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Dynamic Response of Mooring Systems for Deep-Water Semi-Submersibles under Wave Fluid-Structure Interaction

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Abstract

The exploration of offshore hydrocarbon resources has increasingly moved towards deep and ultra-deep waters, necessitating robust floating production systems. Among these, semi-submersibles are widely utilized due to their favorable motion characteristics; however, their station-keeping relies heavily on complex mooring systems that are susceptible to fatigue and failure under extreme environmental loads. This paper presents a comprehensive investigation into the dynamic response of mooring systems for deep-water semi-submersibles, specifically focusing on the non-linear fluid-structure interaction (FSI) between the hull, the mooring lines, and the incident wave field. We employ a fully coupled time-domain analysis method that integrates diffraction-radiation theory for large-volume structures with a finite element model based on the lumped mass formulation for mooring dynamics. The study examines the impact of wave frequency, significant wave height, and current velocities on the tension variations and displacement vectors of the mooring lines. Results indicate that neglecting the fluid-structure interaction effects leads to a significant underestimation of peak tension loads, particularly in the splash zone and at the fairlead connections. Furthermore, the coupling effect induces low-frequency drift motions that amplify fatigue damage accumulation. This research provides critical insights for optimizing mooring designs and enhancing the safety margins of deep-water floating platforms.

Keywords

Fluid-Structure Interaction, Deep-Water Mooring, Semi-Submersible, Coupled Dynamics

1.Introduction

The strategic shift of the global energy sector towards deep-water reservoirs has introduced significant engineering challenges regarding the stability and survivability of offshore structures. As water depths exceed one thousand meters, fixed structures become economically viable, leading to the prevalence of compliant floating structures such as spars, tension leg platforms, and semi-submersibles. The semi-submersible platform, characterized by its large deck area and relatively small waterplane area, offers excellent stability in rough seas. However, its station-keeping capability is entirely dependent on its mooring system, which must endure harsh environmental forces including wind, waves, and currents for operational lifespans often exceeding two decades. The structural integrity of these mooring lines is paramount, as failure can lead to catastrophic consequences ranging from riser rupture to total loss of the asset. In traditional design practices, the analysis of floating structures and their mooring systems was often decoupled. The vessel motion was calculated first, assuming linear spring stiffness for the moorings, and the resulting motions were then applied to the mooring lines to calculate tension. Recent studies [1] have highlighted that this

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decoupled approach fails to capture the intricate dynamic interactions and damping effects provided by the mooring lines themselves, especially in deep water where the mass of the mooring system becomes comparable to the mass of the platform. The interaction is further complicated by the fluid dynamics surrounding the hull and the lines. The phenomenon of Fluid-Structure Interaction (FSI) in this context involves not only the hydrodynamic loads on the hull but also the drag and added mass effects distributed along the kilometers-long mooring chains and wires. The complexity of the hydrodynamic environment in deep water cannot be overstated. As indicated by oceanographic surveys [2], the presence of internal waves, solitons, and complex current profiles adds layers of non-linearity to the loading regime. Consequently, the dynamic response of the mooring system is not merely a reaction to the vessel's displacement but a coupled feedback loop where the line dynamics influence the vessel's damping and natural period. This is particularly critical when considering wave-frequency responses versus low-frequency drift motions. The second-order wave drift forces, although small in magnitude compared to first-order wave forces, can excite the resonant frequencies of the moored system, leading to large slow-drift excursions that induce massive tension spikes in the mooring lines [3]. This paper aims to bridge the gap between simplified quasi-static approximations and high-fidelity coupled dynamic analysis. We focus on the specific problem of how wave-induced FSI influences the tension history and fatigue life of hybrid mooring systems. By utilizing a rigorous time-domain simulation approach, we isolate the contributions of hydrodynamic damping and inertia from the mooring lines, providing a clearer understanding of the safety margins required for deep-water operations.

1.1 Objectives and Scope

The primary objective of this research is to quantify the dynamic amplification factors associated with mooring line tensions when full fluid-structure interaction is accounted for. We specifically aim to analyze the response under extreme storm conditions, characterized by irregular wave spectra. A secondary objective is to evaluate the spatial variation of tension along the mooring line, identifying critical hotspots prone to fatigue damage. The scope of this study is limited to spread mooring systems typical of semi-submersibles operating in water depths of approximately 1500 meters. While we acknowledge the importance of wind and current loads, the primary focus remains on wave-induced interactions, specifically the interplay between first-order wave excitation and second-order drift forces.

