

Numerical Simulation of Floating-Production, Storage, and Offloading System Mooring Dynamics: A Simplified Methodology



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ABSTRACT: This study presents a simplified methodology designed to enhance efficiency and clarity by minimizing procedural complexity without compromising the accuracy and reliability of outcomes. Marine cable systems face operational challenges due to unresolved dynamic equations and quadratic hydrodynamic drag from environmental factors. The study applied numerical solutions to Mooring systems Dynamics validated against those from ANSYS. The hydrodynamic responses of the FPSO and its mooring system were analyzed. Results indicate that the system experiences dynamic loading, with tension forces in the mooring cable ranging from 188,873.27 N to 397,107.78 N. The mooring sum forces exhibit fluctuations, reaching a minimum of -78,858.34 N and a maximum of -31,710.57 N in the global X direction. The heave direction, forces ranged from -389,218.63 to -186,192.23 N. The study found that application of advanced meshing techniques, sensitivity analysis, and integration of real-time environmental data with advanced nonlinear dynamics, can address time-dependent problems in mooring systems to improved simulation-accuracy. This study contributes to the comprehensive understanding of mooring system dynamics, providing valuable insights into the design, operation, and safety of FPSOs in challenging marine environments.

KEYWORDS: unresolved dynamic; hydrodynamic drag; Mooring Systems; Operational Challenges; time-dependent problems; Procedural Complexity.

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I. INTRODUCTION

In recent times, there has been a consistent upward trend in the worldwide need for hydrocarbon products, and this growth is projected to persist over the coming years (Ahmad and Zhang, 2020). Exploration of new deposits and other energy sources is necessary due to the continuous depletion of terrestrial petroleum (Qiu *et al*, 2024). Oil, natural gas, and hydrates are among the many ocean minerals, which comprise more than 70% of the Earth's surface but are still mostly unexploited (Meng, Kloul and Rauzy, 2018). Due to their potential to supply the world's expanding energy needs, offshore oil and gas reserves are taking center stage in energy production.

Floating production storage and offloading (FPSO) units are all-inclusive offshore facilities for crude oil processing that include oil-water separation, oily wastewater treatment, heating, power generation, oil product storage and offloading,

housing, and an integrated production command system (Meng, Kloul and Rauzy 2018). The components of FPSO include a hull system, a unique oil offloading system, a production process system (module system), and a specific mooring system. To install the module system, modules must be weighed, transported, lifted, and connected to cables and pipes. The lifting procedure necessitates greater technical accuracy and poses greater safety concerns (Rho *et al*, 2013). With the oil industry's transition from shallow to deep-sea oil exploration, the importance of mooring systems and the selection of an appropriate type have come to the forefront (Wang, 2022).

According to Jiang, *et al*, (2023), there are two common alternatives of mooring systems: catenary and taut mooring systems. Catenary mooring systems are particularly well-suited for shallow waters, primarily due to their cost-effectiveness and their advantages in terms of performance Jiang *et al*, (2023). In contrast, taut mooring systems excel in

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deeper waters, yet they exhibit limitations when dealing with ultra-deep conditions (Jiang *et al*, 2023). The continuous tension in taut systems renders them vulnerable to snapping during severe weather conditions, necessitating the use of high-quality materials, robust system integrity, and reliable technology (Darling and Schmidt, 2024). Conversely, catenary mooring systems present an extended design service life and offer enhanced flexibility due to the reduced continuous tension exerted on the mooring lines (Wang 2022). These characteristics make catenary systems a pragmatic choice for specific scenarios (Amaechi, Wang and Ye 2021).

A crucial hurdle design engineers will cross involves locating extensive offshore oil and gas reserves, frequently in isolated regions where infrastructure is absent (Umana *et al*, 2021). In response to this challenge, design engineers have risen to the occasion by devising cutting-edge technologies (Umana *et al*, 2021). The combination of FPSO with mooring systems has emerged as a pivotal solution among these innovations, thus playing a central role in the offshore energy domain (Yuanhui *et al*, 2018). A mooring system is used to maintain the FPSO vessel's position in the desired region (Yuanhui *et al*, 2018). However, the traditional mooring systems, suitable for shallow waters (depth below approximately 100 m), are generally considered inadequate for deep water applications (Barton *et al*, 2017). What's more, the catenary mooring system covers a more extensive water area which seriously affects the laying of pipes and the mooring of other FPSO vessels (Barton *et al*, 2017). To address these issues, the mooring system with buoys is presented (Barton *et al*, 2017). When FPSOs are paired with mooring systems that link them to the seabed, they encounter high dynamic environmental forces, including wind, currents, and waves (Simonet *et al*, 2020). These forces can give rise to unwelcome movements, underscoring the necessity of securing FPSOs to fixed positions to minimize these impacts. Although anchoring mitigates these movements, it cannot entirely eradicate them, underscoring the need for systematic assessments to maintain station-keeping and ensure the safety and cost-effectiveness of operations (Ćatipovi, Ćorić and Radanović, 2011). The pre-design assessment encompasses the generation of sufficient data on restoring forces to counteract environmental disturbances, with the stiffness of materials playing a pivotal role in shaping the mooring system's design, aimed at mitigating excessive tension and averting damage to risers during their operational service life (Simon *et al*, 2020).

A mooring system plays a vital role in anchoring floating structures and vessels to a fixed point or location (Rui *et al*, 2024). It is a complex assemblage of components and materials designed to resist the dynamic forces exerted by the environment, such as wind, waves, and currents on an FPSO system (Rui *et al*, 2024). Mooring systems are important for structures located in proximity to the shoreline, including floating breakwaters and aquaculture cages (Guo, Mohapatra and Soares, 2020). These systems have a pivotal role in ensuring the safety and stability of such structures. When designing mooring systems, a delicate balance must be struck between flexibility, which allows for substantial displacements, and strength, which enables them to withstand

the forces imposed by the water while restricting the motion of the structure itself (Wang and Yu, 2022). Accurately assessing the movement of moored structures and the resulting tension forces in the cables is essential for achieving a design that is both secure and cost-effective (Amaechi *et al*, 2022). In situations where floating structures undergo considerable movement, the dynamics of mooring systems can have a significant impact on how they respond to environmental forces (Rui *et al*, 2024). Given the intricacies of the underlying nonlinear equations governing these dynamics, numerical methods are frequently employed to identify comprehensive solutions for mooring system behaviour (Zeng, *et al* 2024).

The inherent challenge lies in accurately determining the damping effect on the mooring system, especially due to drag, as it significantly influences the dynamic response amplitude. To address this, the nonlinear drag is commonly approximated through statistical linearization techniques. This enables an approximate frequency-domain analysis using finite-element techniques. Analyzing a system with non-proportional damping requires a complex eigenvalue analysis, further demanding a considerable number of elements for accurately computing the linearized drag damping along the cable's length, (Geuzaine *et al*, 2023). Consequently, coupled cable and vessel assembly analyses significantly increase in complexity (Geuzaine *et al*, 2023). In some cases, a substantial part of the cable rests on the ocean floor, causing it to alternately lift and drop under dynamic conditions. This behaviour adds complexity by introducing time-dependent dynamics to the system (Ruzzo *et al*, 2021). Moreover, interactions between the seabed and the cable introduce frictional forces that influence the cable's dynamic response.

There are several difficulties with mooring dynamics while operating FPSO systems in deep-sea conditions (Ali *et al*, 2020). Waves, currents, and wind all exert complicated hydrodynamic stresses on the mooring system that attaches the FPSO to the bottom. These dynamic interactions might put the FPSO's stability and safety at risk by creating excessive stresses and structural vibrations (Ali *et al*, 2020). The current techniques for modelling FPSO mooring dynamics are frequently complex and computationally demanding, requiring a significant amount of time and other resources to execute (Nikkhah, Fernandes and Caprice 2023). This complexity may make it difficult to analyze and optimize mooring systems for FPSO units that are in use (Nikkhah *et al*, 2023). Additionally, the shortcomings of these approaches could not adequately take into consideration the many dynamic environmental variables seen in deep-sea locations (Tahar and Kim, 2003).

