Volume (Issue), Year, Page-Page
Research in Education, Technology, and Multiculture
e-ISSN: 3025-6763
https://imrecsjournal.com/journals/index.php/rietm

Hydrodynamic Response Analysis of a Multi-Moonpool Floating Structure Using the Boundary Element Method

Muhammad Taufiq Nur Hidayat [1], Aditya Rio Prabowo [1,*], Ristiyanto Adiputra [1,2,*], Mahfud Alfajar [3], Oleksiy Melnyk [4], Martin Jurkovič [5]

[1]Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta, Indonesia
[2]Research Center for Hydrodynamic Technology, National Research and Innovation Agency (BRIN), Surabaya, Indonesia
[3]P.T. Internik Nusa Prawira, Sidoarjo, Indonesia
[4]Department of Navigation and Maritime Safety, Odesa National Maritime University, Odesa, Ukraine
[5]Faculty of Operation and Economics of Transport and Communication, University of Zilina, Zilina, Slovakia

*Corresponding authors: aditya@ft.uns.ac.id; ristiyanto.adiputra@brin.go.id

Abstract: Over the past decade, marine engineering architecture has adopted moonpool systems for deepwater operations. However, piston-mode resonance remains a critical challenge, causing excessive heave motion. This study aims to evaluate the hydrodynamic response of a displacement-type hull integrated with a multi-moonpool system (one main and sequential cylindrical moonpools) using the Boundary Element Method (BEM). The analysis used ANSYS AQWA based on linearized potential-flow theory, assuming infinite water depth and head-sea conditions. Grid independence tests were conducted at resolutions ranging from 5.0 m to 0.7 m to ensure computational accuracy. The results revealed a significant amplitude deviation in the high-frequency zone (piston-mode resonance), where the BEM solver overpredicted the heave Response Amplitude Operator (RAO) relative to the reference curve. Conversely, in the macro-wave regime, both curves demonstrated perfect asymptotic alignment. The disparity at resonance highlights the inherent limitation of inviscid potential flow theory, which lacks the viscous dissipation needed to account for flow separation and vortex shedding around sharp edges. In conclusion, while BEM is robust for holistic structural mapping, future hydrodynamic optimizations of moonpool structures require integrating viscous damping modifiers to realistically capture amplitude peaks.

Keywords: Boundary element method, Floating structure, Hydrodynamics, Moonpool, Piston mode resonance.

Abstrak: *Selama dekade terakhir, arsitektur teknik kelautan telah banyak mengadopsi sistem moonpool untuk operasi laut dalam. Namun, resonansi mode piston tetap menjadi tantangan kritis karena memicu gerakan heave yang ekstrem. Penelitian ini bertujuan untuk mengevaluasi respons hidrodinamika lambung kapal tipe displacement yang diintegrasikan dengan sistem multi-moonpool menggunakan metode Boundary Element Method (BEM). Analisis dilakukan menggunakan ANSYS AQWA berdasarkan teori aliran potensial terlinierisasi, dengan asumsi perairan dalam dan kondisi head sea. Uji independensi grid dilakukan pada resolusi 5.0 m hingga 0.7 m untuk memastikan akurasi komputasi. Hasil penelitian menunjukkan deviasi amplitudo yang signifikan pada zona frekuensi tinggi (resonansi mode piston), di mana solver BEM memprediksi Response Amplitude Operator (RAO) heave secara berlebihan (overprediction) dibandingkan dengan kurva referensi. Sebaliknya, pada rezim gelombang makro, kedua kurva menunjukkan penyelarasan asimtotik yang sempurna. Disparitas pada titik*

First author et al.
Email: xxx@yyy.ac.id

DOI: http://dx.doi.org/10.23960/jpmipa/v?i?.pp??-??
Received: date month year
Accepted: date month year

resonansi ini menyoroti keterbatasan inheren teori aliran potensial inviskos, yang tidak memiliki disipasi viskos untuk memperhitungkan pemisahan aliran dan pelepasan vorteks di sekitar tepi tajam struktur. Kesimpulannya, meskipun BEM sangat kuat untuk pemetaan struktural holistik, optimisasi hidrodinamika struktur moonpool di masa depan mutlak memerlukan integrasi modifikator redaman viskos untuk menangkap puncak amplitudo secara realistis.