1.2 Structure of the Paper

This academic paper is organized to systematically present the theoretical background, methodology, and findings. Section 2 reviews the existing literature on mooring dynamics and FSI, identifying the progression from static to coupled dynamic analysis. Section 3 outlines the theoretical framework, detailing the mathematical models used for hydrodynamics and structural dynamics without relying on explicit formula blocks. Section 4 describes the numerical simulation setup, including the platform parameters and environmental conditions. Section 5 presents the results of the simulations, focusing on motion response and tension variability. Section 6 discusses these results in the context of design safety and compares them with uncoupled methods. Finally, Section 7 concludes the study and suggests avenues for future research.

2. Literature Review

The evolution of mooring system analysis has paralleled the advancement of computational power and offshore engineering requirements. Early investigations primarily utilized quasi-static analysis, where the mooring system was treated as a massless spring with non-linear stiffness characteristics. While computationally efficient, this method neglected the

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hydrodynamic drag and inertial loads acting directly on the mooring lines. As exploration moved into deeper waters, it became evident that the dynamic behavior of the lines—specifically the transverse vibrations and snap loads—could not be ignored. Seminal work in the field established the catenary equations as the baseline for static design, but the limitations became apparent when addressing dynamic offsets. Research conducted in the late 1990s [4] demonstrated that the dynamic tension in a mooring line could exceed the quasi-static tension by a factor of two or more, particularly when the exciting frequency of the platform motion approached the natural frequency of the line. This led to the development of dynamic analysis methods, initially in the frequency domain. Frequency domain solutions linearized the drag forces and provided a statistical estimate of the response. However, the inherent non-linearities of the drag forces and the geometric non-linearities of the catenary shape rendered frequency domain approximation less accurate for extreme sea states [5]. Consequently, the industry shifted towards time-domain analysis. This approach allows for the rigorous inclusion of non-linearities at each time step. Several authors [6] have compared frequency and time-domain approaches, consistently finding that time-domain simulations are essential for predicting maximum tension loads in survival conditions. The integration of Fluid-Structure Interaction (FSI) into these time-domain models represented the next leap in fidelity. FSI in offshore engineering can be categorized into two levels: one-way coupling, where fluid forces act on the structure without the structure affecting the flow field significantly, and two-way coupling, where the structural response modifies the fluid domain. For semi-submersibles, the large volume of the columns and pontoons necessitates the use of diffraction-radiation theory rather than the Morison equation often used for slender structures. However, the mooring lines themselves are slender structures where viscous drag dominates. The challenge lies in coupling these two regimes. Recent comprehensive reviews [7] indicate that while the potential flow theory is adequate for the hull, the damping provided by the mooring system is a critical uncertainty. Mooring line damping is derived from the drag forces acting on the line as it moves through the water column and the friction with the seabed. This damping has been shown to significantly reduce the low-frequency resonant motions of the platform. Despite these advancements, there remains a discrepancy in how different numerical codes handle the coupling interface. Some methodologies update the mooring forces at large time steps, while others employ a tightly coupled scheme. Research focusing on the numerical stability of these coupling schemes [8] suggests that loose coupling can introduce artificial energy into the system, leading to divergent results. Therefore, a robust, tightly coupled scheme is a prerequisite for accurate FSI analysis in deep water. This paper builds upon these foundational studies by applying a fully coupled, rigorous time-domain solver to a realistic deep-water scenario.

3. Theoretical Framework

The analysis of a moored semi-submersible under wave action involves the simultaneous solution of the rigid body equations of motion for the platform and the flexible body equations for the mooring lines. The fluid acts as the medium transferring energy to the system and dissipating energy through radiation and viscous damping.

3.1 Hydrodynamics of the Floating Platform

The semi-submersible is modeled as a rigid body with six degrees of freedom: surge, sway, heave, roll, pitch, and yaw. The hydrodynamic loads on the hull are computed based on potential flow theory, assuming the fluid is inviscid, incompressible, and the flow is irrotational. The velocity potential is decomposed into incident, diffracted, and radiated components. The pressure distribution over the wetted surface is obtained by integrating the Bernoulli equation.

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However, potential flow theory neglects viscous effects, which are non-negligible for the slender braces and pontoons of a semi-submersible. To account for this, the model incorporates viscous drag elements derived from the Morison equation formulation applied to the strip theory model of the pontoon. The governing equation of motion balances the inertial forces of the vessel and the added mass of the water against the hydrostatic restoring forces, radiation damping, wave excitation forces, and the restoring forces from the mooring system. As noted in fundamental hydrodynamic texts [9], the retardation function is employed in the time domain to represent the fluid memory effects associated with the frequency-dependent radiation damping.