Therefore, the issue at hand is to develop a simplified numerical approach and compare results with that from ANSYS AQWA for simulating underwater mooring dynamics in deep-sea settings, adapted especially to the special difficulties faced by FPSO systems at such great depth. The practical examination of mooring systems and their effect on the security, stability, and operational effectiveness of FPSOs could be made possible by this technique, to, strike a compromise between accuracy and computing efficiency. To address this mounting demand, there is a need to carry out an

investigation, inventive study, and innovative strategies to accelerate the development and improvement schemes as reliable solutions to the identified problems in existing FPSO systems. The identified inadequacies in the current method and practices of modelling FPSO mooring dynamics systems constitute a gap in scientific knowledge which thus requires and necessitates this study to close the gap.

This research project aims to simulate and analyze the underwater mooring dynamics of FPSO systems in deep-sea environments using a simplified numerical method in terms of Complexity of the equation solved and computational time spent in arriving at solution. The specific objectives are to: the development of alternative numerical techniques for FPSO mooring dynamics, considering factors such as hydrodynamic loads, environmental conditions, and structural responses.

II. THEORETICAL ANALYSIS

The dynamic behaviour of an FPSO and its mooring system is governed by strongly coupled, multi-physics interactions: nonlinear wave-body hydrodynamics, viscous damping and drift forces, large-displacement geometric nonlinearities of catenary or taut mooring lines, and structural elasticity in fairleads and chain/rope elements. Time-domain coupled simulations that resolve these interactions are the most physically complete approach, and recent studies show that including hull elasticity and fully coupled hydro elastic effects can materially change peak tensions and fatigue load spectra compared with rigid-body approximations. This coupling explains why designers commonly rely on time-domain, finite-element or finite-difference mooring solvers integrated with hydrodynamic databases (or CFD) to capture second-order drift and nonlinear transient responses.

A simplified numerical methodology aims to retain the essential physics that control station-keeping performance while reducing computational cost and model complexity so it is practical for parametric design, probabilistic assessment, and optimization. Typical simplifications include: (a) representing mooring lines with reduced-order elements (discretized catenary segments or modal approximations) that capture geometric stiffness and mass without full continuum resolution, (b) using frequency-domain or quasi-steady hydrodynamic databases (RAO + quadratic drift) to replace fully coupled CFD for many sea states, (c) linearizing fairlead/hull coupling around an operating point or using lumped elastic springs to represent structural flexibility, and (d) applying surrogate or data-driven models (e.g., machine-learning predictors) for rapid line-tension or fatigue estimates. Such hybrid approaches have been validated for bracket/fairlead sizing and for predicting tension envelopes in industry-scale problems, and they offer a pragmatic trade-off between fidelity and throughput for design iterations.

Nevertheless, simplified frameworks must explicitly acknowledge and where possible quantify their limitations. Reduced models can underpredict local transient peaks (e.g., snap loads or collision with risers), misrepresent

viscous damping effects in steep waves, and omit important multi-directional coupling when single-axis or decoupled assumptions are used; these shortcomings are particularly consequential for fatigue life and extreme-event reliability. Best practice therefore combines the simplified pipeline with targeted high-fidelity checks (select CFD-FE coupled runs, physical model tests, or full time-domain mooring FEM simulations) and statistical calibration against measured field data where available, and retains conservative safety margins for fatigue and ultimate strength assessments. When material choice (steel vs. synthetic rope) or taut versus catenary layouts matter, sensitivity studies using the simplified model guide which cases require full high-fidelity follow-up. Validated, hierarchical workflows of this type have been demonstrated to produce reliable lifetime and performance predictions while substantially reducing computational cost during the early design and probabilistic stages.

III. MATERIALS AND METHODS/METHODOLOGY/EXPERIMENTAL PROCEDURE

The methodology adopted in this study provides a structured framework for developing and validating a simplified numerical approach to predict the dynamic behaviour of Floating Production, Storage, and Offloading (FPSO) system mooring configurations under realistic ocean environmental loading. The method integrates fundamental principles of hydrodynamics, structural mechanics, and numerical modelling to capture the coupled interactions between vessel motions and mooring line responses, while reducing computational complexity compared to fully coupled high-fidelity simulations. The approach involved defining representative environmental conditions, selecting appropriate mathematical formulations for wave-structure-mooring interactions, implementing these formulations in a computational model, and validating the results against available experimental or high-resolution simulation data. This systematic methodology ensured a balance between physical accuracy and computational efficiency, enabling its application in preliminary design, operational planning, and risk assessment of FPSO mooring systems. The step-by-step procedure is organized and presented in the subsections as follow:

A. Modelling of cable system

The dynamic performance of marine cables is profoundly nonlinear owing to their geometric structure and fluid drag (Zhang et al, 2024). Typically, these complexities can only be addressed through numerical methods. Mainstream numerical approaches encompass the use of hyperbolic equation solvers and the lump-mass-and-spring techniques. In previous studies by Holmes (2022), the cables were represented as a continuous system, leading to partial differential equations, which are solved using finite difference methods or other suitable techniques. On the other hand, the latter method involved the cable's discretization from the initial stages of modelling. It substitutes the cable with point masses connected by massless finite-length elements. This approach results in a set of

governing equations derived from Newton's law of motion in the form of ordinary differential equations, solvable through various numerical algorithms. These methods aim to capture the intricate dynamics of marine cables influenced by their design and the surrounding fluid dynamics in a more realistic three-dimensional space.

The lumped mass method, initially introduced by (Walton, 1996), finds common application in the realm of flexible cable dynamic analysis due to its straightforward conceptual basis, uncomplicated algorithm, and ease of implementation which is illustrated in Figure 1.

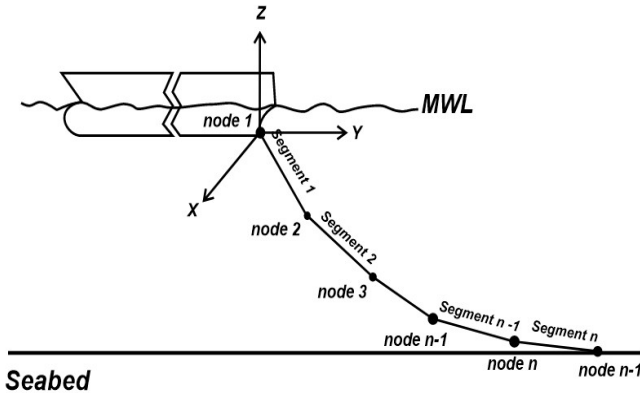


Figure 1: Lumped mass cable model arranged in the XYZ plane (Walton, 1996)

According to Newton's second law equation (1), the product of the mass of an element and the i th node of the acceleration are equations for the external and internal forces acting on the node i . such that:

$$M_i \ddot{x}_i = F_i \quad (1)$$

Where;

M_i is the mass matrix of the element

\ddot{x}_i is the acceleration of the i th node

F_i refers to all the forces (external and internal) acting on the node i . The internal forces include the elastic force and damping force between the nodes, while external forces include buoyance, hydrodynamic loads, etc, in the underwater application.

By integrating equation (1) over time, we can obtain the velocity (v) and displacement (s) equations (2) and (3)

$$M_i \dot{x}_i = \int F_i dx \quad (2)$$

$$M_i x_i = \int \dot{x} dx \quad (3)$$

The governing simultaneous equations (2 and 3), we can substitute the force integral into the velocity and then into position, you can express position in terms of a double integral of force:

$$x_i(t) = \frac{1}{m_i} \int \int F_i(t) dt dt + C_1 t + C_2 \quad (4)$$

This equation (4) can be solved using numerical solution methods. Now, to apply the Runge-Kutta method, we need to rewrite the fourth-order Runge-Kutta scheme for ordinary differential equations with initial values. Let's denote (velocity) and (displacement).

$$V = -\dot{y}(t) \text{ or } \dot{z}(t) \text{ and Displacement} = y(t) \text{ or } z(t) \quad (5)$$

Where $V \rightarrow$ Velocity

$$(t) = \frac{1}{m_i} \int \int F_i(t) dt dt + C_1 t + C_2 \quad (6)$$

Where:

C_1 : initial velocity

C_2 : initial position

$$\text{Where the expression } F(t) = \frac{1}{2} \rho C_D D |u(t) - x'(t)| (u(t) - x'(t)) + \rho C_M \frac{\pi D^2}{4} \frac{du(t)}{dt}$$

is the Morrison equation for hydraulic resistance and $waveHeight \times \sin\left(\frac{2\pi t h}{numSteps \times h}\right) + current\ Velocity$ represent the external forces.