Kata kunci: *Boundary element method, Dinamika fluida, Hidrodinamika, Moonpool, Resonansi mode piston.*

▪ INTRODUCTION

Over the past decade, marine engineering architecture has undergone rapid development, particularly in the design of large-scale floating structures intended for deepwater operations. These massive structures serve as the primary foundation for a wide range of modern offshore operations, from deepwater drilling vessels and wind turbine installations to floating production, storage, and offloading (FPSO) facilities and other advanced platforms (Sheng et al., 2022), (Zhai et al., 2025). The greatest challenge in operating in the open sea environment is the constant exposure to dynamic wave loads. Therefore, evaluating seakeeping characteristics, the ability of a structure to respond to wave excitation while maintaining its stability and mechanical integrity, is a fundamental parameter in the hull design cycle (Sulovsky et al., 2023).

Excessive structural motion response due to wave impact can be fatal. Dynamic motion fluctuations and hydroelastic deformations not only disrupt operational efficiency but also risk compromising the integrity of underwater installations (Zhao et al., 2023). In extreme scenarios, excessive pressure can lead to complete failure of the mooring system, directly endangering the entire platform system (Chen et al., 2024). To mitigate this while optimizing underwater accessibility, modern floating structure designs have widely adopted the integration of moonpool systems (Vijith et al., 2014). In essence, a moonpool is a practical vertical opening in a ship's hull that provides direct access to the seabed, which is inherently protected from surface-wave interactions (Newman, 2005). The installation of this hull gap introduces significant hydrodynamic complexity, despite greatly simplifying operational demands (Cui et al., 2022). It has been clearly demonstrated that the presence of a moonpool changes the fluid flow properties around the hull, increasing hydrodynamic drag (Shahabadi et al., 2017), (Hu et al., 2026). Furthermore, the mean wave drift force, an important metric for platform positional stability, is strongly influenced by the complex fluid interactions around the moonpool gap (Tan et al., 2021).

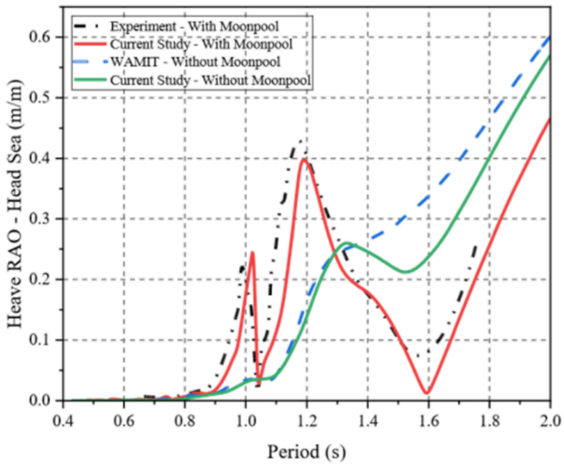


Figure 1. Comparison of Ship Heave Response with and without Moonpool (Fauzi et al., 2026)

The most important fluid-dynamics challenge to anticipate, aside from drag, is piston-mode resonance. As foundational studies have shown, wave-induced water motion inside a moonpool primarily occurs at its natural modes, specifically the sloshing modes (where water oscillates back and forth between walls) and the piston mode, where the enclosed water column heaves vertically, acting somewhat like a rigid body (Molin, 2001). A structure will experience critical oscillatory resonance when the frequency of the incident wave approaches the natural frequency of the fluid inside the moonpool tube (Yang et al., 2013), (Newman, 2018). The entire ship body experiences a sharp increase in vertical translational motion (heave) as a result of this phenomenon (Jiang et al., 2023), (Kristiansen & Faltinsen, 2010). Furthermore, unlike closed tanks, the open bottom of the moonpool allows a nonzero mass flux, which is the primary driver of the piston-mode manifestation (Molin, 2001). Figure 1 illustrates this surge in motion.

