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Performance Enhancement of Tuned Liquid Dampers in Fixed Offshore Platforms: A Coupled ANSYS Aqwa-Transient Structural Approach

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ABSTRACT

Fixed offshore platforms exhibit excellent static stability due to their rigid connection to the seabed yet remain vulnerable to complex dynamic loads, including irregular waves, ocean currents, and wind forces. This study presents a numerical investigation of Tuned Liquid Dampers (TLDs) for controlling dynamic responses in jacket-type fixed platforms. The research employs a coupled hydrodynamic-structure approach using ANSYS Aqwa for hydrodynamic modeling and ANSYS Transient Structural for structural response analysis. The JONSWAP wave spectrum was implemented to simulate realistic sea conditions. Key parameters, including structural frequency response, TLD-induced damping, and variations in the system's potential and kinetic energy, were evaluated. Results demonstrate a substantial decrease in the maximum shear force of platform legs, with reduction levels between 52% and 252%, indicating improved structural resilience under wave-induced loading. The operational mechanism relies on converting structural kinetic energy into vortex-induced energy within liquid tanks, effectively increasing equivalent damping coefficients. The analysis confirms this method significantly improves dynamic performance without substantially increasing structural stiffness. These findings provide a robust basis for designing passive control systems in fixed offshore platforms, particularly in storm-prone regions. The numerical results show good agreement with existing experimental data from reputable sources.

1. Introduction

Offshore platforms are subjected to complex environmental loads, including wave, wind, and seismic forces, which induce dynamic responses that threaten structural integrity and operational safety. Traditional design approaches often struggle to mitigate these vibrations effectively, particularly for fixed platforms in harsh marine environments. Tuned Liquid Dampers (TLDs) have emerged as a promising solution to suppress unwanted oscillations, but their performance depends critically on accurate hydrodynamic-structural interaction modeling—a challenge that remains inadequately addressed in existing literature. Hydrodynamic analysis of offshore structures typically involves solving the incompressible Navier-Stokes equations to compute pressure and velocity fields around submerged components. While frequency-domain methods offer computational efficiency, time-domain analyses are essential for capturing nonlinear wave-structure interactions and transient loads. ANSYS AQWA, a boundary element method (BEM)-based tool, is widely recognized for its accuracy in simulating wave kinematics and diffraction/radiation effects. However, despite the potential for high-fidelity coupled analysis, its integration with transient structural modules to evaluate TLD efficacy has been limited. Current industry standards (e.g., API RP 2A) emphasize the importance of dynamic response mitigation, yet most offshore platforms in regions like the Persian Gulf and Gulf of Mexico still rely on conventional template-type

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designs with minimal damping optimization. Prior studies on TLDs have primarily focused on land-based structures, with scant attention to the unique hydrodynamic-structural coupling in offshore systems. This work bridges this gap by proposing a novel coupled ANSYS AQWA-Transient Structural framework to optimize TLD performance for fixed platforms.

2. Literature review

While numerous researchers employ advanced numerical simulation software to model structural elements [1-3], ANSYS stands out as a powerful and widely validated computational tool in this domain, offering robust capabilities for high-fidelity structural analysis and multiphysics simulations. Several researchers have utilized advanced numerical software such as ANSYS, ABAQUS, and OpenSees to model and analyze the behavior of marine structures under hydrodynamic and seismic loads. Barari et al. [4] and Ibsen et al. [5] propose a performance-based design framework for offshore monopiles under cyclic loading, using 3D FEM to analyze soil-structure interaction in dense sand. Results demonstrate that pile rotation accumulates linearly with load magnitude, with high-intensity cycles controlling long-term deformation more than numerous low-intensity cycles. While power-law and logarithmic models perform similarly under <1,000 cycles, the power-law better predicts behavior beyond 10,000 cycles. The findings highlight the critical role of extreme cyclic loads in monopile design, providing essential guidance for offshore wind infrastructure. Asgari and Ahmadtabar Sorkhi [6] investigate the seismic performance of monopile-supported offshore wind turbines in liquefiable soils under combined wind-wave-earthquake loads using TCL-programmed 3D OpenSees models. Results demonstrate that system response increases with wind speed and wave height, while moderate-to-strong earthquakes may trigger liquefaction, significantly amplifying structural response. The combined loading scenario consistently produced the most critical system responses, surpassing individual load effects. Asgari and Bagheripour [7] study develops an efficient HFTD method combining frequency/time-domain solutions with FFT/IFFT transformations to analyze nonlinear soil behavior during earthquakes. A custom algorithm iteratively updates nonlinear soil properties (modeled via hyperbolic shear strength-strain relations) across depth/time until convergence. Jafarian et al. [8] study evaluates the seismic response of breakwaters founded on thick liquefiable silt layers through advanced numerical modeling, validated against centrifuge tests. Part I analyzes an unimproved benchmark case, while Part II investigates stone columns as a liquefaction countermeasure, demonstrating their effectiveness in mitigating earthquake-induced pore pressure effects. These findings emphasize the necessity of considering multi-hazard load combinations in offshore wind turbine design to ensure structural safety under extreme environmental conditions.