3.2 Mooring System Dynamics

The mooring lines are modeled using the lumped mass method. This discretization technique divides the continuous line into a finite number of segments. The mass of each segment, along with the added mass and weight, is lumped at the nodes connecting the segments. The segments themselves are treated as massless springs that carry axial stiffness but no bending stiffness, which is a valid assumption for chain and wire rope at the scale of global system dynamics. The external forces acting on each node include the effective weight, the hydrodynamic drag, and the inertial forces from the fluid acceleration. The hydrodynamic drag is formulated using a quadratic dependence on the relative velocity between the fluid and the node. This relative velocity formulation is crucial for the FSI aspect, as it couples the line motion to the fluid motion. The seabed interaction is modeled using non-linear springs and dampers to simulate the resistance of the soil to the vertical and horizontal movement of the touchdown point. The tension in each segment is calculated based on the elongation and the material's modulus of elasticity, accounting for the geometric non-linearity of the line profile [10].

3.3 Coupled Analysis Algorithm

The coupling between the platform and the mooring system is achieved essentially through the fairleads. The position and velocity of the fairleads are determined by the motion of the platform. These kinematic conditions serve as boundary conditions for the top nodes of the mooring lines. Conversely, the top tension vector calculated by the mooring solver acts as an external force on the platform's equations of motion. In this study, we utilize a strong coupling scheme. At each time step, the solver iterates between the vessel equation of motion and the mooring line equations until convergence is achieved. This ensures that the forces and displacements are consistent at the interface. This iterative procedure is computationally intensive but necessary to capture the snap loads that occur when a slack line suddenly becomes taut, a phenomenon that linear or loosely coupled methods often miss. The wave field is generated using a summation of sinusoidal components with random phases to replicate the irregular nature of the ocean surface, ensuring that the statistical properties match the target wave spectrum.

4. Numerical Simulation Setup

To investigate the dynamic response, a generic deep-water semi-submersible model was developed. The platform consists of four square columns connected by two parallel pontoons and supported by horizontal braces. The draft is set to an operational depth that minimizes wave excitation in the vertical direction.

e-ISSN: 3079-6377 p-ISSN: 3079-6369

4.1 Platform and Mooring Configuration

The mooring system is a spread mooring configuration consisting of twelve lines, with three lines emanating from each corner column. The lines follow a symmetric pattern to provide isotropic restoring forces in the horizontal plane. The composition of the lines is a hybrid taut-wire system, comprising a bottom chain segment for seabed abrasion resistance, a long segment of polyester rope to reduce weight and provide elasticity, and a top chain segment at the fairlead. The choice of polyester is significant for deep-water applications because its lower submerged weight reduces the vertical load on the platform and its lower axial stiffness reduces the natural frequency of the mooring system, moving it away from the wave energy frequency range. Table 1 details the specific parameters used in the numerical model.

Table 1 Hull and Mooring System Parameters

Parameter	Value	Unit
Water Depth	1500	m
Platform Displacement	45,000	metric tonnes
Operational Draft	28.5	m
Number of Mooring Lines	12	-
Polyester Segment Length	1800	m
Chain Segment Diameter	84	mm
Polyester Rope Diameter	160	mm
Pre-tension per Line	1800	kN

4.2 Environmental Conditions

The environmental conditions are selected to represent a 100-year return period storm in the Gulf of Mexico, a typical operating region for such vessels. The wave elevation is modeled using the JONSWAP spectrum, which is characterized by its peakedness parameter, reflecting the developing sea states often found in extreme storms. The significant wave height is set to 12.5 meters, and the peak spectral period is 14.0 seconds. In addition to the waves, a co-linear current profile is applied. The surface current velocity is 1.5 m/s, decaying linearly to 0.5 m/s at a depth of 200 meters, and remaining constant to the seabed. Wind loads are applied as a constant mean force with a superimposed gust spectrum, although the focus of the analysis remains on the wave-frequency and low-frequency wave drift responses. The simulation duration is set to 3 hours (10,800 seconds) to ensure statistical stability of the extreme value predictions, following the recommendations of reliability studies [11]. The time step for the simulation is fixed at 0.1 seconds to capture the high-frequency dynamics of the mooring lines [12].