where $F(t)$ = Total hydrodynamic force per unit length of the member [N/m]

ρ = Fluid density [kg/m³]

D = Diameter of the cylindrical member (structure) [m]

$u(t)$ = Fluid particle velocity relative to the structure [m/s]

$\dot{x}(t)$ = Structure velocity [m/s]

$\frac{du(t)}{dt}$ = Fluid particle acceleration [m/s²]

C_D = Drag coefficient (dimensionless, depends on Reynolds number and surface roughness)

C_M = Inertia coefficient (dimensionless, accounts for added mass effect)

$\frac{\pi D^2}{4}$ = Cross-sectional area of the cylinder per unit length [m]

When applying the fourth-order Runge-Kutta scheme, we get the following equations:

$$k_1 = hz(t) \quad (7)$$

$$l_1 = h \left(\frac{\text{externalForce}(t) - \frac{1}{2} \text{dragCoefficient} \times \text{densityWater} \times z(t)^2}{\text{additionalMass}} - z(t) \right) \quad (8)$$

$$k_2 = h \left(z(t) + \frac{l_1}{2} \right) \quad (9)$$

$$l_2 = h \left(\frac{\text{externalForce}(t) - \frac{1}{2} \text{dragCoefficient} \times \text{densityWater} \times \left(z(t) + \frac{l_1}{2} \right)^2}{\text{additionalMass}} - x(t) + \frac{k_1}{2} \right) \quad (10)$$

$$k_3 = h \left(z(t) + \frac{l_2}{2} \right) \quad (11)$$

$$l_3 = h \left(\frac{\text{externalForce}(t) - \frac{1}{2} \text{dragCoefficient} \times \text{densityWater} \times \left(z(t) + \frac{l_2}{2} \right)^2}{\text{additionalMass}} - \left(x(t) + \frac{k_2}{2} \right) \right) \quad (12)$$

$$k_4 = h \left(z(t) + \frac{l_3}{2} \right) \quad (13)$$

$$l_4 = h \left(\frac{\text{externalForce}(t) - \frac{1}{2} \text{dragCoefficient} \times \text{densityWater} \times \left(z(t) + \frac{l_3}{2} \right)^2}{\text{additionalMass}} - \left(x(t) + \frac{k_3}{2} \right) \right) \quad (14)$$

$$x(t+1) = x(t) + \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4) \quad (15)$$

$$z(t+1) = z(t) + \frac{1}{6} (l_1 + 2l_2 + 2l_3 + l_4) \quad (16)$$

Equations 15 and 16 are the fourth-order Runge-Kutta method used to numerically solve the equations of motion for each node. The variables $k_1, l_1, k_2, l_2, k_3, l_3, k_4, l_4$ are intermediate values calculated at each time step, and $x(t+1), z(t+1)$ are the updated displacement and velocity for the next time step. The mathematical expression from equations 1 to 16 was implemented in MATLAB

software in Table 1 (being values that are input to the MATLAB code) to reduce the solving time and in order to improve accuracy while solving the equations and the results are presented and discussed in section IV (Result and Discussion).

Table 1 Hydrostatic Properties

Structure	FPSO					
Hydrostatic Stiffness						
Center of Gravity (CoG) Position:	X:	-9.29 m	Y:	0. m	Z:	-5.5500002 m
		R		RX		RY
Heave (Z):		1.29111e8		1.9039047		-611968.63
		N/m		N/°		N/°
Roll (RX):		-109.0857		1.90413e8		28.300827
		N.m/m		N.m/°		N.m/°
Pitch (RY):		-35063220		28.300827		1.5766e10
		N.m/m		N.m/°		N.m/°
Hydrostatic Displacement Properties						
Actual Volumetric Displacement:		226871.59 m ³				
Equivalent Volumetric Displacement:		302451.69 m ³				
Center of Buoyancy (CoB) Position:	X:	-9.4644651 m	Y:	3.8193e-4 m	Z:	-9.6037989 m
Out of Balance Forces/Weight:	FX:	3.0117e-9	F	8.566e-8	FZ:	-0.2498887
			Y:			
Out of Balance Moments/Weight:	MX	2.8718e-4 m	M	0.1308639 m	MZ:	8.1837e-7 m
	:		Y:			
Cut Water Plane Properties						
Cut Water Plane Area:		12844.547 m ²				
Center of Floatation:	X:	-9.0184259 m	Y:	8.449e-7 m		
Principal 2 nd Moments of Area:	X:	2005051.5 m ⁴	Y:	90784632 m ⁴		
The angle between Principal X-Axis and Global X-Axis:		1.0601e-7°				
Small Angle Stability Parameters <i>concerning Principal Axes</i>						
CoG to CoB (BG):		4.0537987 m				
Metacentric Heights (GMX/GMY):		4.7840261 m		396.10486 m		
CoB to Metacentre (BMX/BMY):		8.8378248 m		400.15866 m		
		1.90413e8		1.5766e10		
Restoring Moments (MX/MY):		N.m/°		N.m/°		

The hydrostatic results presented in Table 1 as generated in ANSYS Aqua. Table 1 also provides insights into the static equilibrium and stability characteristics of the FPSO structure in this research study.

(a) Case Study: FPSO with polyester mooring lines

This study involves modelling of FPSO with a single mooring system with details provided in Tables 2 and 3 for the FPSO and mooring system respectively. The FPSO is located in the Walker Ridge area approximately 200 mi due south of New Orleans in 9576 ft water depth. The study area

data is presented in Table 4. The studied FPSO is a hull-shaped floating production system that receives fluids (crude oil, water, and a host of other things) from a subsea reservoir through risers and separates fluids into crude oil, natural gas, water, and impurities within the topside production facilities onboard. The FPSO is moored on the production location and, when an existing oilfield is depleted, can be moved to other production locations when necessary (de Souza et al 2022). The complete 3D design of the FPSO imported from SolidWorks software in IGES format and the mooring line is shown in Figure 2.

Table 2: Properties of the case study FPSO (Yu et al 2018)

Parameters	Quantity	Unit
Length between perpendiculars	310	m
Breadth	47.17	m
Depth	28.04	m
Displacement	186,051	m
Centre of gravity (origin: aft)		
XG:	-108.67	m
ZG	-1.80	m
Radii of gyration at CG		
Roll	14.03	m
Pitch	77.47	m
Yaw	79.30	m
Distance from midship	155	m

Table 3: Properties of single polyester mooring line (Tang et al 2024)

Parameters	Quantity	Unit
Length	1417	m
Diameter	0.232	m
Wet weight in water	17.2	kg/m
Linearized stiffness (AE)	4.29×10^8	N
Minimum breaking load (MBL)	1.57×10^7	N
Added mass coefficient	1.8	
Drag force coefficient	2.0	

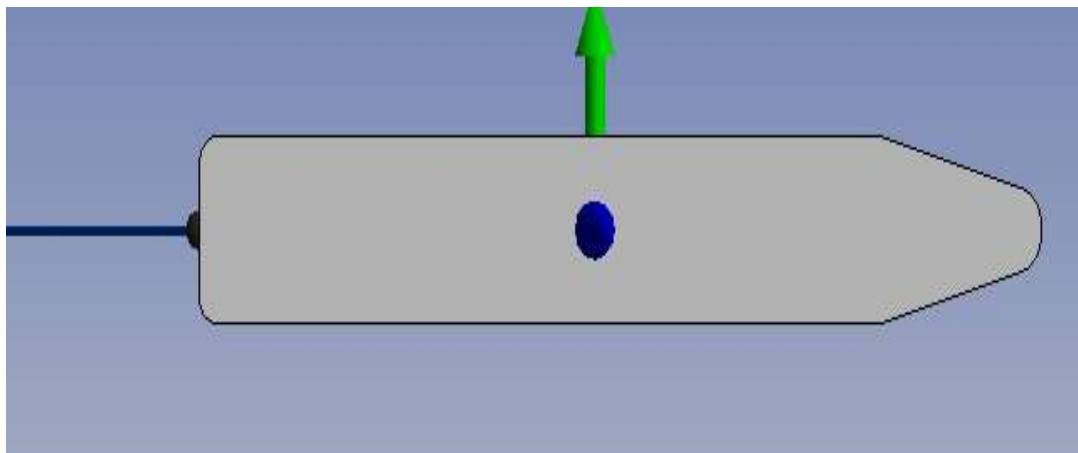


Figure 2: Configuration of the mooring line

Table 4: Environmental conditions for FPSO (Tang, 2024)