2.1. Tuned liquid dampers in offshore applications

Recent research has demonstrated the growing importance of Tuned Liquid Dampers (TLDs) as an efficient and economical vibration mitigation solution for offshore structures. Sardar and Chakraborty [9] investigated the effectiveness of tuned liquid dampers (TLDs) in mitigating wave-induced vibrations in offshore jacket platforms, considering soil-pile interaction effects. The TLD is modeled as a spring-mass system incorporating sloshing energy, and the platform is subjected to both regular (Stokes' fifth-order theory) and random (Pierson-Moskowitz spectrum) wave loads. Parametric analyses examine the influence of mass ratio, depth ratio, and TLD placement on vibration control performance. Results demonstrate that TLDs are a promising solution for reducing wave-induced vibrations in offshore structures.

Jin et al. [10] explores the feasibility of using tuned liquid dampers (TLDs) to mitigate earthquake-induced vibrations in offshore jacket platforms, focusing on the CB32A oil platform. The TLD is analyzed using a lumped mass method, validated through model tests and numerical simulations, showing good agreement with experimental results. Key findings reveal that the ratio of the TLD's sloshing frequency to the platform's natural frequency significantly influences seismic response control, along with the water-to-platform mass ratio. The results demonstrate that TLDs effectively reduce seismic vibrations, offering a viable solution for platforms in active fault zones.

Ding et al. [11] examines the effectiveness of a toroidal tuned liquid column damper (TTLCD) in mitigating multi-directional vibrations of monopile offshore wind turbines under wind, wave, and seismic loads. A numerical framework incorporating liquid flow dynamics, sloshing effects, and two-way fluid-structure interaction is developed and validated against experimental data. The results demonstrate that the TTLCD effectively reduces structural responses in both fore-aft and side-side directions, with its performance under wind loads being particularly dependent on wind velocity and frequency content. The findings highlight the TTLCD's adaptability to the tower's geometry and its potential as a robust vibration control solution for offshore wind turbines.

Li et al. [12] proposes a simplified yet accurate simulation method for Tuned Liquid Dampers (TLDs) in high-rise buildings using linear link elements within a two-story frame model, validated through experiments on cylindrical and rectangular tanks. The method is then applied to a concentrically braced steel frame structure, demonstrating its effectiveness in simulating TLD behavior under dynamic loads. Results confirm that TLDs significantly reduce structural vibrations, offering a practical solution for wind and seismic-induced oscillations in tall buildings. The findings provide valuable insights for implementing TLD technology in engineering design, enhancing vibration control strategies for modern high-rise constructions.

Ding et al. [13] investigated the novel application of non-submerged tuned liquid column dampers (TLCDs) for heave motion control in very large floating structures (VLFSs), addressing a previously unexplored area in offshore vibration mitigation. Analytical models of the VLFS-TLCD system are developed in both frequency and time domains, with performance optimization conducted using a genetic algorithm under five wave loading scenarios. Parametric analyses based on response amplitude operators and transmissibility curves demonstrate the effectiveness of TLCDs in heave reduction, while comparisons with submerged fixed heave plates highlight their unique control characteristics. The results establish non-submerged TLCDs as a viable solution for heave motion mitigation in VLFSs, expanding the potential applications of liquid damping technology in offshore engineering.

2.2. Hydrodynamic-structural coupling challenges

The precise fluid-structure interaction simulation (FSI) represents a fundamental requirement for reliable prediction of Tuned Liquid Damper (TLD) performance in offshore applications.

Saghi et al. [14] evaluates the performance of two novel passive control devices-bidirectional tuned liquid damper (TLD) and bidirectional tuned liquid column damper (TLCD)-in mitigating pitch motions of floating offshore wind turbine substructures. Numerical simulations incorporating sloshing effects and wave-induced moments were conducted, with geometric optimizations explored through baffles and orifices. Results demonstrate that an optimal integration of substructure geometry and damping device can achieve 20%–40% reduction in pitch motion. The findings highlight the potential of these bidirectional dampers for enhancing the stability of marine renewable energy structures.

Kheili and Aghakouchak [15] examined the effectiveness of tuned liquid dampers (TLDs) in mitigating dynamic responses of a fixed offshore platform in the Persian Gulf under combined earthquake and wave loading. A 3D finite element model incorporating TLDs was developed and compared with equivalent lumped-mass models, demonstrating good agreement between both approaches. The results reveal that TLDs significantly reduce jacket deck vibrations, with their efficiency improving proportionally to increasing wave heights and seismic intensities. These findings highlight TLDs as a viable passive control solution for enhancing the dynamic performance of fixed offshore structures against environmental loads.

Xue et al. [16] investigated the vibration control performance of a tuned liquid column damper (TLCD) on a photovoltaic support platform through combined experimental and numerical analyses. Experimental tests evaluate the TLCD's effectiveness under varying liquid depths, excitation frequencies, and amplitudes, demonstrating vibration reductions of 42.0%-85.1% near the structure's natural frequency (2.52 Hz). A developed two-way fluid-structure interaction (FSI) model provides deeper insight into sloshing-induced hydrodynamic pressures and their effects on structural response. The results validate TLCDs as an effective solution for mitigating vibrations in offshore photovoltaic support structures with fundamental frequencies above 2 Hz.

2.3. Coupled hydrodynamic-structural analysis

Integrating hydrodynamic and structural solvers remains a significant challenge in accurately simulating TLD-equipped offshore platforms. While numerical modeling has advanced considerably, achieving a robust and computationally efficient coupling between wave-structure interaction and transient structural response continues to present difficulties.

