	-8.4E+07
60	-1.9E+07	-27929120	-3.8E+07	-5E+07	-6.3E+07	-7.8E+07
80	-8951641	-12890363	-1.8E+07	-2.3E+07	-2.9E+07	-3.6E+07
100	2983880	4296787.6	5848405	7638734	9667772	11935521

120	10443581	15038757	20469419	26735568	33837203	41774324
140	13427461	19335544	26317824	34374301	43504975	53709846
160	7459701	10741969	14621014	19096834	24169430	29838803
180	0	0	0	0	0	0

Appendix E: Graphical representation of Longitudinal Current Force Coefficients, Lateral Force Coefficient, and Current Yaw Moment Coefficient Versus the Current Angle of Attack Respectively

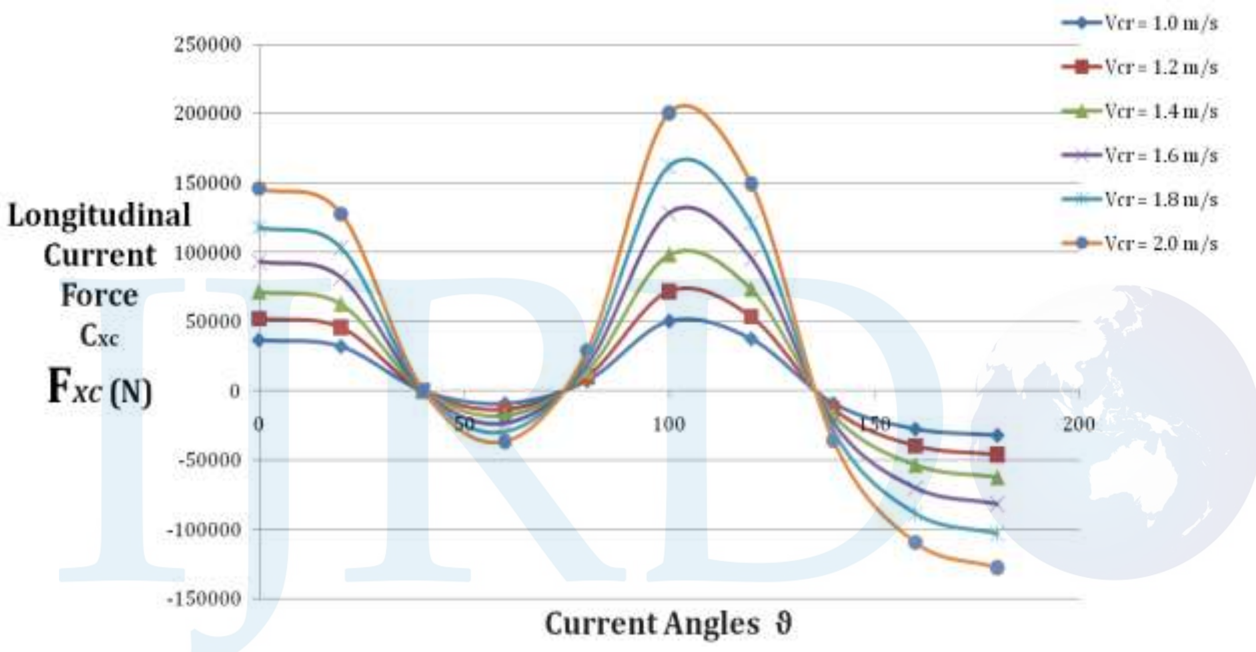

Fig. E.1: Longitudinal Current Force Coefficients versus angle of attack

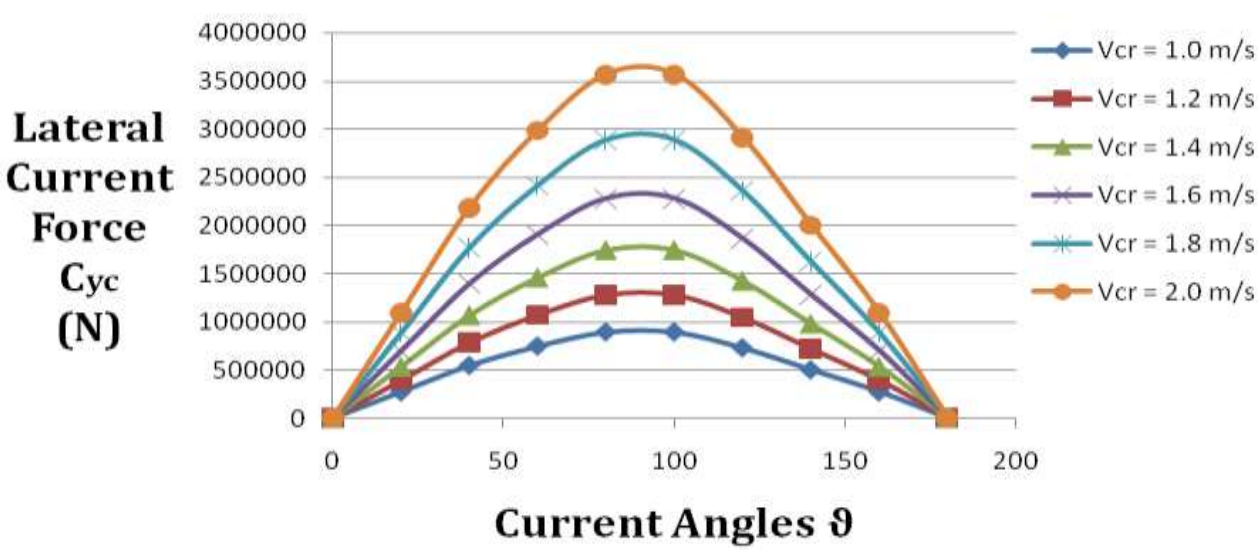

Fig. E.2: Lateral Current Force Coefficients versus angle of attack

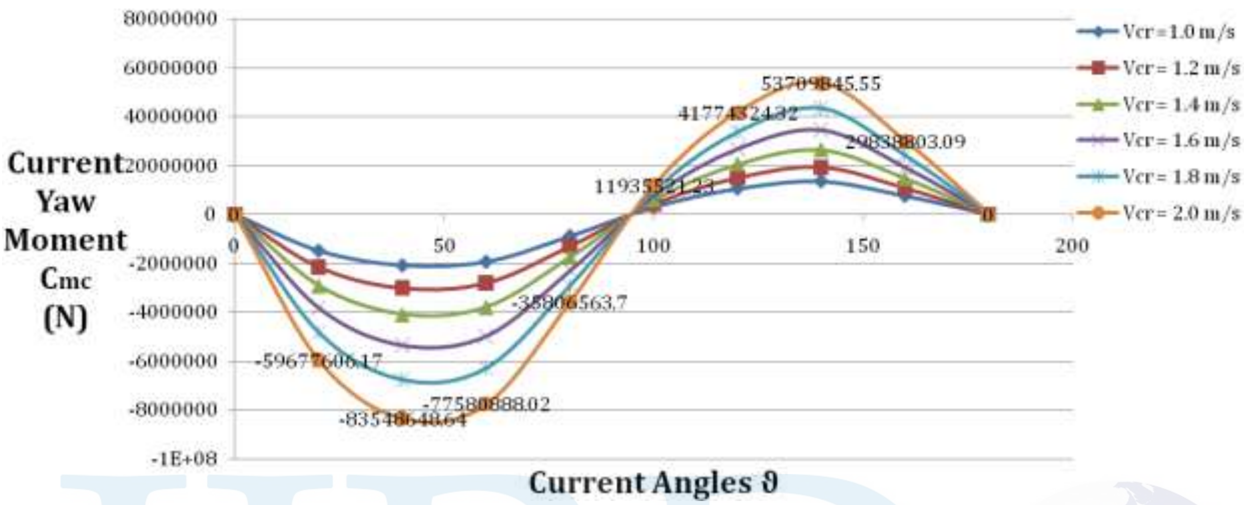

Fig. E.3: Current Yaw Moment Coefficients versus angle of attack

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