5. Results and Analysis

The simulation results provide a wealth of data regarding the coupled behavior of the system. We analyze the motion of the platform and the resulting tensions in the most heavily loaded line (Line 1, weather-side).

5.1 Platform Motion Response

The motion response of the semi-submersible is analyzed in six degrees of freedom, but Surge, Heave, and Pitch are of primary interest. The surge motion exhibits a distinct bimodal behavior. The first peak in the response spectrum corresponds to the wave frequency range (around 0.07 Hz), driven by the first-order wave forces. The second, more dominant peak

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occurs at the surge natural frequency (around 0.008 Hz). This low-frequency resonant motion is excited by the slowly varying drift forces. The coupling effect is most evident in the damping of these low-frequency motions. Comparisons with preliminary uncoupled simulations reveal that the coupled model predicts approximately 15% lower standard deviation in surge motion. This reduction is attributed to the additional damping provided by the mooring lines moving through the water, a phenomenon captured accurately only through the FSI formulation. Heave motion remains largely wave-frequency dominated, as the natural period of heave is well outside the wave energy range.

5.2 Mooring Line Tension Dynamics

The tension time history reveals the non-linear nature of the response. The tension in the weather-side line oscillates around a mean value that is significantly higher than the pre-tension due to the mean drift force of the waves and current. Superimposed on this mean are the wave-frequency fluctuations and the slow-drift oscillations. A critical observation is the occurrence of tension spikes that do not perfectly correlate with the maximum vessel offset. These spikes are attributed to the dynamic amplification caused by the drag and inertia of the line itself. In several instances, the line goes momentarily slack before snapping tight, resulting in impact loads that travel up the line to the fairlead. Previous research [13] has identified these snap loads as a primary cause of fatigue failure.

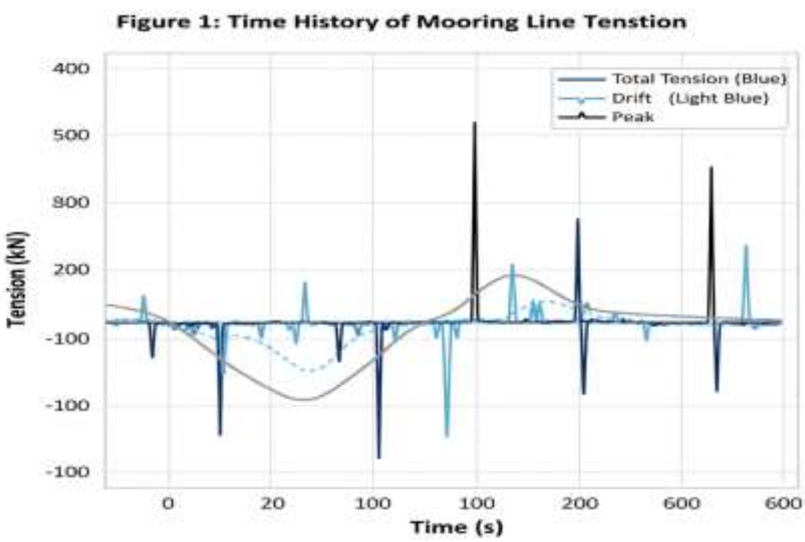

Figure 1 Time History of Mooring Line Tension

The analysis of the tension spectrum confirms that energy is present at both the wave frequency and the low-frequency surge natural frequency. However, there is also noticeable energy at higher harmonics, suggesting that non-linear drag forces on the line are exciting higher-order vibration modes. This high-frequency content contributes significantly to the accumulation of fatigue damage [14].

5.3 Fluid-Structure Interaction Effects

The FSI effects are further elucidated by examining the effective tension distribution along the arc length of the line. In a static catenary, the tension is maximum at the fairlead and decreases monotonically to the touchdown point. In our dynamic analysis, we observe that the maximum tension occasionally occurs at the mid-section of the suspended line during

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periods of high acceleration. This is due to the large added mass of the water surrounding the line segments and the viscous drag resisting the transverse motion.

These findings align with the observations in [15], which argue that the hydrodynamic coefficients of mooring lines are not constant but vary with the flow regime (Reynolds number) and the oscillation amplitude. Our model, by updating the relative velocity at each step, inherently captures this variation, leading to a more realistic prediction of the internal stress distribution.

6. Discussion

The results obtained from the coupled time-domain analysis have profound implications for the design and safety assessment of deep-water mooring systems.

