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Analysis of Mooring Lines for a Typical Floating, Production, Storage, and Offloading (Fpso) System

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ABSTRACT: This paper is aimed at analyzing the behavior of mooring lines otherwise called cable for floating, production, storage and offloading (FPSO) system using computational tools such as Orcaflex, ANSYS AQWA, and MATLAB. The analysis was carried using two regimes (static and dynamic) and a novel computational tool termed Orcaflex was used as a means for modelling and verification of result. The dynamic equations of motion were augmented upon and implemented based on modified Larange's equation whose solution was solved using the fourth order Runge-Kutta method. The effective loads against the arc length of the line were obtained for static and dynamic conditions. The resultant tensions at hang-off point (A) and touchdown point (B) are 11109.56 kN and 4249.93kN respectively in the positive sense. In the dynamic case, the results of displacement of point A were obtained while velocity and acceleration were also evaluated in coordinate axes for lines P1 and S1. This differences in the results were noted which could be attributed to the method adopted. Orcaflex makes use of the approximate (Plank method) while the empirical method from experimental investigation is used in MATLAB. Consequently, the validation of the result for dynamic analysis was performed by comparing the simulated results with data published by other researchers. Agreement was noted in the result for effective loads with minimal variations which could be attributed to the difference in the coefficients of added mass, inertial and damping.

KEYWORDS: Mooring Lines, FPSO, Static and Dynamic Conditions, Hang-off, Touch-down

I. INTRODUCTION

The exploration of oil and gas resources at onshore as well as in shallow offshore waters is progressively moving into deeper waters due to the diminution of these resources. One of the major means of oil exploration at such deep water and ultra-deep water is by use of floating production storage and offloading (FPSO) system [1]. In Nigeria for instance, a number of FPSOs have so far been installed while many other production systems are anticipated. This is attributed to increased upstream activities.

The influence of extreme sea conditions on structures in deeper waters has been observed and research in this area is ongoing to give a pre-knowledge of the effects of waves and other environmental forces on the structures to enhance operational planning and future design decision.

The use of mooring systems continues its sustenance over time for deep water and/ or ultra-deep waters application. This is because of low long-term cost of maintenance and low technical know-how required compared to the other means. In the design analysis of FPSO and its' mooring and riser systems, the study of loads and motions of the systems (singled and coupled) are to be considered. It is a general practice to use initial condition data of the North Sea for the design of both FPSO and its' subsystems which may lead to high cost of production of the structures or incorrect analyses of the motions of the structures due to the fact that environmentally, the North Sea is an extremely harsh.

Several methodologies exist for the analyses of systems operating in shallow and deep waters. The recent and the most commonly used methodology is computational fluid dynamics which makes use of different numerical schemes in both the frequency domain and the time domain. It is noted that the existing equations used for analysis of these systems are basically evaluated in consideration of extremely hostile environment of the North Sea and the Gulf of Mexico (GOM) as both are the pioneer areas of oil and gas exploration. Finally, most equations used for analysis were derived from models of fixed offshore structures. Using the above stated models and methodology for the analysis of FPSO, mooring systems and risers in ultra-deep water and benign environments such as in West Africa may therefore be unrealistic.