Due to their much higher computational efficiency than Computational Fluid Dynamics (CFD) methods, traditional numerical techniques based on the Boundary Element Method (BEM) have become the industry standard for predicting these complex motion anomalies (Newman, 2004). To analyze the sensitivity of the ship motion response, numerical evaluation of changes in the hull size ratio and opening configuration has proven crucial (Fauzi et al., 2026). Driven by this urgency, the objective of this study is to use the commercial solver ANSYS AQWA to benchmark a BEM against the seakeeping profiles of a full-scale floating structure with a multi-moonpool system. The three main objectives of this study are: (1) to replicate the Heave Response Amplitude Operator (RAO) curve under bow wave conditions; (2) to examine the mesh sensitivity using a grid independence study; and (3) to assess the theoretical limitations of the BEM in representing fluid resonance in the hull opening area.

▪ METHOD

▪ Mathematical Formulation of Wave and Floating Structure Interaction

The hydrodynamic modeling in this study is based on Potential Flow Theory. This mathematical approach assumes that the fluid (seawater) is inviscid, incompressible, and irrotational (Newman, 2004). This classical linearized potential-flow formulation has historically proven highly effective in treating both two- and three-dimensional moonpool oscillation problems under the assumption of infinite water depth (Molin, 2001). Based on these assumptions, the scalar flow velocity potential, $\Phi(x, y, z, t)$, is conditioned to satisfy the law of conservation of mass through the Laplace Equation within the fluid domain:

$$\nabla^2\Phi = 0 \qquad (1)$$

The solution to the Laplace Equation requires the establishment of boundary conditions across the entire computational domain (Fauzi et al., 2026):

Seabed boundary condition: Assumes no fluid flow penetrates the seabed at depth $z = -d$,

$$\frac{\partial\Phi}{\partial z} = 0 \qquad (2)$$

Free surface boundary condition: A linear combination of kinematic and dynamic conditions at the undisturbed water surface elevation ($z = 0$),

$$\frac{\partial\Phi}{\partial z} = -\frac{1}{g}\frac{\partial^2\Phi}{\partial t^2} \qquad (3)$$

Body surface boundary condition: The velocity of the fluid particles directly in contact with the structure's hull must equal the normal velocity of the body element (v_n),

$$\frac{\partial\Phi}{\partial n} = v_n \qquad (4)$$

The total flow potential is the sum of the incident wave, diffraction, and radiation potentials. The hydrodynamic pressure (p) is obtained through the linearized Bernoulli Equation:

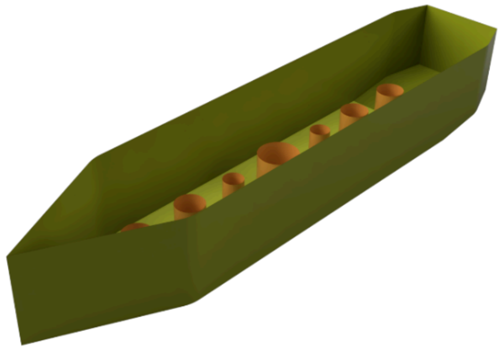
$$p = -\rho\frac{\partial\Phi}{\partial t} - \rho g z \qquad (5)$$

The area integration of the fluid pressure across the immersed hull webs (including the internal curvature planes of the seven moonpool tubes) is translated into an added mass matrix (A_{jk}) and a wave radiation attenuation (B_{jk}) (Fauzi et al., 2026). The 6-DOF matrix Newtonian equation of motion is expressed as:

$$\sum_{j,k=1}^{6}\left[-\omega^2\left(M_{jk} + A_{jk}(\omega)\right) + i\omega B_{jk}(\omega) + C_{jk}\right]\xi_k = F_j(\omega) \qquad (6)$$

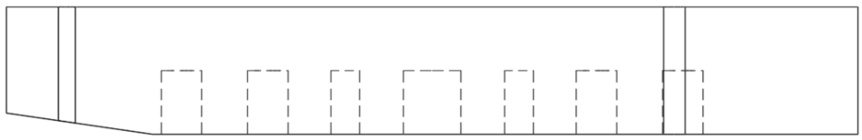
In the formulation of equation (6) above, ω indicates the circular frequency of the wave, M_{jk} is the mass inertia matrix of the structure, C_{jk} represents the hydrostatic restoring force of the water plane, ξ_k is the amplitude response displacement, and F_j is the combined Froude-Krylov excitation force. The analysis in this study is focused on solving the vertical motion amplitude parameters (xi_3) expressed in the form of a non-dimensional Response Amplitude Operator (RAO) Heave (Fauzi et al., 2026).