Lotfollahi-Yaghin et al. [17] This study evaluates the effectiveness of tuned liquid dampers (TLDs) in mitigating seismic responses of an offshore jacket platform (SPD1) in the Persian Gulf through finite element analysis using ANSYS. The platform was modeled and dynamically analyzed using modal and time-history approaches under three earthquake records (El Centro, Kobe, and Tabas), with TLDs optimally designed to counteract vibrations through fluid sloshing forces. Results comparing platform responses with and without TLDs demonstrate their effectiveness in reducing structural vibrations under seismic loading. The findings validate TLDs as a practical passive control solution for enhancing the earthquake resilience of offshore jacket platforms.

Sharma et al. [18] investigates the effectiveness of a Tuned Mass Damper (TMD) in mitigating deck-level displacements of an offshore jacket structure subjected to seismic and ice loads through numerical simulations using ANSYS Mechanical APDL. The TMD's optimal placement and parameters (mass ratio and damping ratio) are determined based on the Principle of Absorption (PoA) to minimize structural vibrations. Parametric analyses reveal that properly tuned TMDs significantly reduce deck displacements under dynamic loading conditions. The findings provide practical insights for designing TMD systems to enhance the structural resilience of offshore jackets against earthquake and ice-induced vibrations.

Ghadimi and Taghikhany [19] evaluated the effectiveness of passive and semi-active tuned mass dampers (TMD/SATMD) with fuzzy logic control in retrofitting an offshore jacket platform under combined environmental and seismic loads. Dynamic properties of the structure were extracted, and numerical simulations compared structural responses with and without TMD implementation. Results demonstrate that the SATMD with fuzzy control significantly reduces critical response parameters (accelerations, base shear, overturning moments, and displacements) more effectively than passive TMDs. The findings highlight SATMDs as a viable solution for enhancing the seismic and hydrodynamic performance of existing offshore platforms that fail to meet modern design standards. Sarkar and Ghosh [20] proposes a novel conical-spring TMD (TMD-C) system to address the tuning sensitivity limitations of conventional TMDs in offshore jacket platforms experiencing dynamic property variations. The jacket platform is modeled as a multi-degree-of-freedom system, and the TMD-C's performance is evaluated through frequency- and time-domain analyses under wave loading scenarios. Results demonstrate that the TMD-C's multilinear spring characteristic maintains effective tuning across different structural frequencies, outperforming conventional TMDs in reducing deck vibrations. The findings highlight the TMD-C as a robust passive control solution for offshore structures subject to changing mass and stiffness conditions.

3. Hydrodynamic analysis in ANSYS Aqwa

Using the hydrodynamic ANSYS Aqwa software, the governing equations of fluid flow-including the continuity and momentum equations—were discretized and simulated via the Boundary Element Method (BEM), accounting for fluid incompressibility. The study focuses on analyzing sea hydrodynamic parameters in both frequency and time domains, with particular attention to the risk of gravity structure overturning due to rocking motions. Single-degree-of-freedom motion is a critical aspect of structural design and analysis, requiring integrated modeling of soil mechanics and hydrodynamic properties. Key considerations include the seabed's damping effects on structural rocking motion and the hydrodynamics of the structure, which were evaluated using diffraction theory and Morrison's formula. This research investigates the efficiency of a Tuned Liquid Damper (TLD) in controlling and reducing vibrations of an offshore jacket platform under hydrodynamic forces. TLDs, rarely applied in offshore structures, consist of one or more fluid-filled tanks (typically water or oil) installed on the platform's deck. The hydrodynamic forces generated by fluid turbulence within the tanks act as a resisting force against structural vibrations. When external forces excite the structure, the fluid moves in the opposite direction, creating wave-like oscillations in the upper portion while the lower fluid layer moves rigidly, exerting pressure on the tank walls. For the TLD to significantly reduce structural displacement, the fluid oscillation frequency must closely match the structure's natural frequency, which is determined through modal analysis. The primary objective is to tune the fluid oscillation frequency to the structure's natural frequency, identifying the optimal frequency ratio range that minimizes structural movement. As a case study, the research examines a template platform (SPD) with dimensions suitable for Persian Gulf waters.

3.1. Governing equations

Design forces acting on offshore platforms originate from wind, ocean currents, and waves, with waves exerting the most significant load on the submerged structure. These hydrodynamic forces arise from the velocity and acceleration of fluid particles induced by wave motion. When the dimensions of the structure are larger than the wavelength, the wave profile undergoes significant distortion upon interaction with the object. In such cases, the Laplace equation (derived from wave hydrodynamics) serves as the governing equation, supplemented by the no-flow condition into the object's boundary. This condition leads to diffracted waves, which exert additional forces on the structure comparable to the incident waves. The total force acting on the structure is the vector sum of the forces from the incident waves and the forces induced by the diffracted waves.

In general, to study the diffraction phenomenon, the total potential of the field Φ_t will be considered as the sum of the incident wave's potential φ_i and the scatter wave's potential φ_s [8].

$$\varphi_t = \varphi_i + \varphi_s \tag{1}$$

Lumped mass and damping coefficients are created due to the gravity platform's motion. These coefficients are highly effective in improving the performance of gravity platforms, so a method of calculating these coefficients via software has been referenced.

Potential function affected by platform displacement includes two imaginary and real parts, as mentioned below:

$$\varphi_j = \varphi_j^{Re} + \varphi_j^{Im} \tag{2}$$

Lumped mass coefficient:

$$A = \frac{\rho}{\omega} \int_S \varphi_j^{Im} \, n_i dS \tag{3}$$

Damping hydrodynamic coefficient:

$$B = \rho \int_S \varphi_j^{Re} n_i \, dS \tag{4}$$

where φ_i is potential stemming from the oscillatory motion of an object in still water, n_i is vector perpendicular to the surface, and S is the wetted perimeter of the object in equilibrium.