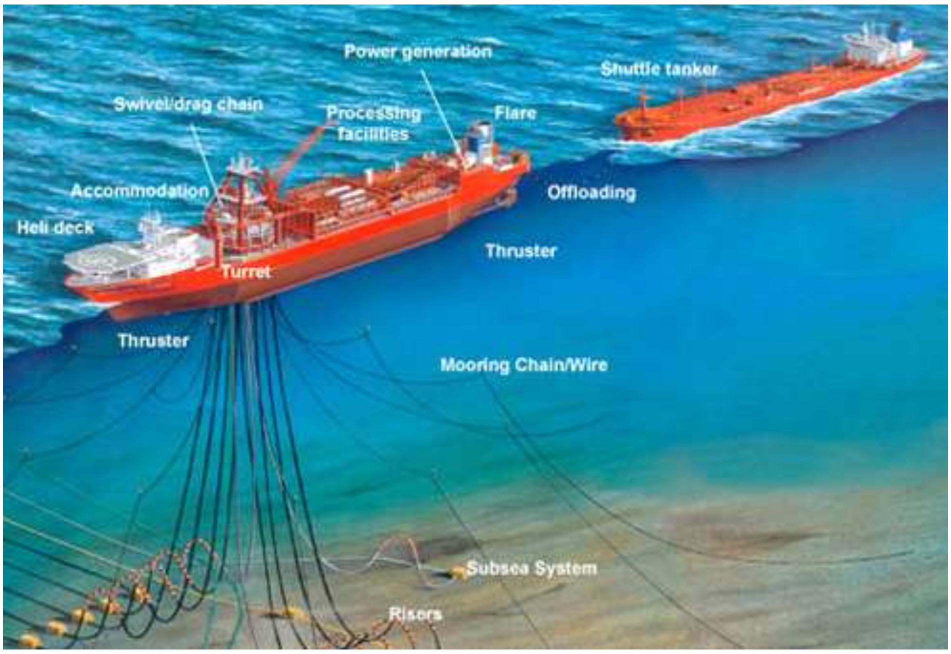

Plate 1.1: FPSO and Subsea System [2]

The primary focus of this study is to carry out analyses of load and motion responses of mooring systems of a known FPSO, X, and to analyze coupled FPSO-mooring system in consideration to the various West Africa ocean conditions.

This paper could also enhance the development of a robust computational model to facilitate the design and analysis of mooring system for any FPSO. Its procedural approach could enhance design optimization; and collective parametric study; and guarantee system reliability. These could be achieved by proper determination of prevalent motions and forces, within adequate safety margin for expected variations in environmental elements. The developed program is a preliminary step for the development of a more comprehensive design and analysis software for industrial applications and academic demonstration.

II. EXTENT OF PAST WORK

Mooring lines and SCRs are generally treated as cable structures. The analysis of cable structures has been of interest for a very long time such that investigators had begun to consider the dynamic response of a cable system since the early fifties. At the time, research was concerned mostly with the violent motion of towed speed measuring bodies in air and the effects of surface motion on ocean moorings. Since then, the rapid growth of ocean and offshore engineering applications has led to further development of steady-state dynamic cable system analysis methods [3].

Most recent application relate to the use of multi-component mooring systems in ultra-deep water to secure FPSOs as oil and gas exploration moves deeper into the seas. These applications require the ability to accurately predict the static and dynamic forces in the cable system resulting from loads imposed by gravity, current, and waves to ensure that a cost-effective cable system with adequate strength of minimum size and weight is achieved. Several techniques and methodologies have as a result, been developed over the years to achieve this [4].

Literature review of various researches reveals a great variety of approaches used for the analysis of cable and cable-like systems such as mooring lines and risers. A number of numerical modeling and analysis tools ranging from the catenary shape formulations to the finite element method (FEM) have been introduced. For cable structures having small displacements and a well-defined geometry such as guyed towers or suspension bridges, it is common to replace the cables by a series of short truss links and apply nonlinear finite element programs developed for solid structures to determine their tension displacement characteristics. However, for other types of cable structures such as mooring lines, catenary formulations are often applied to first obtain their static configurations before using either the FEM or the lumped mass method (LMM) to determine their final tension displacement characteristics. Most of the literature reviewed fall into either of these with only a few exceptions as discussed in the following paragraphs.

Skop and O'hara [5] presented a method of imaginary reactions which is globally convergent for the analysis of loaded cable array. The technique does not require the evaluation of derivatives and converges rapidly. There are two drawbacks to this method; the first is the requirement that the user makes a reasonable engineering guess as to the components of reaction at the redundant anchor, and the second is the requirement that there are no internal loops or cable segments with zero tension condition. Therefore, this method, like the FEM is more suitable to structures with small displacements and having a well-defined geometry before the start of the analysis.

Mooring lines and risers are subject to displacements of the same order of magnitude as the size of the structures themselves and their configurations are not known before the start of the analysis. Usually, a static analysis is conducted to find the static equilibrium configuration before carrying out a quasi-static or dynamic analysis. The dynamic analysis can be complicated by the occurrence of singular behavior such as line snapping and slacking. For these types of structures, the numerical method developed by Pevrot and Goulois [6] may be more appropriate, since from given loads and positions of the ends of a cable, the program can determine the complete geometry of the cable, its end forces, and its tangent stiffness matrix.

Van den Boom [7] in 1985, presented a lumped mass method (LMM) for the dynamic analysis of mooring lines. The mathematical model used was a modification of the lumped mass method by Nakajima and Motorola [8]. Results from the study show the importance of dynamic analysis for various mooring configurations and how dynamic tension amplification is strongly influenced by geometrical, material and drag nonlinearities.