- **Multi-Moonpool Architectural Design and Floating Structure Geometry**

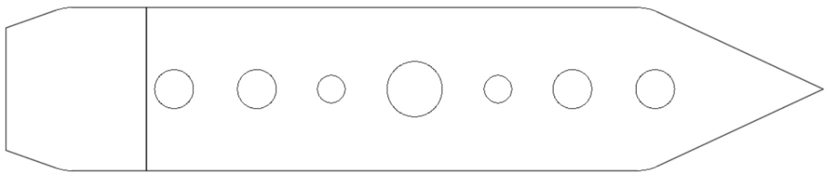


This study object is modeled using a full-scale displacement-type architecture. As presented in **Figure 2**, the structural configuration includes one main moonpool unit in the midship area, accompanied by several additional cylindrical openings distributed sequentially along the hull's longitudinal axis.

(a)



(b)



(c)

Figure 2. Ship Geometry with Multi-Moonpool Configuration: (a) isometric, (b) plan, and (c) profile views.

- **Inertia Matrix Equivalence and Weight Parameters**

A major challenge in dynamic computation is determining the center of inertia for a hull with complex gaps. Therefore, the mass properties are set at 68,205 MT to stabilize the solver's calculation matrix. The main dimension specifications of the structure are tabulated in **Table 1**.

Table 1. Main Dimensions of the Floating Structure's Primary Parameters

No	Parameters	Variable	value	units
1	*Length Overall*	LoA	177.300	meter
2	(*Beam*)	B	35.464	meter
3	*Draft*	d	13.299	meter

- **Marine Domain Restriction and BEM Convergence**

To obtain a pure wave propagation profile without interference from seabed reflections, the simulation is executed under Infinite Water Depth conditions. The wave heading angle is locked at 180° (head sea). The mesh discretization of the hull structure panels is shown in **Figure 3**.

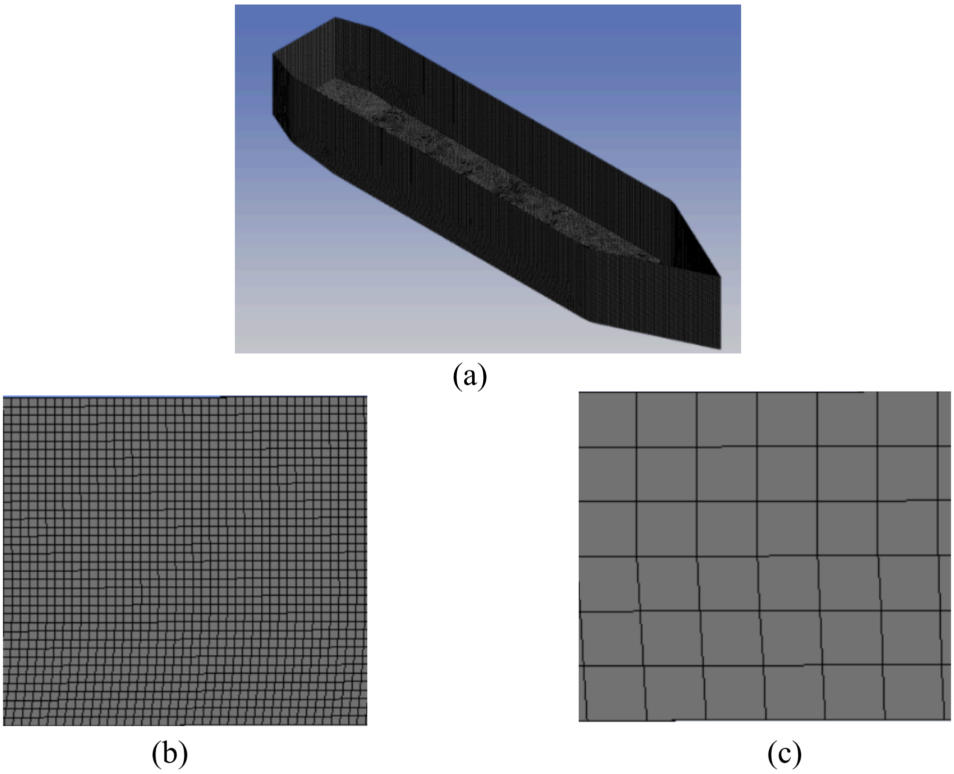


Figure 3. Computational Mesh of the Ship Model: (a) isometric view, (b) 0,7m mesh detail, and (c) 5m mesh detail.