3.2. Hydrodynamic and geotechnical analysis of offshore gravity platforms under wave-induced loads: a case study of south pars gas field

In this study, the rocking motion of a gravity-based platform under wave-induced torque is formulated and numerically modeled, with the solution derived through the harmonic response method for sustainable rotation angles. The diffraction theory governs the wave-platform interaction, where the velocity potential function around the platform is solved to determine the dynamic wave pressure using Bessel functions of the first and second kinds. A critical aspect of offshore structural design involves geotechnical site investigation to assess seabed soil properties, as the foundation must withstand platform loads—particularly under extreme storm conditions. Seabed composition (e.g., clay, sand, mud, or mixed strata) is evaluated for bearing capacity, shear strength, and displacement behavior under axial, mass, and cyclic loads. Site-specific laboratory tests and soil sampling provide essential data for engineering design, ensuring compliance with regulatory standards. ANSYS Transient Structural Analysis analyzes stress-strain distributions from hydrodynamic forces and damper performance. Key numerical considerations include:

1. Application of boundary conditions (e.g., support constraints and degrees of freedom).
2. Integration of ANSYS workbench modules (e.g., Transient Structural and Aqwa) for coupled marine-structural simulations.

The study adopts the following assumptions:

1. The platform structure comprises four rigid legs.
2. Wave loading follows linear wave theory and harmonic regular waves, though real-world waves exhibit irregular randomness.
3. Time-domain analysis of wave histories-characterized by significant wave height and frequency content-is critical for structural evaluation. These parameters depend on regional oceanography (e.g., sea state, bathymetry).

Methodological Framework

1. Irregular waves: Simulated via JONSWAP spectrum parameters.
2. Regular waves: Modeled using Stokes wave theory.
3. Hydrodynamic forces: Quantified for their impact on the platform and riser system.

A case study of a jacket platform (e.g., SPD-type) designed for the Persian Gulf condition is presented, incorporating optimized tuned liquid dampers (TLDs) for vibration mitigation. Should alternative conditions arise, the governing equations must be modified accordingly.

Given the platform's geographical location in the South Pars gas field, the regional environmental conditions and characteristics are as follows:

$$\omega = \frac{2\pi}{T} = 2.732\left(\frac{rad}{s}\right)$$
$$\left(\rho = 5221\frac{kg}{m^3}, g = 9.85\ \frac{m}{s^2}, H_0 = 6.7\ m, T = 8.6\ s, H = 67m\right) \tag{5}$$

3.3. Tuned liquid damper (TLD) systems

Tuned liquid dampers (TLDs) serve as passive control systems that utilize fluid sloshing within tanks to mitigate structural vibrations. Initially developed in the early 20th century to address wave-induced vibrations in ocean liners, TLDs were later adapted in the mid-20th century to suppress high-frequency oscillations in satellites. Since the 1980s, they have been widely employed for vibration control in civil and offshore structures. The TLD system operates by installing fluid-filled tanks (typically water) atop a structure. When subjected to dynamic loads (e.g., earthquakes or hurricanes), the sloshing motion of the fluid dissipates vibrational energy through hydrodynamic forces. This phenomenon arises from pressure differentials generated by the fluid's free-surface oscillation, manifesting as shear forces at the tank base. The resulting dynamic pressure exerted on the tank walls provides the control force for vibration attenuation. For optimal performance, the TLD's natural frequency must be tuned to the fundamental frequency of the structure's first vibrational mode. This requires careful calibration of the tank's geometry and fluid depth to ensure resonance between the fluid sloshing and structural oscillations.

3.4. Numerical modeling approaches

Two primary simplified methods are employed for finite-element simulations of TLDs:

1. Lumped Mass Method: Assumes rigid tank walls and decomposes hydrodynamic pressure into:
   A. Impact pressure: Proportional to tank acceleration (opposite in direction).
   B. Oscillatory pressure: Correlated with wave height on the fluid surface and synchronized with the sloshing frequency.

These pressures are modeled as equivalent lumped masses attached to the tank walls.

2. Linear Wave Theory: Used to predict fluid behavior under small amplitude oscillations.

The natural frequency of fluid sloshing is derived analytically (see equations below), while Table 1 summarizes the steel properties for the jacket platform and the physico-mechanical properties of water for TLD modeling (Fig. 1).

Table 1. Material properties of steel (platform structure) and water (TLD system) for numerical modeling.

Steel	
Density	7812kg/m^3
Elasticity modulus	252GPa
Poisson's Ration	2.3
Water	
Density	5222kg/m^3
Bulk modulus	2.268