Khan and Ansari [9] in 1986 derived the equations of motion including the allowance for anchor motion for a multi-component mooring line using the modified Lagrange’s equation. They also presented a numerical solution for different mooring configurations that can occur using the static configuration obtained from the catenary equations as the starting point [10]. The whole mass of the vessel as well as half of the mass of the topmost segment of the line was lumped at the attachment point of one line. This can create problems in the analysis since in practice the vessel is connected to several mooring lines from different directions. In addition, only external force due to current drag was considered on both line and vessel which will lead to underestimating the exciting force on the vessel.

Hugh [11] in 1995 studied the advances in steel catenary risers design and concluded that steel catenaries present economical design configurations for flow line /platform interfaces across a broad spectrum of platform types and environmental conditions. He argued that catenaries can be used as an alternative to conventional arrangements for both rigid and flexible pipes to predict response satisfactorily, provided that sufficient care is taken in the modeling and analysis. He further noted that in difficult conditions, such as high temperature and high-pressure applications, steel catenaries possibly present the only viable design alternative available.

Barltrop [12] in 1998 co-authored a two-volume guide for the design and analysis of floating structures which is an excellent reference for practical design and analysis mooring systems for both rigs and floating production systems. A finite element (FE) model for the coupled motion analysis of a turret-moored ship operating in 150m, 330m and 2000m water depths was presented by Ormberg and Larsen [13]. The results show that the traditional uncoupled approach may be severely inaccurate, especially for floating structures operating in deep waters.

Huang [14] discussed in detail the mooring system design considerations for FPSOs from the designer’s point of view. These include the selection of vessel size, design pretension, turret location, mooring pattern, line configuration and anchoring point. Chaudhury [15] in 2001, developed a methodology in the form of a FORTRAN computer program, code named NICDAF, to perform non-linear integrated coupled dynamic analysis of SCRs.

It was pointed out in Kazuo et al. [16] that the dynamics of the entire system comprising of the FPSO, mooring system and risers affect the number and dimension of the line. A time domain simulator called Dynsim was therefore proposed. Several models of the coupled system were studied; and three models were chosen by the investigators to enhance the findings. Hydrodynamic forces especially, the damping and the wave drift forces were identified in other works, and was studied in

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surge motion mostly. Dynasim was therefore used for the implementation of the hydrodynamic forces (hull inertia and damping forces and moments as well as current loads) in the surge, sway and yaw motions for validation of numerical results with experimental test.

III. MATERIALS AND METHODS

To analysis the behaviors of the mooring lines/ risers and FPSO, difference regimes are considered. Static regime is used when the motion responses of a moored FPSO are outside the wave exciting frequency range of the mooring system [1]. When the motion responses of the moored vessel are small or within the wave exciting frequency range, dynamic regime is used. Here, the lines' dynamic behaviors are included and the inertia masses of the lines are not neglected. The next section discusses the static regime of the moored FPSO.

- **Static Load Analysis**

Load analyses are taken in the following sections for the cables and FPSO.

- **Current Loads**

Using equation (3.1), the current load can be obtained. The variables of the FPSO are used in this equation in combination with the environmental constants such as density and current velocity.

(3.1)

- **Wind Loads**

Similar empirical equations were used in the calculation of wind loads in longitudinal, lateral and yaw motions respectively. A multi-component mooring line is shown in Figure 3.1, where the attachment point, n +1, of the mooring line, is connected to the FPSO, and point 1 is connected to the seabed or to the anchor head.

The sum of forces on the elementary component can be analyzed in both tangential and normal directions of the line as shown in (3.2) and (3.3).

(3.2)

(3.3)

- **Generalization of Multi-Component Mooring Line Equations**

The derivation of multi-component equations for mooring line and catenary risers is emphasized in [1]. Based on this reference, the following equations (3.4 to 3.6) are reformulated for the determination of the motion of a point on the line.

(3.4)

(3.5)

(3.6)