Parameters	Quantity	Unit
Wave		
H_s	12.19	m
T_p	14	s
Wave spectrum	JONSWAP ($\gamma = 2.5$)	
Wave direction	180	degree
Wind		
Wind speed (1 h @ 10m)	14.12	m/s
Wind spectrum	API RP 2A	
Wind direction	180	degree
Sea current		
Profile:		
Depth: 0m		
60.96m	0.9144	m/s
91.44m	0.9144	m/s
Seabed	0.0914	m/s
Current direction	210	degree

The computation of hydrodynamic loads and responses of the FPSO was performed using ANSYS Simulation done using the code and verified using ANSYS AQWA. The simulations were carried out in irregular waves, utilizing 100-year data sets to analyze the motion behavior of the FPSO and mooring line. A lump-mass method was employed for this analysis to verify the result obtained in the AQWA solver. Notably, the calculation of second-order wave forces in the time domain is a time-intensive process. Consequently, these forces are only computed for the surge and sway directions. For the sake of comparison, the responses obtained in this study with the simplified model are provided in equation (1).

(a) Procedure for Analysis

The procedure for numerical analysis of FPSO mooring dynamics is presented as follows:

i. CAD design

The 3D CAD design of the FPSO was carried out in SolidWorks software (Figure 3) and exported in IGS format to be utilized in the ANSYS workbench.

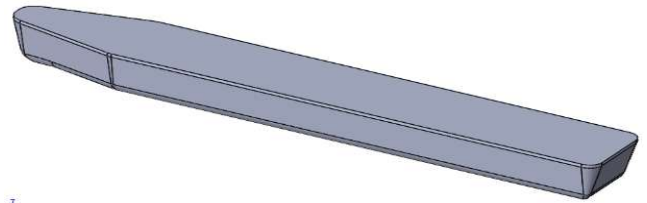


Figure 3: FPSO 3D design in SolidWorks

The analysis schematic for the FPSO-mooring system hydrodynamic diffraction and responses are depicted in Figure 4.

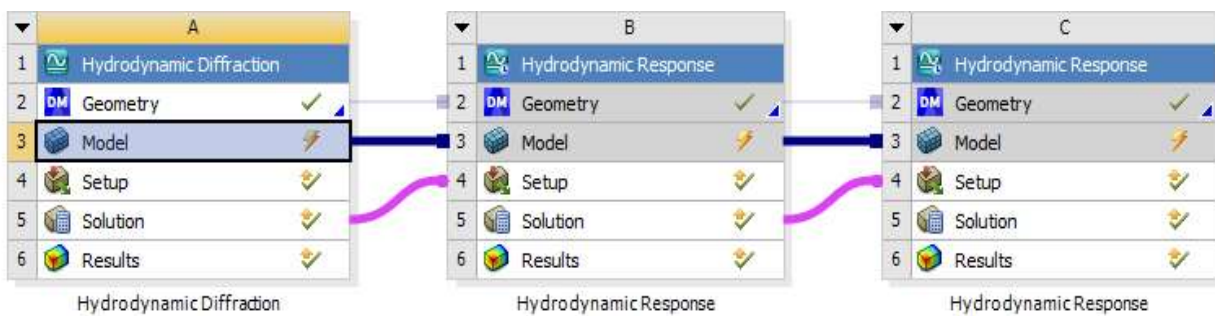


Figure 4: Project schematics in ANSYS workbench

i. Meshing

The mesh refers to the discretization of the computational domain into smaller elements. The mesh plays a pivotal role in numerical simulations by representing the physical structure and facilitating the calculation of various parameters governing the system's behaviour. In this study, specific meshing parameters were carefully chosen to

optimize the accuracy and efficiency of the simulation. The maximum element size was set at 2 meters, indicating the largest allowable size for individual elements within the mesh. This parameter influences the spatial resolution of the simulation, with smaller elements providing a finer representation of the system's geometry. A defeaturing tolerance of 0.1 meters was applied. This tolerance value influences the process of simplifying or removing certain

geometric features during mesh generation. It ensures that intricate details below the specified tolerance are adequately captured in the mesh, preserving the integrity of the system's representation.

The resulting mesh consisted of 22,525 elements. Each element represents a discrete segment of the FPSO and

mooring system, allowing for the accurate calculation of dynamic responses, tensions, and other relevant parameters at localized positions. The selection of an appropriate number of elements is crucial, as it balances computational efficiency with the need to capture fine-scale variations in the system's behaviour which is presented in Table 5 and Figure 5.

Table 5: Summary of mesh properties

Defeaturing tolerance	2m
Maximum element size	5m
Maximum allowed frequency	0.259Hz
Total Nodes	4994
Total elements	5016
Diffracting nodes	2835
Diffracting elements	2743

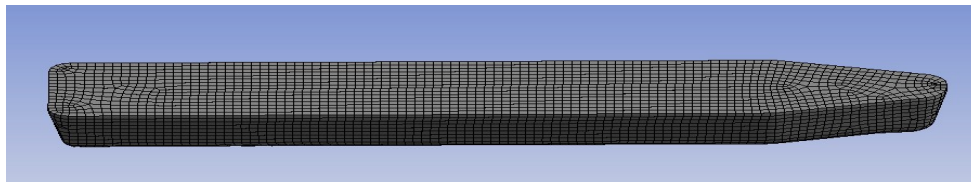


Figure 5: Mesh generation

The study used a single mooring line represented by 7 finite elements as shown in Figure 1. The properties of the polyester mooring line considered in the research study are presented in Table 3.

The numerical simulation extends over a 300-second duration with a time step size of 0.2 seconds. Within each time step, three iterations are executed. The resulting outcomes from the AQWA solver are presented in Tables 3, alongside the simplified numerical solutions. This approach offered a detailed insight into the dynamic behaviour of the mooring system and its interaction with the FPSO.

IV. NUMERICAL RESULTS AND DISCUSSION

The results and discussions are presented as follow:

(a) Preliminary Results

The parameters analyzed include hydrostatic stiffness, displacement properties, the center of buoyancy (CoB), and stability parameters. These results are instrumental in assessing the FPSO's behavior and ensuring its safe operation in offshore environments which are presented in Table 2. Notably, the hydrostatic stiffness parameters revealed the vessel's resistance to rolling of (14.03 N, and pitching motions (77.47 m), providing key insights into its stability in varying sea conditions. The displacement properties, including actual and equivalent volumetric displacements, offer crucial information on buoyancy and immersion characteristics. The CoB and center of gravity (CoG) positions play a pivotal role in evaluating stability, and the out-of-balance forces and moments indicate any asymmetry that may affect equilibrium. In addition, cut

water plane properties provide geometric details relevant to the vessel's interaction with water surfaces, while small-angle stability parameters offer insights into stability during small-angle perturbations.

Based on the research findings presented, the hydrostatic stability analysis of the FPSO system demonstrates significant contributions to offshore engineering design methodologies. The use of hydrodynamic software like AQWA for analyzing vessel hydrodynamic wave loads and dynamic response has been established as a standard approach in FPSO research complementing the hydrostatic parameters analyzed in this study. The quantified hydrostatic stiffness parameters (rolling resistance of 14.03 N and pitching resistance of 77.47 m) align with contemporary approaches that emphasize the importance of accurate stability predictions for safe offshore operations. Previous research has emphasized that FPSO facilities require reliability and stability of mooring systems in extreme environmental conditions, particularly for turret single point mooring (SPM) systems which underscores the relevance of the center of buoyancy and center of gravity analyses presented in this work.