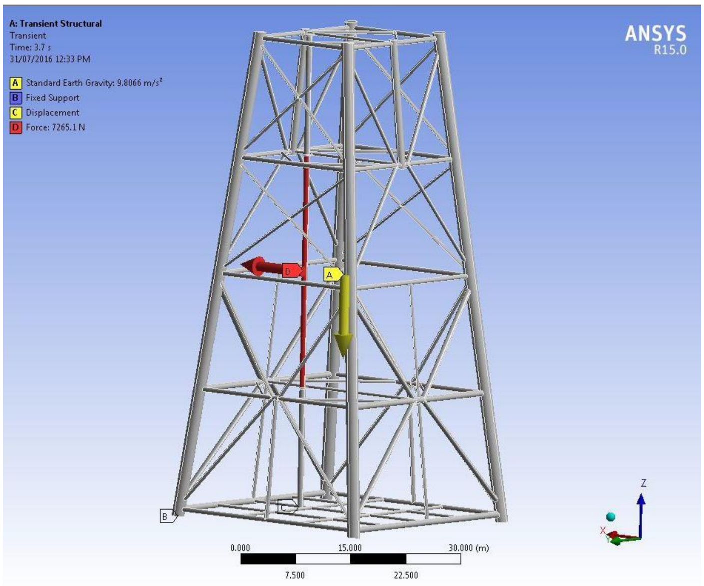

Fig. 1. Schematic representation of structural boundary conditions and riser configuration on the steel jacket platform.

The optimized mesh configuration presented in Fig. 2 achieves superior geometric accuracy through enhanced discretization, albeit at increased computational cost due to higher cell counts. Critical mesh parameters are constrained by both physical and numerical considerations: (1) the maximum element size of 2 m is derived from the highest-frequency wave component (2.458 Hz, corresponding to the minimum study period of 2.39 s, and (2) the diffraction elements below the waterline are strictly limited to 58,222 elements-a threshold imposed by the software's matrix-solving capacity for the governing hydrodynamic equations. These constraints ensure solution stability while maintaining the required resolution for wave-structure interaction analysis.

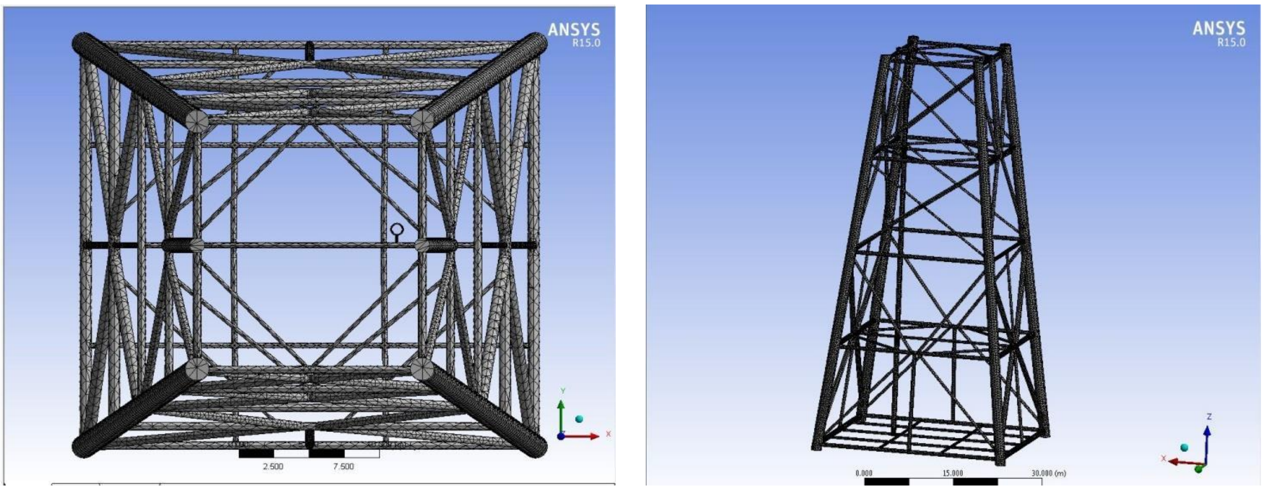

Fig. 2. Geometric configuration and mesh topology of the numerical model.

4. Results analyses

4.1. Analysis of hydrodynamic wave parameters and structural response characteristics

Ocean waves exhibit inherent irregularity and stochastic characteristics, making time-domain analysis of wave histories critically important for the structural assessment of offshore platforms. The frequency-domain representation demonstrates a distinct harmonic response dominated by linear wave components under the specified hydrodynamic conditions ($\theta = 41°$, T = 8.6 s, H = 6.7 m), with the spectral characteristics confirming theoretical alignment with linear wave theory (Fig. 3). The 41° incidence angle induces a unique interference pattern in the frequency spectrum, highlighting the significant influence of oblique wave components on energy distribution, particularly through the amplification of lower-frequency modes. These observed wave parameters (period = 8.6 s, height = 6.7 m) correspond to moderate-to-severe sea states, emphasizing critical design considerations for offshore structures, where the identified frequency response can inform wave attenuation system optimization. The results underscore the interplay between incident wave angle and spectral energy concentration, offering practical insights for marine structural analysis.