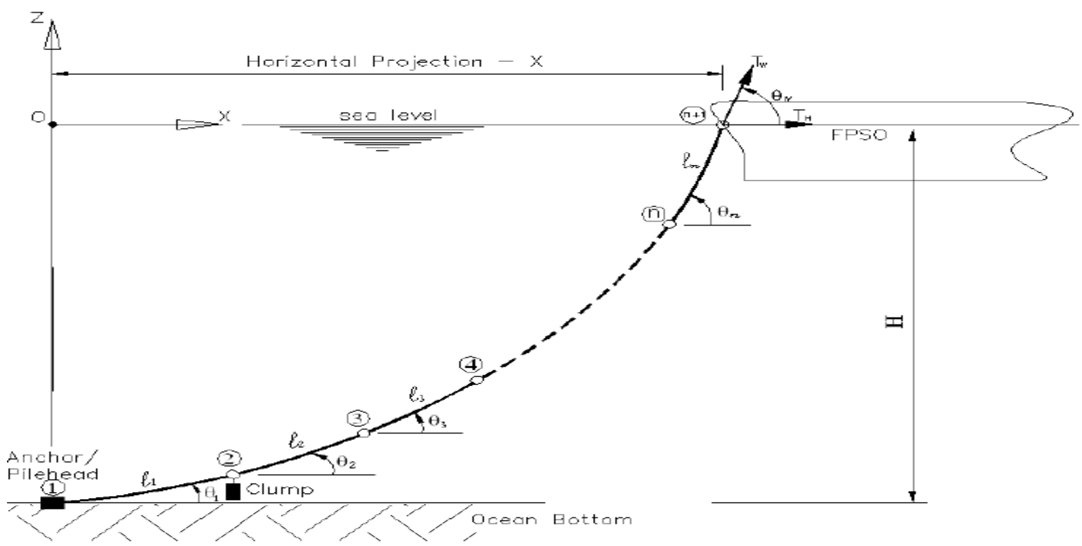

Figure 3.1: Hydrodynamic Forces (D and F) Per Unit Length in the Normal and Tangential Directions and the Tension [1]

- **Derivation of Dynamic Mooring System of Equations**

When the wavelength L, is greater the diameter, D of the line, then the dynamics of the mooring lines and risers becomes extreme valuable [17]. This line can be modeled as a slender structure

Khan & Ansari [18] in 1986, applied the modified lagrange's equation for cable motion permitting the employment of holonomic constraints [1]. This derivation is explained below. According to [1]

(3.7)
Where, T = the total kinetic energy of the system
U = the potential energy of the system
= the virtual work of non-conservative forces acting on the system.
( ) = symbol denoting the first variation or virtual change in the quantity
t_1, t_2 = times at which the configuration of the system is known
The generalized coordinates are defined as any set of N-independent quantities which are sufficient to completely define the position of every point within an N-degree of freedom [1]. By substitution of (3.7) into (3.8) and integrating the terms involving by parts and neglecting the second derivative of T give,

(3.8)

In general, (3.8) can only be satisfied when the terms in the square bracket vanish for each value of i since the coordinates p_i and their variations (i = 1,2,…,N) must be independent.

- **FPSO RAO**

The RAOs of the vessel were generated in ANSYS AQWA, with the met-ocean condition of West African waters whose environment parameters are given in Table 3.1.

Table 3.1: West Africa Sea Condition [19]

Parameters	Return Period		
	1-yr	100-yr	1000-yr
Swell Hs (m)	3	4	4.5
Swell Tp (s)	13.5	15.5	16
Associated Sea Hs (m)	1	1	1.5
Associated Sea Tp (s)	6	6	6

- **Principal Particulars of the FPSO and Mooring Lines Used**

Table 3.2 shows the primary parameters of the vessel while Table 3.3 shows the particulars of mooring lines used in modeling. The development of the oil field is based on subsea wells connected to a FPSO facility and stabilized crude oil export via oil tanker using an offloading buoy.
The mooring lines consist of four components, namely; the top chain, spiral stranded wire, bottom chain and anchor chain.

The lengths and diameters of each segment of the line are (155 m & 157mm), (2220 m & 14 mm), (334 m & 147 mm) and (25 m & 147 mm) for top chain, spiral stranded wire, bottom chain, and anchor chain respectively.

- **Modeling with OrcaFlex**

OrcaFlex is a fully 3D non-linear time domain finite element program capable of dealing with arbitrarily large deflections of the flexible from the initial configuration. A lumped mass element is used which greatly simplifies the mathematical formulation and allows quick and efficient development of the program to include additional force terms and constraints on the system in response to new engineering requirements [20].

- **Orcaflex Software Environment**

The vessel's RAOs in all the six-degree of freedom were imported into Orcaflex for further analyses. Orcaflex software was therefore used for motion and load response analyses. Figure 3.2 shows the different views of the models developed in Orcaflex for the analysis. After modelling of the FPSO and mooring lines, and setting environmental parameters, Orcaflex was ran for both static and dynamic cases of the mooring responses.