- **RESULT AND DISCUSSION**

The evaluation of the number of elements, peak amplitude values, and relative differences across various mesh configurations is summarized in Table 2. There are differences in the convergence characteristics between the two peaks. The 2nd Peak RAO value (macro waves) is stable and reaches the convergence line from the 2.0 m element size with a fluctuation approaching 0.000%. Conversely, the 1st Peak RAO (piston-mode resonance) requires a higher mesh resolution to capture hydrodynamic pressure gradients at the moonpool boundaries. This convergence trajectory is shown in **Figure 4**.

Table 2. Mesh convergence evaluation based on the number of elements and the relative difference of peak amplitudes.

Mesh Resolution (m)	Total Elements	1st Peak RAO (m/m)	Relative Dif 1 (%)	2nd Peak RAO (m/m)	Relative Dif 2 (%)
5.0	954	0.21974	-	0.99901	-
4.0	1.523	0.23273	5.91	0.99907	0.006
3.0	2.487	0.22404	3.73	0.99907	0.000
2.0	5.158	0.24542	9.54	0.99910	0.003
1.5	8.775	0.26735	8.94	0.99910	0.000
1.0	19.636	0.27102	1.37	0.99910	0.000
0.7	38.748	0.26966	0.50	0.99911	0.001

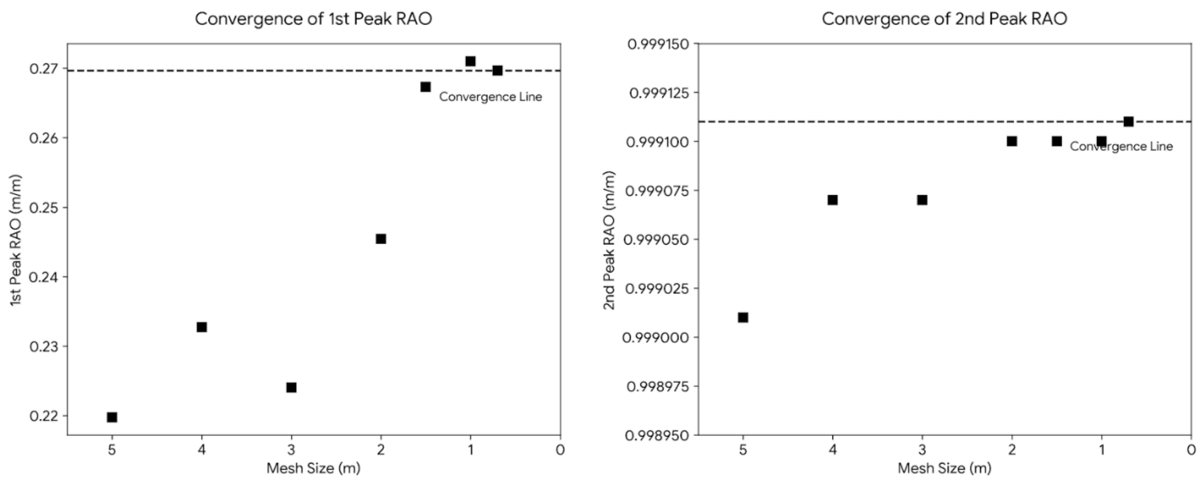
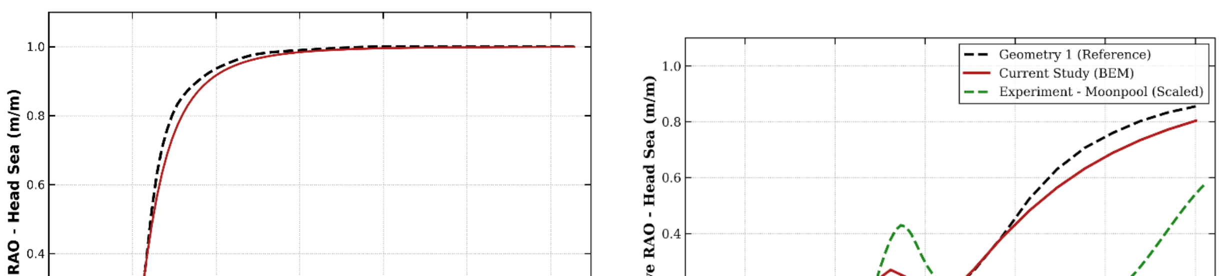