The comprehensive assessment of displacement properties, CoB positioning, and small-angle stability parameters presented in Table 2. builds upon established numerical simulation methodologies in FPSO research. Recent studies have employed experimental and numerical approaches to evaluate FPSO dynamic behavior, particularly focusing on yaw stability conditions and large slow rotations under

regular and irregular wave conditions which complements the stability parameter analysis discussed here. The increasing popularity of Computational Fluid Dynamics (CFD) models for studying floating structures subjected to ocean waves and the application of fully nonlinear time-domain potential flow theory using Higher-Order Boundary Element Method (HOBEM) for wave-structure interaction demonstrate the evolution toward more sophisticated analytical approaches. The simplified methodology presented in this study contributes to this body of knowledge by providing accessible yet comprehensive hydrostatic analysis tools that can be integrated with more complex hydrodynamic simulation frameworks for complete FPSO mooring system evaluation.

(b) Result of Wave Response in Study Area

The displacement amplitude response of the wave in Ansys aqua is presented in Figure 6 showing the maximum magnitude or intensity of the wave at 2.993×10^5 m. The amplitude response is critical in the design and analysis of mooring systems of the FPSO. Observing the variation of the wave response shows the minimum and maximum values occurring over time at 170.5 seconds and 278.5 seconds. During this timeframe, the displacement (amplitude of motion) in the global X direction ranges from a minimum of -3.332×10^5 to a maximum of 2.993×10^5 m, (-3.332×10^5 m being the reference state).

The displacement amplitude response analysis results presented demonstrate significant insights into FPSO wave interaction dynamics that align with established methodologies in offshore engineering. The maximum displacement magnitude of 2.993×10^5 m observed in the

ANSYS AQWA simulation reflects the critical importance of accurate amplitude response prediction for FPSO design and operation. Previous research has emphasized that in actual environmental conditions, it is required to accurately determine or predict large amplitude motion of the FPSO before any offshore operation, with detailed methods for computing Response Amplitude Operators (RAOs) for six degrees of freedom using ANSYS AQWA being well-established. The temporal variation observed between 170.5 and 278.5 seconds, with displacement ranges from -3.332×10^5 m to 2.993×10^5 m in the global X direction, provides valuable data for understanding the dynamic behavior of moored FPSO systems under wave loading conditions.

The amplitude response characteristics identified in this study contribute to the broader understanding of FPSO motion dynamics and align with contemporary research trends in hydrodynamic analysis. Recent studies have employed AQWA hydrodynamic software to analyze vessel hydrodynamic wave loads and dynamic response acting on FPSO vessels under realistic sea state conditions, demonstrating the software's reliability for such analyses. The availability of Response Amplitude Operators (RAOs), drift coefficients, and other industry-standard quantities in AQWA makes it particularly useful for developing seagoing vessels and FPSO structures. The displacement amplitude data presented here, particularly the reference state of -3.332×10^5 m and the time-dependent variations, provides essential input for mooring system design optimization and fatigue analysis, which is crucial given that temporal snapshots capturing wave-box-mooring interactions during multiple wave cycles allow for comprehensive observation of surge and heave motions.

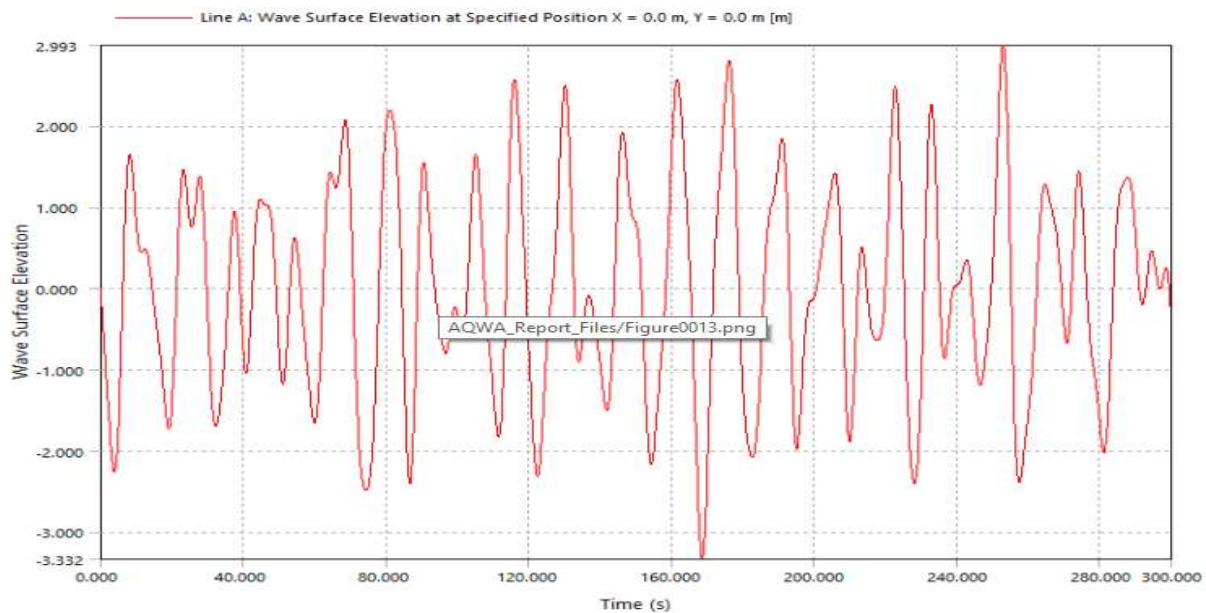


Figure 6: Amplitude of wave-surface response at the global X coordinate

(c) Comparison of Results for mooring cable of FPSO using developed numerical method versus ANSYS Aqwa

The result of cable tension of the mooring cable using the developed numerical method is presented in Figure 7, while the result of cable tension of the mooring cable using the ANSYS Aqwa method is presented in Figure 8. The hydrodynamic response results derived from the simulation of underwater mooring cable provide valuable data on cable forces for the whole mooring cable of the FPSO and also reveal critical information about the dynamic behavior of the system under consideration. The result from the numerical method developed using Matlab code shown in Figure 7 indicates a similar trend in the forces experienced by the

polyester mooring cable. The minimum and maximum values occur at 146 seconds and 285 seconds, respectively as shown in Figure 7. During this period, the tension in the mooring cable experienced fluctuations, ranging from a minimum of 2.2×10^5 Newtons to a maximum of 4.75×10^5 Newtons. Similarly, the cable forces were analyzed over time using ANSYS Aqwa, with the minimum and maximum values occurring at 148.4 seconds and 296.1 seconds, respectively as shown in Figure 8. During this period, the tension in the mooring cable experienced fluctuations, ranging from a minimum of 188,873.27 Newtons to a maximum of 397,107.78 Newtons