Table 3.2: Principal Particulars of FPSO, X

Item	Value	Unit
Gross Tonnage	219830	T
Deadweight	499155.6	T

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Length overall	330	M
Beam	61	M
Depth	33.5	M
Tropical Draught	25.81	M
Block coefficient	0.96	-
Year	2017	N/A

Table 3.3: Mooring Particulars

Item	Value	Unit
Number of sections on each line	4	-
Total length	2734	M
Number of clusters	4	-

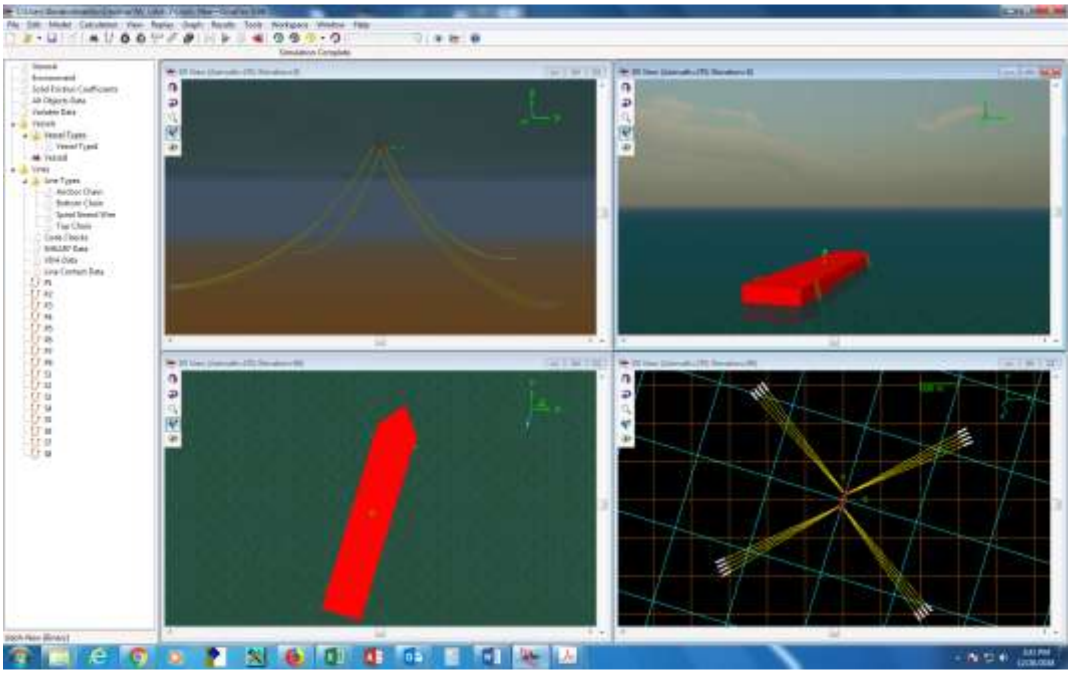

Figure 3.2: Plan and Elevation Views of an FPSO and Mooring Line

IV. RESULTS AND DISCUSSION

- **Static Analysis of the Mooring Lines**

Results for static analysis are shown in Tables 4.1 and 4.2 indicating the full static components of the mooring line P1 at endpoints A and B respectively. Each line of the mooring lines was segmented into 4 primary line types or sections which include the top chain, spiral stranded wire, bottom chain and anchor chain.

The nodal natural periods were obtained for the four sections and their values are (0.02077, 0.0211, 0.0216, and 0.0241) axial periods for top chain, spiral stranded wire, bottom chain and anchor chain respective and (0.2598, 0.269, 0.0436, and 0.0464) lateral periods for top chain, spiral stranded wire, bottom chain and anchor chain respectively.

Table 4.1: Results of Force at End A of P1

Parameter	Value
Total Force (kN)	11109.56
End Tension (kN)	-9930.43
End Shear Force (kN)	4980.93
End Curvature (rad/m)	0.552
End Force Azimuth (deg)	127.15
End Force Declination (deg)	153.36
End Force Ez-angle (deg)	153.36
End Force Exy-angle (deg)	86.15

Table 4.2: Results for Effective Tension at End B of PI

Parameter	Value
Total Force (kN)	4249.93
End Tension (kN)	-105.56
End Shear Force (kN)	4248.62
End Curvature (rad/m)	0.253
End Force Azimuth (deg)	127.15
End Force Declination (deg)	91.42
End Force Ez-angle (deg)	91.42
End Force Exy-angle (deg)	127.15

- **Results of Dynamic Analysis of the Mooring Line**

The results for dynamic behavior of the line P1 were obtained in terms of displacement, velocity and acceleration in three coordinate axes which showed that at initial time; the displacement increases but tends to stabilize with time which is as expected in hydrodynamic analysis. These results show that the motion of line at the attachment point A cannot become zero which is true for any floating body.