Figure 4. Asymptotic distribution curve of mesh convergence at the first and second resonance peaks

Based on this analysis, the **0.7 m** element size was adopted as the final operational resolution. At this size, the relative difference percentage at the 1st Peak reached 0.50%, well below the conventional numerical tolerance limit (2%), confirming the occurrence of absolute grid convergence with a total of 38,748 elements. The benchmarking process was performed by directly comparing the actual BEM computed RAO Heave curve profile (Current Study) with the reference study curve labeled Geometry 1. This comparison of dynamic responses under Head Sea excitation is presented in Figure 5. The reference used (Ravinthrakumar, Kristiansen, Molin, & Ommani, 2020) serves as a baseline validity checkpoint to ensure the adequacy of the BEM matrix distribution pattern.



(a) (b)

Figure 5. Comparison of Heave RAO Profiles between Present BEM Study and Reference Data under Head Sea Condition

The hydrodynamic behavior is visually divided into two separate zones by the comparison curve. A striking amplitude deviation is evident at the moonpool resonance peak in the high-frequency range (wave period less than 15 s). Compared with the reference data, the actual BEM computational curve exhibits a higher, sharper spike. As quantitatively detailed in Table 3, the absence of viscous dissipation in the BEM solver led to a significant amplitude overprediction of 68.77% at the resonance peak, accompanied by a 1.24-second phase shift compared to the reference geometry. This is a natural phenomenon that illustrates the theoretical limit of the inviscid potential-flow solver (Fu et al., 2026). When the wave frequency coincides with the fluid's intrinsic frequency in the tube, the software will automatically overpredict without viscous-friction damping.

Table 3. Comparison of Heave RAO peak values at piston-mode resonance

Parameter	Geometry 1 (Reference)	Current Study (BEM)	Deviation
Resonance Wave Period (s)	8.00	9.24	+ 1.24 s
Peak Heave RAO (m/m)	0.1598	0.2697	+ 68.77%

▪ CONCLUSIONS

This study demonstrated the applicability of the Boundary Element Method (BEM) implemented in ANSYS AQWA to evaluate the hydrodynamic behavior of a full-scale displacement-type floating structure with a multi-moonpool configuration under head sea conditions. The numerical model successfully reproduced the overall heave response characteristics and achieved solution convergence through systematic mesh refinement, confirming the reliability of the adopted computational framework. The comparison with reference data showed that the BEM approach provides accurate predictions in the macro-wave regime, where hydrostatic restoring effects dominate the system response. However, significant deviations observed near the piston-mode resonance highlight the inherent limitations of inviscid potential-flow formulations in capturing viscous dissipation associated with flow separation and vortex shedding around moonpool boundaries. These findings contribute to a deeper understanding of the hydrodynamic performance of multi-moonpool structures and indicate that future design optimization and response prediction efforts should incorporate viscous damping corrections or coupled high-fidelity numerical models to better characterize resonance and operational reliability in offshore applications.

▪ REFERENCES

Chen, M., Yang, L., Sun, X., Pan, J., Zhang, K., Lin, L., … Chen, Z. (2024). Dynamic Analysis of a Barge-Type Floating Wind Turbine Subjected to Failure of the Mooring System. *Journal of Marine Science and Engineering*, *12*(4). https://doi.org/10.3390/jmse12040617

Cui, J., Chen, X., Sun, P. N., & Li, M. Y. (2022). Numerical investigation on the hydrodynamic behavior of a floating breakwater with moon pool through a coupling SPH model. *Ocean Engineering*, *248*. https://doi.org/10.1016/j.oceaneng.2022.110849

Fauzi, F. N., Satrio, D., & Adiputra, R. (2026). Hydrodynamic Responses of Floating Oscillating Water Column for Wave Energy Conversion. *E3S Web of Conferences*, *687*, 01010. https://doi.org/10.1051/e3sconf/202668701010