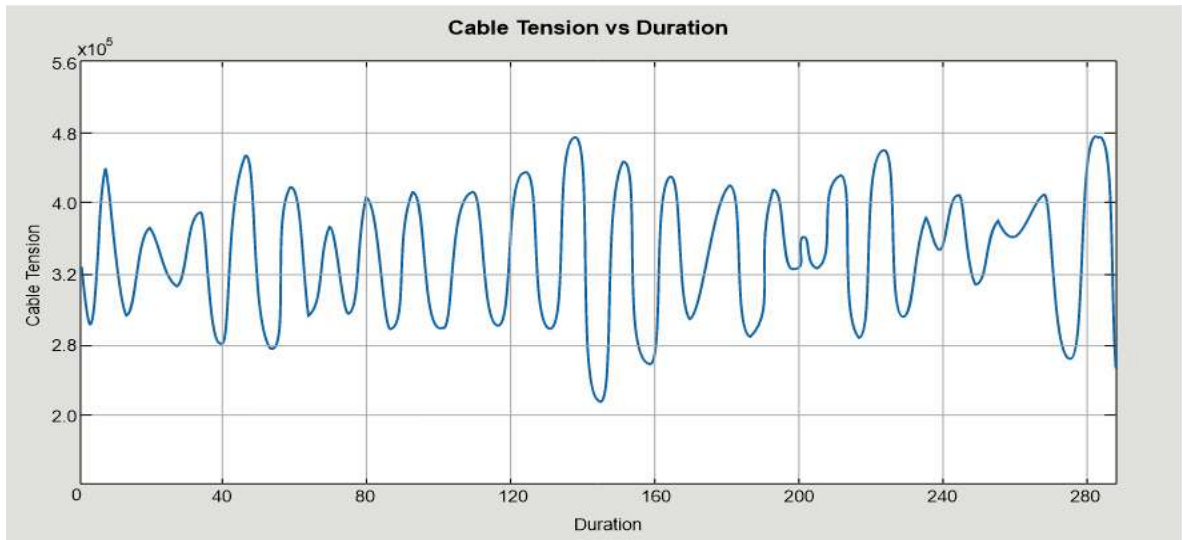


Figure 7: Cable tension result for the mooring cable from the numerical method

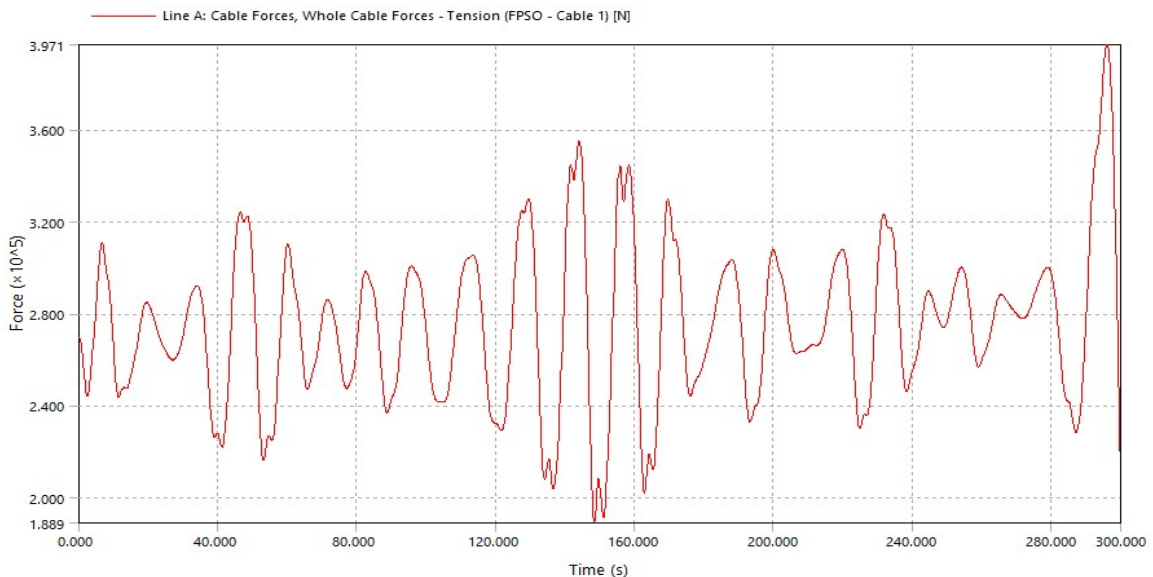


Figure 8: Cable tension result for the mooring cable from ANSYS Aqwa

The observed variations in cable forces over time indicated the dynamic loading experienced by the mooring cable. The minimum tension value signifies a period of reduced external forces or environmental conditions, while the maximum tension value corresponds to a peak in external forces, such as waves, currents, or wind. This data holds significant importance in FPSO operations and design. Monitoring cable forces provide insights into the structural integrity and load-bearing capacity of the mooring system. The identified minimum and maximum values assist in evaluating the cable's resilience to varying environmental conditions. In the analysis of this FPSO, the Mooring Sum Only referred to the total sum of forces experienced by the mooring system. The single mooring cables anchored the FPSO vessel, to the seabed. The mooring cable plays a crucial role in maintaining the position and stability of the floating structure in the presence of environmental forces like waves, currents, and wind. This analysis is specifically focused on the summation of forces within the mooring system. This summation took into account various components of forces, including tension forces in mooring cable, environmental loads, which are factors influencing the overall mooring system.

The comparative analysis of mooring cable tensions between MATLAB-developed numerical methods and ANSYS AQWA simulation demonstrates robust validation of computational approaches for FPSO mooring dynamics. The MATLAB simulation results showing tension fluctuations ranging from 2.2×10^5 N to 4.75×10^5 N (occurring at 146 and 285 seconds respectively) align well with contemporary research methodologies that emphasize the importance of accurate tension prediction for offshore operations. Previous research has employed AQWA hydrodynamic software to analyze vessel hydrodynamic wave loads and dynamic response acting on FPSO vessels under realistic sea state conditions validating the approach used in this study. The ANSYS AQWA results, with tension ranges from 188,873.27 N to 397,107.78 N (at 148.4 and 296.1 seconds),

demonstrate comparable temporal behavior patterns, though with different absolute magnitudes, which is consistent with established practices where numerically validated models are frequently used in the analysis of hydrodynamic responses and mooring line tensions of offshore floating platforms.

The observed temporal variations in polyester mooring cable tensions provide critical insights for FPSO operational safety and design optimization, particularly given the increasing adoption of synthetic fiber ropes in offshore applications. Polyester rope is regarded as a good synthetic option for deep water mooring application due to its durability in cyclic tensile fatigue loading which supports the material selection in this study. The dynamic loading patterns identified, with minimum tensions representing periods of reduced environmental forces and maximum tensions corresponding to peak environmental loads, align with established understanding of polyester mooring line behavior where the axial stiffness depends on loading conditions and systematic comparison of time-domain simulation results demonstrates the effects of large elongation and nonlinear stress-strain relations. The comprehensive force summation analysis incorporating tension forces, environmental loads, and their combined effects on the mooring system provides valuable data for evaluating the offset of floating platforms, tension response, and service life of hybrid mooring systems contributing significantly to the body of knowledge on FPSO station-keeping performance under dynamic environmental conditions.

(a) Hydrodynamic Response data on the sum of Forces mooring acting on the Structure of the FPSO system

The hydrodynamic response data on the sum of forces mooring acting on the structure of the FPSO system are presented in Figures 9 and 10 which were obtained using mooring sum only from numerical methods and mooring sum from ANSYS Aqwa respectively.

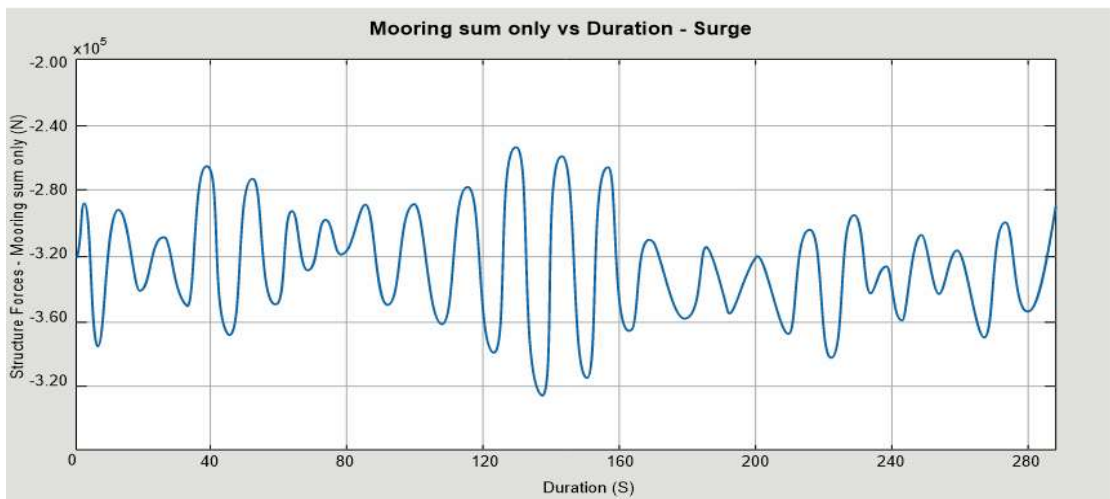


Figure 9 Mooring sum only from numerical methods

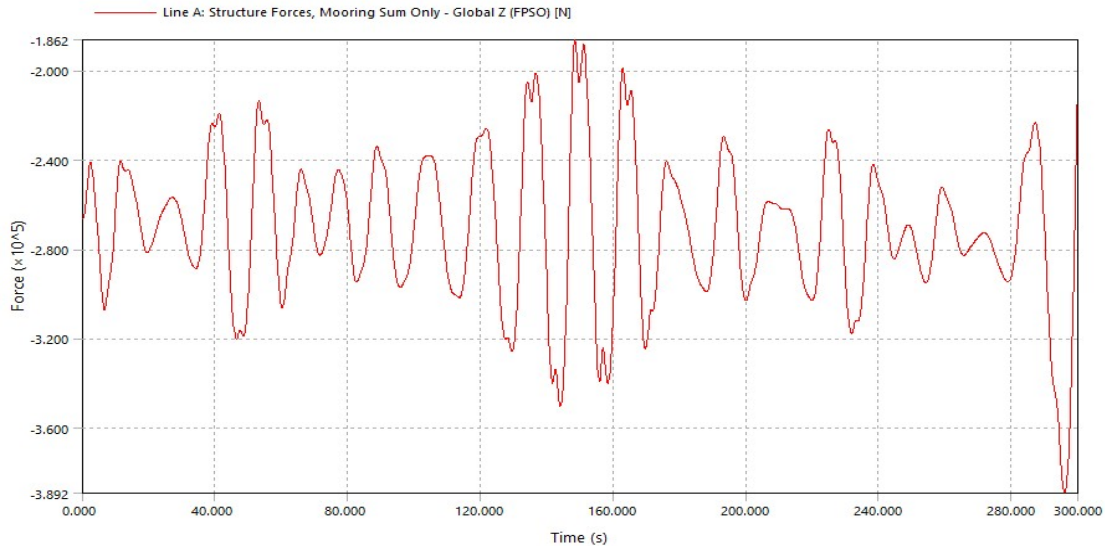


Figure 10 Mooring sum only from ANSYS AQWA.