Figure 4.1 shows the end force at attachment point or hang-off point A verse time. The average end force at A of the line P1 is 13674 kN. The values of end force gradually increase in magnitude up to the mid of the successive crest as time increases at about 5sec and decrease down. The significant of this graph is that it helps to know the mooring end force at end A as time progresses.

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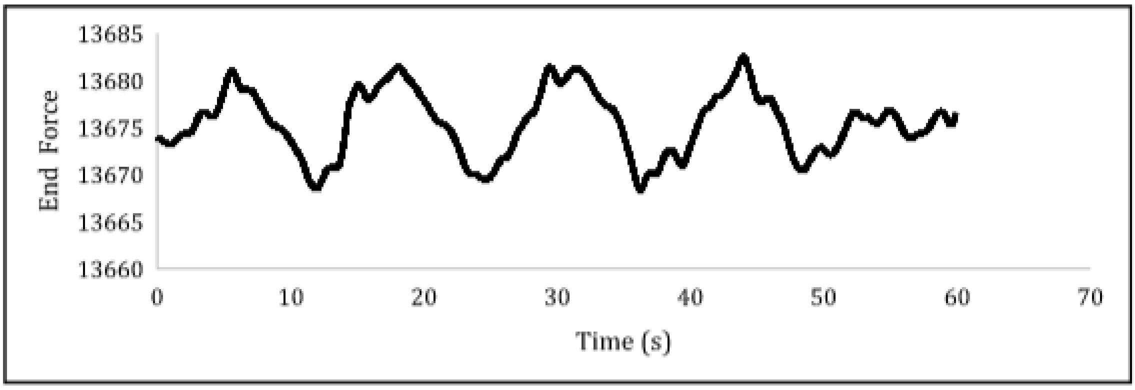

Figure 4.1: End Force, at Attachment point A, Verse Time

Figure 4.2 shows the mooring effective force at end B verse time. The maximum effective force at end B of the mooring is experienced at time 0sec with gradual decrease in magnitude at successive crest as time increases. The significant of this graph is that it helps to know the mooring effective force at end B as time progresses. The sense of the end force at B is negative and decreases as time increases. Figure 4.3 shows the velocity at touchdown point B which shows the motion of the line at that point. As expected, the velocity is small and can be negligible with a wave form presentation.