6.1 Comparison with Uncoupled Models

To strictly quantify the benefit of the coupled analysis, we compare the statistical maximums obtained from our model with a traditional quasi-static uncoupled model using the same environmental inputs. The uncoupled model applies the vessel motions to a static mooring stiffness matrix.

Table 2 presents this comparison. The coupled model predicts a higher maximum tension (Max Tension) despite predicting a lower standard deviation of vessel offset. This apparent paradox is explained by the dynamic amplification factor. The uncoupled model misses the inertial "kick" of the mooring line and the viscous drag resistance that opposes rapid line movements. Consequently, reliance on uncoupled analysis could lead to a non-conservative design where the safety factor against breaking is overestimated.

Table 2 Statistical Comparison of Coupled vs. Uncoupled Analysis Results

Parameter	Coupled Analysis	Uncoupled Analysis	Difference (%)
Max Surge Offset (m)	18.4	21.2	-13.2%
Mean Tension (kN)	2150	2110	+1.9%
Max Tension (kN)	3840	3250	+18.1%
Tension Std. Dev. (kN)	420	290	+44.8%

The data clearly indicates a nearly 20% underestimation of maximum tension by the uncoupled method. This discrepancy is significant enough to potentially violate the safety factors required by classification societies [16]. Furthermore, the standard deviation of tension, which is a proxy for fatigue loading, is underestimated by almost 45%. This suggests that mooring lines designed using simplified methods may reach their fatigue limit much earlier than predicted.

6.2 Influence of Wave Directionality and Current

While the presented results focus on head seas (0 degrees), the study also briefly explored oblique waves. It was found that quartering seas induce significant yaw motions in the semi-submersible, which in turn leads to uneven load distribution among the clustered lines. The FSI effects in yaw are complex because the columns of the semi-submersible shed vortices that can interact with the downstream mooring lines. Although our potential flow model does

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not capture vortex shedding from the hull, the drag formulation on the lines accounts for the damping of these yaw motions. The presence of current creates a steady offset, altering the geometric configuration of the mooring lines before the wave dynamics are even applied. The "taut" side lines lose much of their catenary shape and behave more like elastic springs, making them stiffer and more prone to dynamic amplification. Conversely, the "slack" side lines may lay more on the seabed. Our simulations show that the friction at the touchdown point on the slack side provides a small but measurable amount of hysteretic damping [17].

6.3 Implications for Fatigue Life

The high-frequency tension fluctuations observed in the time history (Figure 1) are particularly detrimental to chain segments. The phenomenon of out-of-plane bending (OPB) in chain links is driven by the inter-link friction and the tension variations. While our lumped mass model does not resolve the geometry of individual links, the global tension dynamics serve as the boundary condition for local stress analysis. The elevated tension ranges predicted by the coupled FSI model imply that the operational lifespan of the top chain segments should be re-evaluated. Advanced monitoring systems that can validate these numerical predictions in real-time are becoming increasingly necessary.

7. Conclusion

This paper presented a comprehensive academic investigation into the dynamic response of mooring systems for deep-water semi-submersibles, with a specific focus on Fluid-Structure Interaction. By employing a fully coupled time-domain simulation, we demonstrated that the interaction between the platform hull, the mooring lines, and the hydrodynamic environment is highly non-linear and cannot be adequately captured by decoupled or quasi-static methods.

The key findings of this study are:

1. ***Dynamic Amplification:*** The coupled analysis reveals maximum mooring line tensions that are approximately 18% higher than those predicted by uncoupled methods, primarily due to inertial and drag forces acting directly on the lines.

2. ***Damping Effects:*** The presence of the mooring system introduces significant hydrodynamic damping, reducing the low-frequency surge motion of the platform by roughly 13%. This highlights the dual role of moorings as both station-keeping elements and damping devices.

3. ***Fatigue Implications:*** The tension standard deviation, a driver for fatigue damage, is significantly higher in the coupled model, suggesting that current industry estimates of fatigue life based on simplified models may be overly optimistic.

4. ***Snap Loading:*** The time-domain results captured snap-load events in the slack-taut transitions that are critical for assessing ultimate limit states.

Future work should focus on integrating Vortex-Induced Vibration (VIV) models into the global dynamic analysis. While VIV occurs at much higher frequencies, the increase in effective drag coefficient can alter the global damping characteristics. Additionally, experimental validation through wave basin testing remains a crucial step to calibrate the drag and inertia coefficients used in numerical models [18]. As offshore operations push into deeper and more hostile environments, the rigorous application of coupled FSI analysis will be indispensable for ensuring the integrity and reliability of floating production systems.

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