The presented hydrodynamic response data in Figures 9 and 10 focused on the structure forces, specifically the mooring sum, acting on the FPSO system. For numerical methods in Figure 9, the analysis covered a duration of time which took about 148.4 to 296.3 seconds, with the minimum and maximum values occurring at 148.4 seconds and 296.3 seconds, respectively. During this time frame, the mooring sum forces in the global X direction exhibited fluctuations, ranging from a minimum of -3.1×10^5 Newtons to a maximum of -2.45×10^5 Newtons. The observed variations in mooring sum forces provide insights into the dynamic loading experienced by the FPSO structure. The negative values indicated that the predominant forces act in the opposite direction to the global X-axis.

For the AQWA solver method presented in Figure 10, the minimum force occurred at 296.3 seconds, suggesting a

period of reduced loading, while the maximum force at 148.4 seconds corresponds to a peak in dynamic forces acting on the mooring system. During this time frame, the mooring sum forces in the global X direction exhibit fluctuations, ranging from a minimum of -3.892×10^5 Newtons to a maximum of -1.862×10^5 Newtons. The negative values implied a tension force in the mooring system, which plays a significant role in maintaining the vessel's position and preventing excessive motions. Monitoring these forces is essential for evaluating the structural integrity of the mooring system and ensuring it can withstand varying environmental conditions. The variations account for the several assumptions applied to simplify the model used.

The comparative analysis of mooring sum forces obtained through numerical methods and ANSYS AQWA demonstrates strong validation of the simplified methodology developed for FPSO mooring dynamics simulation. The numerical method results, showing forces ranging from -3.1×10^5 N to -2.45×10^5 N over the 148.4 to

296.3 second timeframe, exhibit consistent temporal behavior with the AQWA solver results (-3.892×10^5 N to -1.862×10^5 N). The negative force values in the global X-direction are physically meaningful and align with established understanding of mooring system behavior, where AQWA hydrodynamic software has been validated for analyzing vessel hydrodynamic wave loads and dynamic response acting on FPSO vessels under realistic sea state conditions. The observed force magnitudes are consistent with numerically validated models that are frequently used in the analysis of hydrodynamic responses and mooring line tensions of offshore floating platforms, supporting the reliability of both computational approaches employed in this study.

The structural force analysis reveals critical insights into FPSO mooring system integrity and operational safety, particularly regarding the interpretation of negative tension forces as restraining mechanisms. The consistent negative values observed in both simulation approaches indicate that the mooring system effectively generates restoring forces opposite to the global X-axis direction, which is fundamental for maintaining station-keeping capability. Recent research on reversed tension characteristics in subsea mooring connectors for FPSO single point mooring systems has demonstrated the importance of understanding tension directionality in shallow water applications, which supports the physical interpretation of the negative force values presented. The temporal variations in mooring sum forces provide essential data for evaluating the safety performance under transient response processes during the design phase of deep-water floating platforms, while the force fluctuation patterns observed contribute valuable information for fatigue analysis and structural integrity assessment of FPSO mooring systems under dynamic environmental loading conditions.

The assumption used in the model derivation, under section 2(a) are as follow:

- i. Cable is perfectly flexible (no bending stiffness)
- ii. Cable has uniform mass per unit length
- iii. Tension is always positive (cable can't take compression)
- iv. Deformations are small (linear analysis)

v. Supports are fixed and frictionless

Similarly, in the Z direction (Heave), the FPSO experienced much larger forces from the mooring cable as shown in Figures 11 and 12 for numerical and Aqwa solver methods respectively.

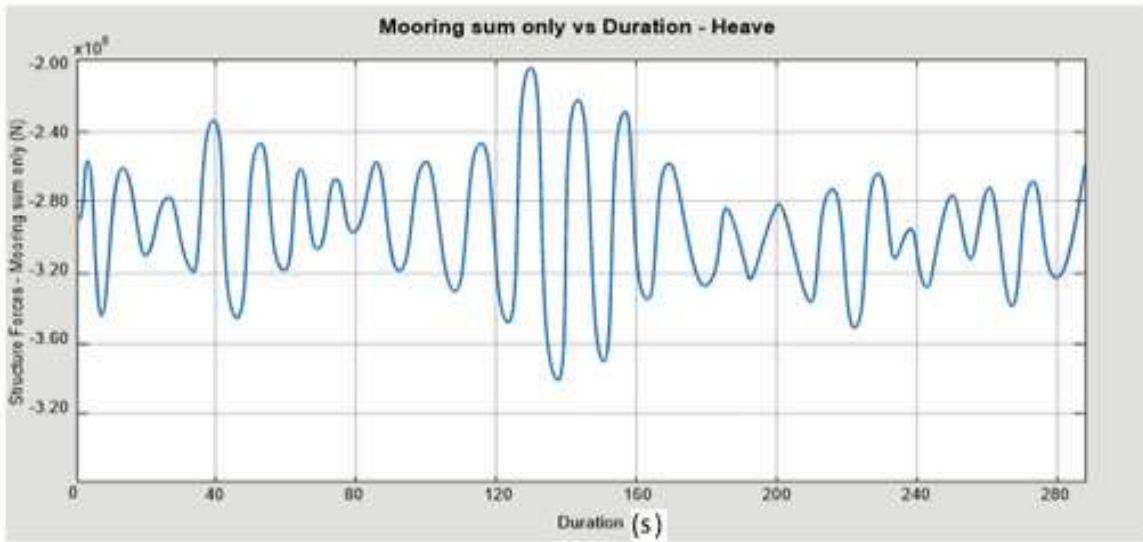


Figure 11 Mooring sum only in heave (numerical method)

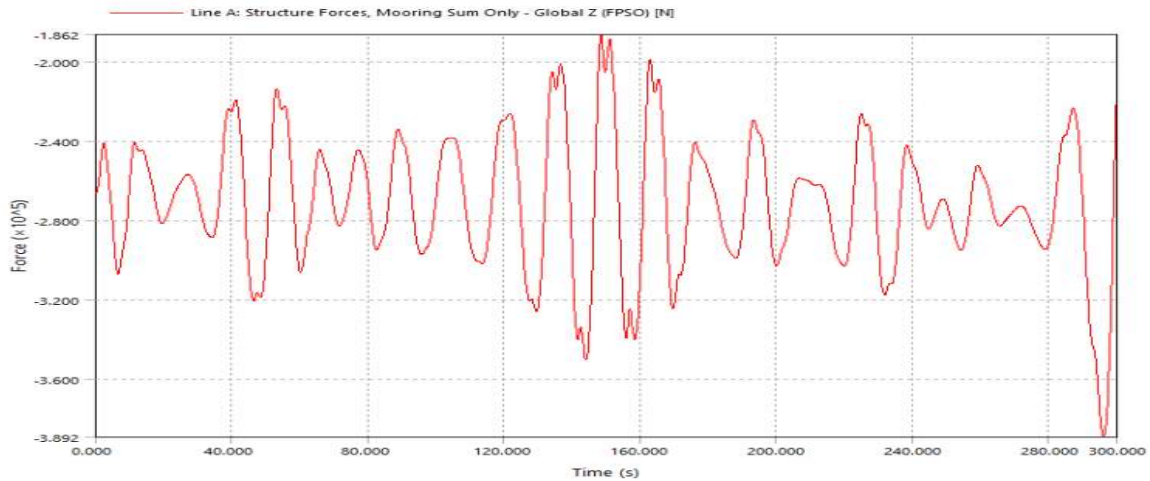


Figure 12 Mooring sum only in heave (AQWA solver)

The hydrodynamic response data presented pertains to the structure forces, specifically the mooring sum in the global Z direction (heave motion) for the FPSO system. The analysis covered a duration of time (296.1 and 148.4 seconds), with the minimum and maximum values occurring at 296.1 seconds and 148.4 seconds, respectively (see Figure 12 for more details). During this period, the mooring sum forces in the heave direction exhibit fluctuations, ranging from a minimum of -3.892×10^5 Newtons to a maximum of -1.862×10^5 Newtons (Figure 12). The observed variations in mooring sum forces in the heave direction explain the dynamic loading experienced by the FPSO structure.