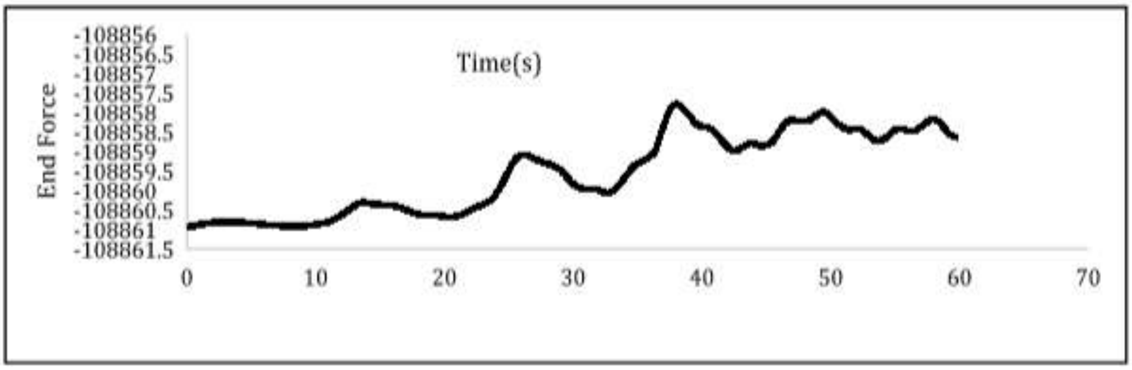

Figure 4.2: Velocity at End B

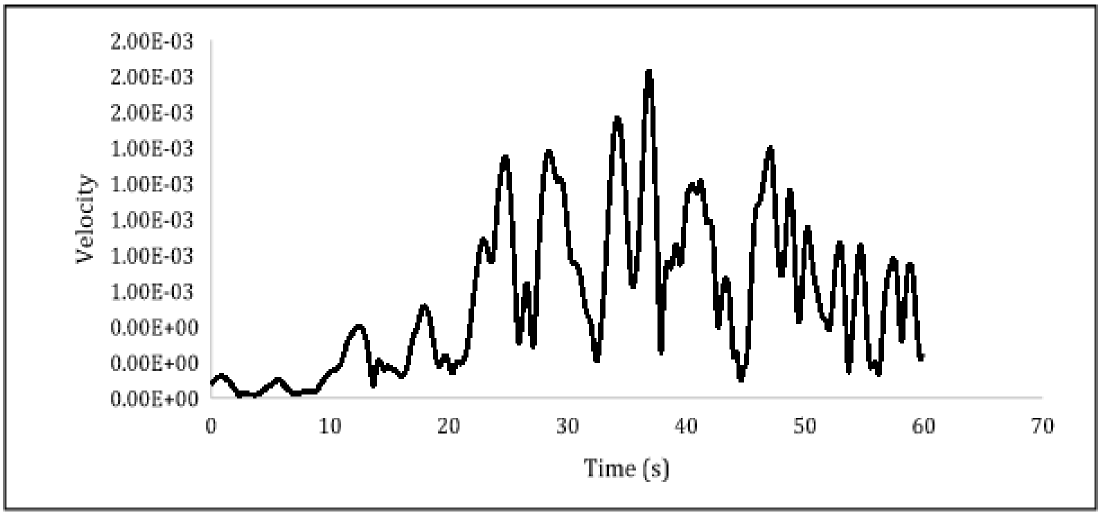

Figure 4.3: Velocity of Touchdown Point against Time B Verse Time

Figure 4.4 shows the mooring relative velocity at touchdown point verse time. The velocity at touchdown point of the mooring is the movement experienced by the mooring line at the point of interaction with the seabed. The relative velocity at touchdown point of the line is zero. The significant of this graph is that it helps to know the mooring relative velocity at touchdown point as time progresses.

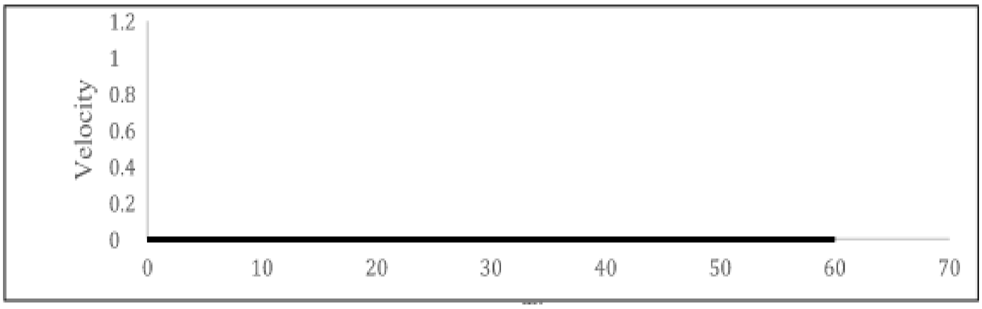

Figure 4.4: Velocity of End Point B Verse Time

Figure 4.15 shows the mooring line velocity at end B verse time. Sine, the relative velocity at end B was approximately equal zero as time progresses. This is due to the fact that the wave amplitude tends to affect the mooring line at point A (at sea level) alone and have minimal or no effect at point B (at seabed).

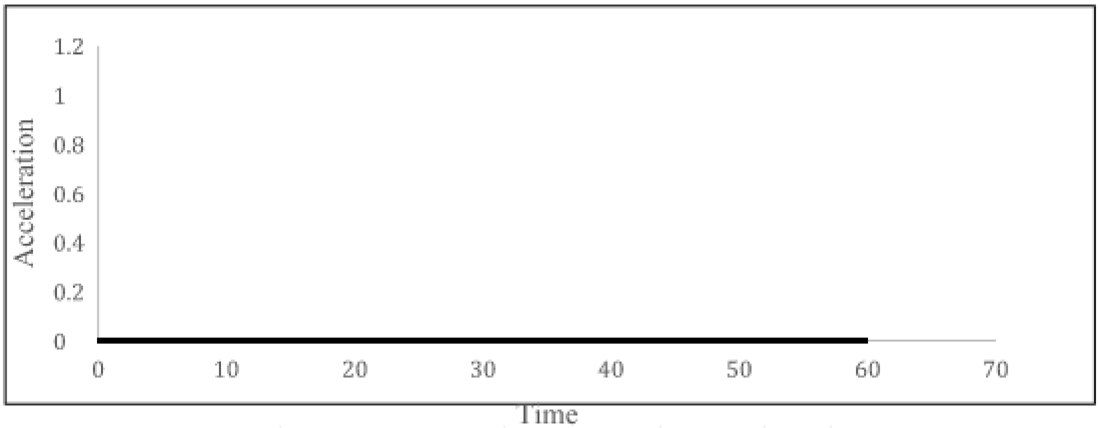

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Figure 4.5: Acceleration of End Point B against Time

- **Validation of Results for Dynamic Analysis**

The comparison of the results obtained in this paper for numerical calculation of the dynamic characteristics of a multi-component mooring line is represented by 16 segments for line P1. P1 was remodeled with details from Table 4.3 which is made up of homogeneous steel chain with stud-less link. In the present model, a clump weight was attached to line at a horizontal distant of 17.56 m. The weight of the clump is 1.823kg. The anchor point is traditionally fixed to the seabed, and it is in coincident with the origin of the line P1. The attachment, end A, was set to lie on the free surface.