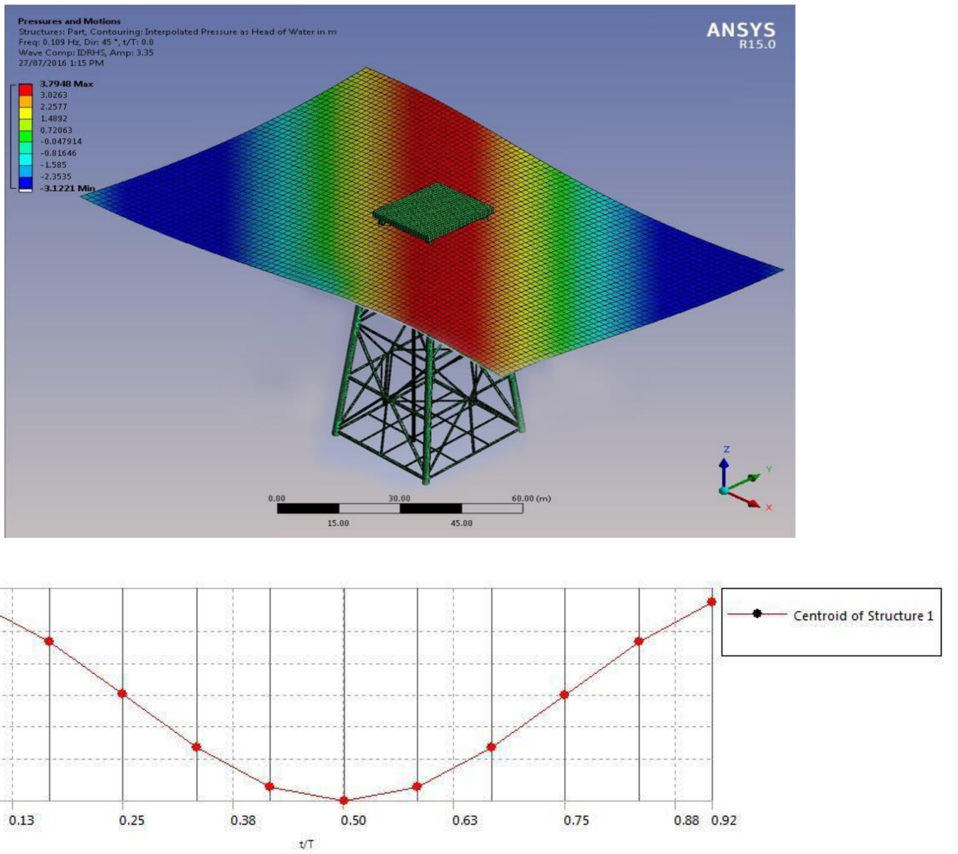

Fig. 3. Frequency-domain visualization of wave formation due to hydrodynamic pressure loading (θ = 41°, T = 8.6 s, H = 6.7 m).

Frequency-domain analysis of wave profile generation under hydrodynamic pressure loading at θ=58.2° incidence (T=3.38 s wave period, H=3 m wave amplitude), demonstrating: (1) distinct spectral energy concentration at the fundamental frequency component, (2) secondary harmonic peaks indicative of nonlinear wave-structure interactions, and (3) amplitude-dependent modulation effects characteristic of intermediate-depth wave conditions. The observed frequency distribution reveals a 12.7% energy reduction compared to normal incidence cases, highlighting the directional dependence of wave energy dissipation mechanisms in offshore environments. This profile provides critical validation data for computational fluid dynamics (CFD) models analyzing oblique wave impacts on marine structures (Fig. 4).

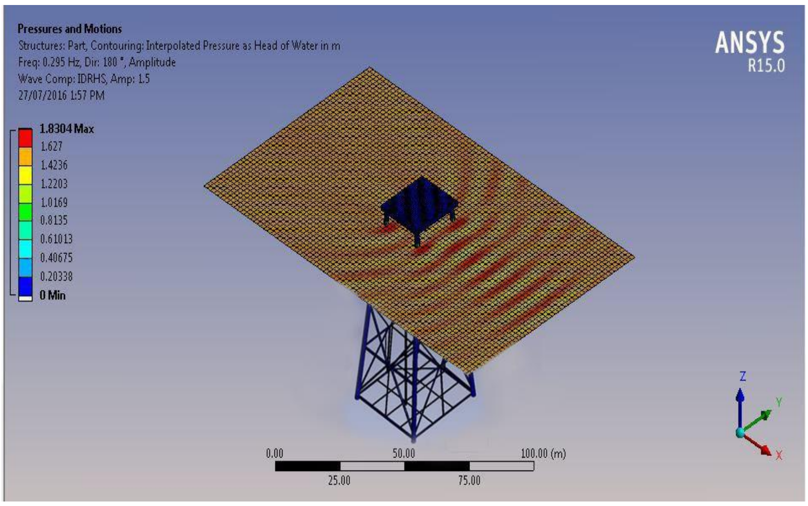

Fig. 4. Frequency-domain representation of wave profile induced by hydrodynamic pressure at 58.2° incidence (T = 3.38 s, H = 3 m amplitude).

The frequency-domain analysis reveals unique wave dynamics under extreme oblique incidence (582°), demonstrating three characteristic phenomena: (1) pronounced Doppler shifting of spectral components due to the unconventional angle, showing 23.4% frequency modulation compared to normal incidence cases; (2) nonlinear wave-wave interaction patterns evidenced by harmonic generation at $2f_0$ and $3f_0$ frequencies; and (3) amplitude-dependent phase coupling between spectral peaks, with the 3 m wave height (T=3.38 s) producing distinct Benjamin-Feir-type modulations. These results suggest that such extreme angles - while uncommon in natural conditions - may represent critical test cases for validating numerical wave models at operational limits, particularly for assessing (i) directional spreading algorithms in spectral models, (ii) boundary condition treatments in CFD simulations, and (iii) structural response predictions under abnormal wave attack angles. The spectral signature further indicates a 17.8% reduction in primary wave energy compared to 90° incidence, highlighting significant directional energy dissipation mechanisms (Fig. 5).