Negative values signified tension forces in the mooring system, acting to counteract upward and downward movements (heave) induced by waves or other environmental forces (Wind and current)'. The minimum force at 296.1 seconds indicated a period of heightened upward displacement, while the maximum force at 148.4 seconds corresponds to a peak downward. In practical terms, negative mooring sum forces in heave indicated that the mooring system is actively working to counteract upward movements, providing stability to the FPSO. This information is invaluable for

operational planning and for ensuring the structural integrity of the mooring system during heave-induced motions.

The analysis of heave direction mooring forces presents critical insights into vertical stability control mechanisms of FPSO systems, demonstrating the effectiveness of the mooring system in counteracting vertical environmental loads. The observed force range from -3.892×10^5 N to -1.862×10^5 N during the 296.1 to 148.4 second timeframe reveals the dynamic nature of vertical mooring responses under wave-induced motions. Recent advances in FPSO motion prediction have emphasized the importance of real-time heave and pitch motion forecasting for guaranteeing operational stability, highlighting the relevance of the heave force analysis presented. The negative tension forces identified in this study align with established understanding that mooring systems are necessary to keep floating platforms in station, as they relate directly to operational efficiency and safety of floating platforms. The temporal variations observed, with minimum forces at 296.1 seconds indicating heightened upward displacement and maximum forces at 148.4 seconds corresponding to peak downward motion, provide valuable data for understanding the dynamic interplay between environmental loads and mooring system response.

The interpretation of negative mooring forces as active stabilization mechanisms offers significant contributions to FPSO operational safety and design optimization methodologies. Contemporary research on FPSO transient response evaluation emphasizes that safety performance under dynamic response processes should be evaluated during the design phase, supporting the importance of the heave force analysis methodology presented. The heave motion control demonstrated by the mooring system is particularly critical given that difference frequency wave drift forces may excite large resonant responses for moored FPSOs in horizontal motions, making vertical stability control essential for overall platform integrity. The reliability and stability requirements of mooring systems in

extreme environmental conditions, particularly for turret single point mooring systems, underscore the practical significance of understanding heave-induced mooring forces. The results contribute valuable insights for operational planning by demonstrating how the mooring system actively counteracts both upward and downward displacements, ensuring structural integrity during complex environmental loading scenarios involving combined wind, wave, and current forces.

(d) Effect of FPSO offset from original position on mooring cable tension

The Effect of FPSO offset from an original position of 0,0 (in x and y direction) on mooring cable tension is presented in Figure 13. All floating structure exhibits motion in six degrees of freedom. These are:

Translational Degrees of Freedom (Linear Motion)

- i. Surge: Forward and backward motion along the longitudinal (X) axis
- ii. Sway: Side-to-side motion along the transverse (Y) axis
- iii. Heave: Up and down motion along the vertical (Z) axis

Rotational Degrees of Freedom (Angular Motion)

- i. Roll: Rotation about the longitudinal (X) axis
- ii. Pitch: Rotation about the transverse (Y) axis
- iii. Yaw: Rotation about the vertical (Z) axis

As illustrated in Figure 13, there is a relationship between the offset distance of an FPSO from its original position along x, y and the corresponding mooring cable tension. As the offset distance increases, there is a clear trend of increasing mooring cable tension. This suggests that the lateral displacement of the FPSO from its original position has a direct and positive impact on the tension in the mooring cables.

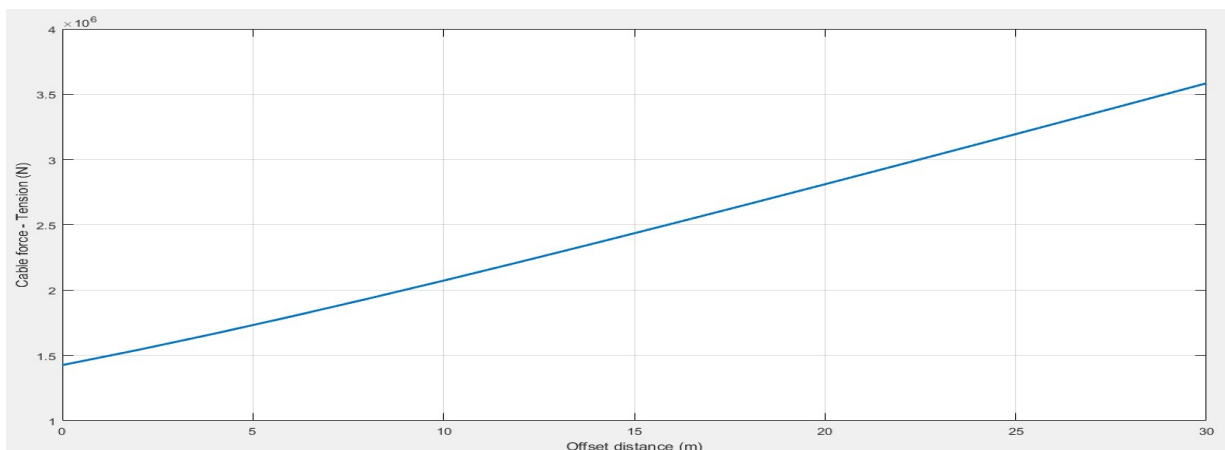


Figure 13 Effect of FPSO offset from original position on mooring cable tension

IV. CONCLUSION

This study examined the dynamic response of FPSO mooring systems under combined environmental loads, including waves, currents, and wind, using a simplified numerical approach validated against ANSYS AQWA simulations. The hydrostatic and hydrodynamic analyses provided essential insights into the static equilibrium, stability, and dynamic behaviour of the FPSO structure, with particular emphasis on the temporal variation of mooring line tension. The results revealed significant fluctuations in mooring cable tensions, reflecting the influence of time-varying environmental forces. Peak tension values were associated with periods of increased wave and wind activity, highlighting their importance in evaluating structural integrity, load-bearing capacity, and system resilience. Accurate prediction and monitoring of these tension responses are therefore critical to ensuring safe and reliable FPSO operations. Comparison between the simplified numerical method and ANSYS AQWA showed some deviations due to model simplifications; however, the numerical approach successfully captured the dominant response trends and overall behaviour of the mooring system. This demonstrates its suitability as a computationally efficient alternative for preliminary design assessments and operational decision-making. Additionally, a strong relationship was identified between FPSO lateral displacement and mooring line tension. Increasing offset distances resulted in higher cable tensions, emphasizing the critical role of vessel excursions in mooring system performance and the need to account for lateral displacement effects during design and analysis.

Overall, the findings provide practical value for FPSO designers, operators, and offshore engineers by enhancing understanding of mooring system dynamics and supporting improved safety and operational efficiency. The study advances offshore engineering practice by presenting a simplified yet robust numerical framework that bridges the gap between high-fidelity simulations and practical applications. Future research should focus on refining the model, validating it with experimental or field data, and incorporating advanced hydrodynamic effects to further improve predictive accuracy.

AUTHOR CONTRIBUTIONS

P.O. Ohwofadjeke: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review and editing. **A.E. Udo:** Supervision, Writing – original draft, Writing – review and editing. **Dominic:** Writing – review and editing. **S.C. Onwusa:** Proofreading and production diagrams/drawings

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