The water depth was set to 3 m above the seabed which is considered to be flat and the total horizontal excursion of the attachment point at the position of static equilibrium was taken as 17.56m. Figure 4.27 shows this comparison of the present work as modeled in Orcaflex with published data. Though concession was observed there were some variation in the result which could be caused by the coefficients of added mass, inertial, and damping in the three methods.

Table 4.3: Principal Particulars of Chain [1]

Particulars	Values	Units
Weight per Length in water	0.1938	kg/m
Weight per Length in air	0.222	kg/m
Equivalent Diameter	0.599	Cm
Volume per Length	28.2	cm^3 /m
Modulus of elasticity	2.15×10^6	kg/cm

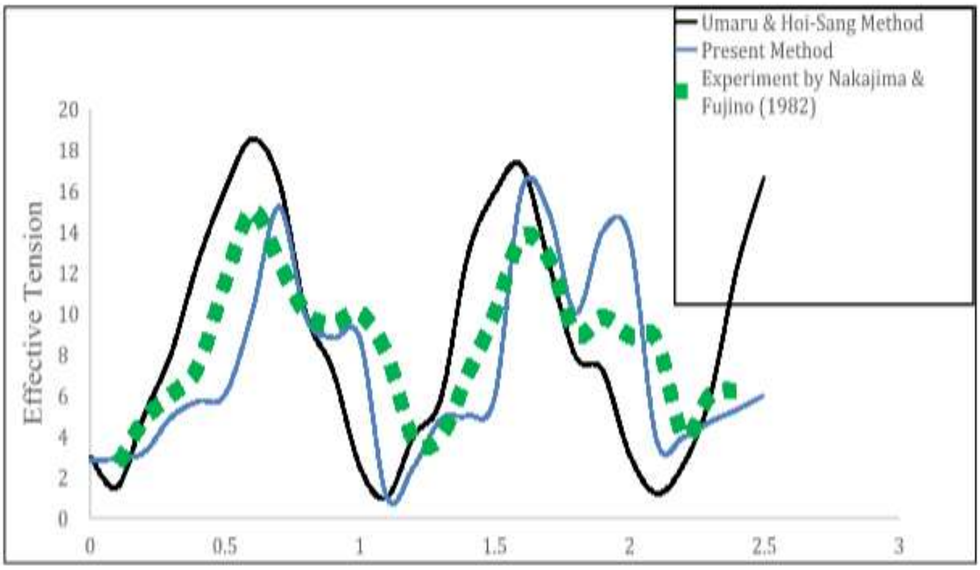

Figure 4.6: Dynamic Horizontal Tension at Attachment Point

V. CONCLUSION

The behavior of subsea systems especially mooring and FPSO is important for safety and design of the structures or system. In this work, the use of a computational tool has been investigated and results presented in both static and dynamic conditions using real data collected from field survey. The data was use to run analysis on a FPSO mooring using the Orcaflex and the results from the Orcaflex was validated using MATLAB.
The results of FPSO motions in 6-degree of freedom due to environmental loads were obtained and used in the analysis of dynamic behaviour of the mooring lines. Also, the coupling of the FPSO motions due to wave with mooring line resulted in the determination of effective tension along each line. For line labeled P1, the results are given in Figures 4.1 to 4.5.

Taking a point on the line P1 at the seabed indicates there is approximately zero relative motions of the line since the point is fixed or anchored to the seabed. This shows that the analysis using OrcaFlex has a model that is apt and close to reality. It is seen also from the graphs plotted in this work that the point A on the line seems to have high motion compared to other points along the line.

The coupling of wave phenomena or responses to the behavior of mooring line using appropriate wave model has greatly enhanced solution to proper analysis of the lines but still requires comparative study to ascertain the fact that Ochi wave model is the optimal wave model for analysis of systems used in WA waters. The dynamic signature results were compared with other published work to ensure accuracy and validation of the software.

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