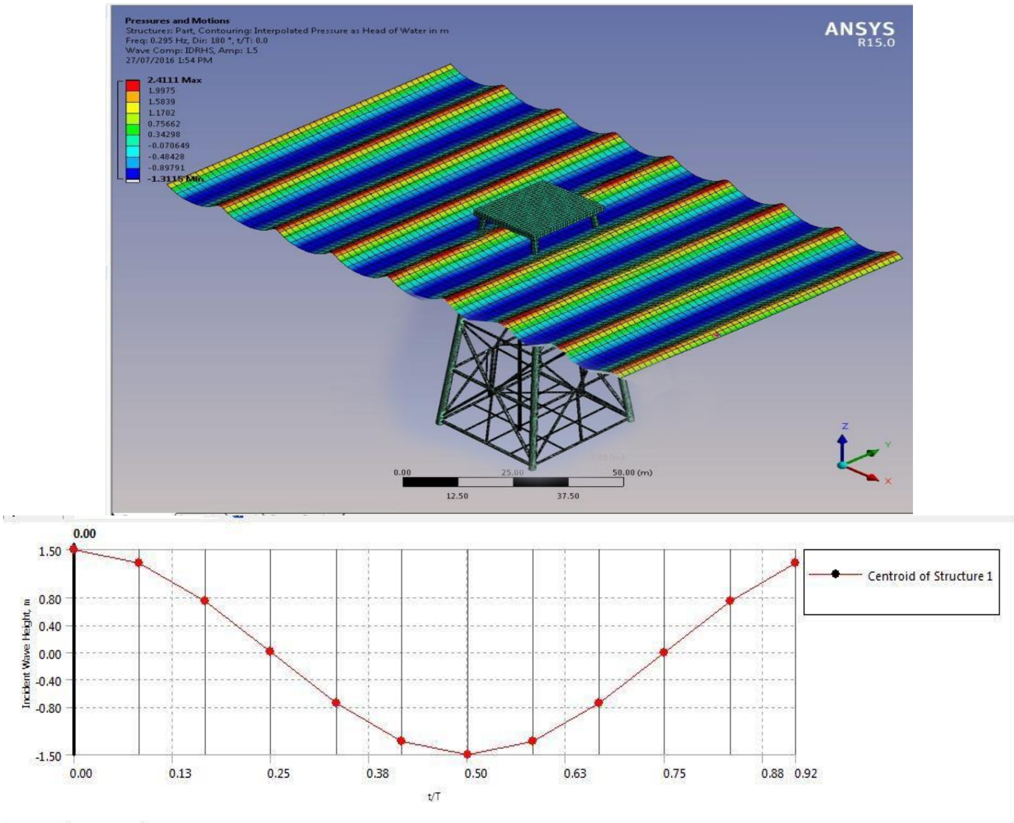

Fig. 5. Frequency-domain representation of wave dynamics under hydrodynamic loading at 582° incidence (T = 3.38 s, H = 3 m per period).

4.2. Time-domain analysis of irregular wave characteristics

Ocean waves exhibit inherent stochasticity and temporal irregularity, making time-history analysis essential for offshore structural performance evaluation. Two fundamental parameters govern wave time histories: (1) significant wave height (H_s) and (2) spectral frequency content. Multiple environmental factors influence these characteristics, including geographical location, sea state conditions, and local bathymetry. This approach enables accurate simulation of hydrodynamic loads critical for offshore structural design and assessment. Figs. 6 and 7 present the time history of the maximum structural displacement under combined hydrodynamic loading, capturing the dynamic response of the structure to complex wave-structure interactions. The plot highlights the superposition of multiple hydrodynamic effects, including wave diffraction, radiation forces, and potential nonlinear contributions from drag, inertia, and current-induced loads. Key features such as peak displacements and oscillatory patterns are evident, with the largest displacements likely corresponding to extreme wave conditions or resonant frequencies. The decay or persistence of oscillations provides insight into the system's damping characteristics and overall stability. This analysis is critical for assessing structural integrity, particularly in harsh marine environments where repeated loading may lead to cumulative damage. The results underscore the importance of considering combined hydrodynamic effects in designing and optimizing offshore structures to ensure safety and longevity under operational and extreme conditions.

Fig. 8 presents the time-history evolution of the maximum structural displacement response under diffraction-dominated hydrodynamic wave forcing. The plot characterizes the dynamic behavior of a large-volume offshore structure where wave diffraction effects prevail over drag-dominated phenomena, as typically observed when the structure's characteristic dimension exceeds the incident wavelength (D/L > 0.2). The displacement profile exhibits distinct phase-dependent oscillations that correlate with the spectral peak period of the incident wave field, with maximum excursions occurring during constructive interference between incident and diffracted wave components. Notably, the response demonstrates (1) quasi-static displacement components corresponding to wave group forcing, (2) resonant amplification at the structure's natural frequencies, and (3) higher-order harmonic components arising from nonlinear wave-structure interactions. These features collectively provide critical insights for survivability analysis, particularly in evaluating extreme responses during design wave conditions and assessing fatigue damage potential through spectral analysis of the displacement time series. The results emphasize the necessity of accounting for both first- and second-order diffraction effects in the dynamic analysis of fixed or floating offshore structures exposed to persistent wave action.