Fu, S., Gao, W., Li, Y., Xie, Y., Wang, T., & An, C. (2026). Research on Prediction Method for Heave Motion of Cylindrical FPSO Based on Viscous Correction. *Journal of Marine Science and Engineering*, *14*(5). https://doi.org/10.3390/jmse14050474

Hu, J., Zhang, Z., Song, C., Wang, J., Yu, X., & Zhang, D. (2026). Motion Characteristics and Drag-Reduction Optimization of Moonpool Drillships in Irregular Waves. *Journal of Marine Science and Engineering*, *14*(10). https://doi.org/10.3390/jmse14100890

Jiang, S. C., Ran, Y. Q., & Feng, A. (2023). On the hydrodynamic behaviour of second-order harmonic induced sloshing-mode resonance in moonpool. *Marine Structures*, *92*. https://doi.org/10.1016/j.marstruc.2023.103503

Kristiansen, T., & Faltinsen, O. M. (2010). A two-dimensional numerical and experimental study of resonant coupled ship and piston-mode motion. *Applied Ocean Research*, *32*(2), 158–176. https://doi.org/10.1016/j.apor.2009.10.001

Newman, J. N. (2004). *Progress in wave load computations on offshore structures*.

Newman, J. N. (2018). *Resonant response of a moonpool with a recess*.

Newman, J. N. (2005). *Wave effects on vessels with internal tanks*.

On the piston and sloshing modes in moonpools. (2001). In *J. Fluid Mech* (Vol. 430).

Ravinthrakumar, S., Kristiansen, T., Molin, B., & Ommani, B. (2020). Coupled vessel and moonpool responses in regular and irregular waves. *Applied Ocean Research*, *96*. https://doi.org/10.1016/j.apor.2019.102010

Shahabadi, M., shadlaghani, A., & Mansoorzadeh, S. (2017). Evaluation of Moonpool Effects on Hydrodynamic Resistance of a Supply Vessel, Using Experimental and Numerical Methods. *International Journal of Maritime Technology*, *7*, 1–9. https://doi.org/10.18869/acadpub.ijmt.7.1

Sheng, W., Tapoglou, E., Ma, X., Taylor, C. J., Dorrell, R. M., Parsons, D. R., & Aggidis, G. (2022). Hydrodynamic studies of floating structures: Comparison of wave-structure interaction modelling. *Ocean Engineering*, *249*. https://doi.org/10.1016/j.oceaneng.2022.110878

Sulovsky, I., Hauteclocque, G. de, Greco, M., & Prpić-Oršić, J. (2023). Comparative Study of Potential Flow and CFD in the Assessment of Seakeeping and Added Resistance of Ships. *Journal of Marine Science and Engineering*, *11*(3). https://doi.org/10.3390/jmse11030641

Tan, L., Ikoma, T., Aida, Y., & Masuda, K. (2021). Mean wave drift forces on a barge-type floating wind turbine platform with moonpools. *Journal of Marine Science and Engineering*, *9*(7). https://doi.org/10.3390/jmse9070709

Vijith, P. P., Viswanathan, S., & Panneerselvam, R. (2014). *MOONPOOL EFFECTS ON A FLOATING BODY*. Retrieved from www.jifactor.com

Yang, S. H., Yang, Y. J., Lee, S. B., Do, J., & Kwon, S. H. (2013). Study on Moonpool Resonance Effect on Motion of Modern Compact Drillship. *Journal of Ocean Engineering and Technology*, *27*(3), 53–60. https://doi.org/10.5574/ksoe.2013.27.3.053

Zhai, H., Yan, C., Shi, W., Zhang, L., Zeng, X., Han, X., & Michailides, C. (2025). Experimental Study on the Hydrodynamic Analysis of a Floating Offshore Wind

Turbine Under Focused Wave Conditions. *Energies*, *18*(15). https://doi.org/10.3390/en18154140

Zhao, X., Xue, F., Chen, L., Göteman, M., Han, D., Geng, J., & Sun, S. (2023). Hydrodynamic analysis of a floating platform coupled with an array of oscillating bodies. *Ocean Engineering*, *287*. https://doi.org/10.1016/j.oceaneng.2023.115439