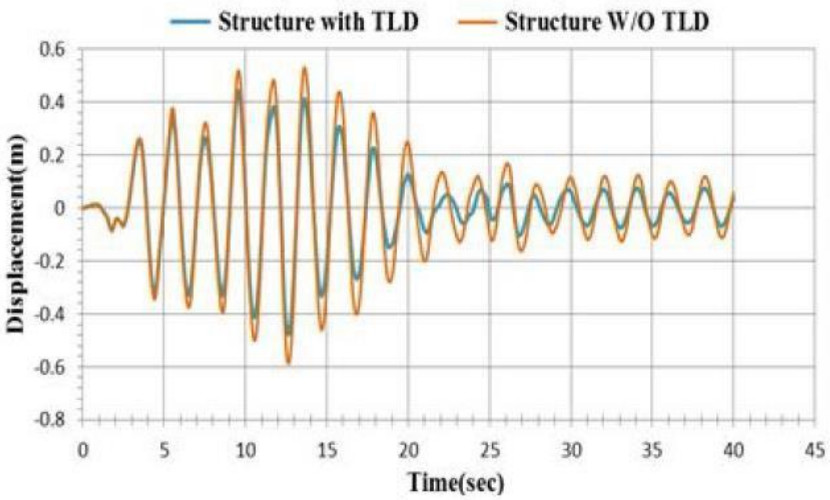

Fig. 6. Time-history of maximum structural displacement under combined hydrodynamic loading.

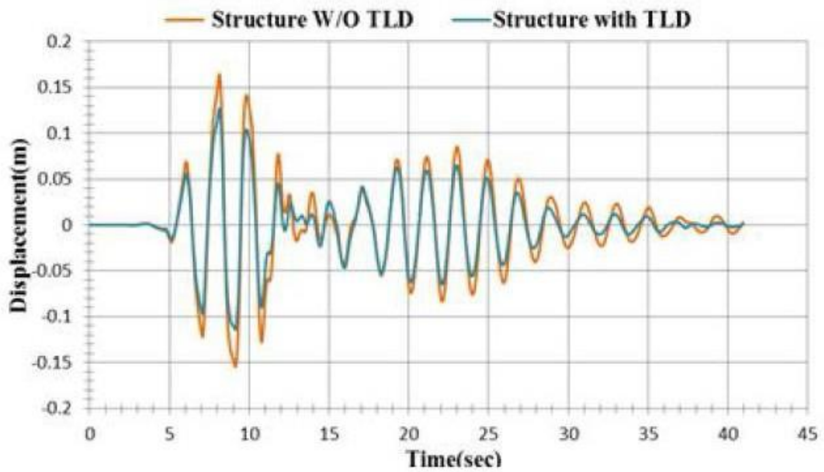

Fig. 7. Time-history of peak structural displacement under combined hydrodynamic loading.

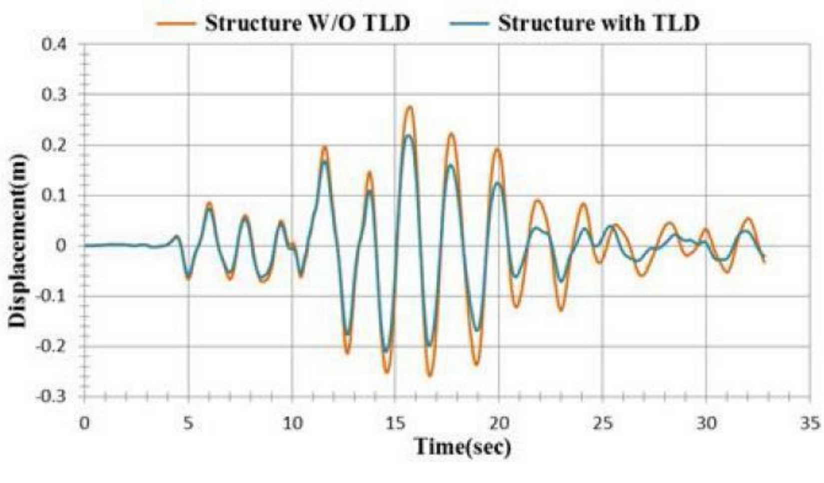

Fig. 8. Time history of the maximum structural displacement induced by diffraction-dominated hydrodynamic wave forces.

5. Conclusions

This study systematically evaluated the effectiveness of a tuned liquid damper (TLD) system in mitigating the dynamic response of offshore platforms subjected to hydrodynamic forces. The key findings are categorized and summarized as follows:

1. The TLD system significantly reduced the maximum displacement of the platform's upper deck, with reductions ranging between 25% and 52%, demonstrating its efficacy in suppressing low-frequency oscillations.
2. A substantial decrease in the maximum shear force of platform legs was observed, with reduction levels between 52% and 252%, indicating improved structural resilience under wave-induced loading.

3. The system effectively damped vibrations, reducing the upper deck's maximum acceleration by 58% to 272%, highlighting its potential to enhance operational safety and fatigue life.
4. An exponential decay trend was identified between hydrodynamic force reduction and increasing wave torque, suggesting diminishing returns at higher load intensities.
5. The stabilizing influence of the TLD led to asymptotic convergence of total force and torque values, approaching a near-constant equilibrium state under sustained wave action.
6. Close agreement was observed between analytical solutions and numerical simulations for regular waves, validating the adopted modeling framework.

Statements & Declarations

Author contributions

Mohammad Ali Arjomand: Conceptualization, methodology, Investigation, Formal analysis, project administration,Resources, Writing - Review & Editing.

Mohsen Bagheri: Conceptualization, methodology, software, validation, formal analysis, investigation, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration.

Yashar Mostafaei: Conceptualization, Methodology, investigation, resources, data curation, Project administration.

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Declaration

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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