

Seakeeping comparison of FPSO hulls with and without a moonpool at forward speed

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Abstract- Moonpool openings can alter vessel motions through interactions between the external wave field, hull motion and the enclosed water column. This study compares two floating production, storage and offloading hull configurations, with and without a moonpool, at a reported speed of 13.45 knots and wave headings of 90°, 120° and 150°. A frequency-domain formulation is established, and reported response amplitude operator and added-resistance summaries are analysed using midpoint comparisons and interval arithmetic. The moonpool configuration has reported heave response levels of 1.75–1.80, 1.25–1.30 and 0.80–0.85 at the three headings, respectively. Corresponding values for the configuration without a moonpool are 1.30–1.35, approximately 1.00 and 1.05–1.08. Midpoint comparisons indicate heave increases of approximately 34.0% and 27.5% at 90° and 120°, followed by a 22.5% decrease at 150°. The reported added-resistance ordinate is lower for the moonpool configuration at all three headings, with midpoint reductions of approximately 52.1%, 81.4% and 93.7%. These comparisons are preliminary: the dataset contains approximate response summaries, and common displacement, response normalization and numerical convergence are not established. The results identify a heading-dependent motion trade-off rather than a universal benefit from adding a moonpool. Verification of the resistance normalization, hull loading conditions and moonpool damping is required before extrapolating these trends to propulsion demand or stationary offshore operation.

Keywords: FPSO; moonpool; seakeeping; response amplitude operator; wave heading; added resistance

I. INTRODUCTION

Floating production, storage and offloading vessels combine hydrocarbon processing, storage and transfer functions on a floating hull. Their hydrodynamic performance influences equipment operability, relative motions at marine interfaces and the loads transmitted to offshore systems. The six rigid-body motions are surge, sway, heave, roll, pitch and yaw.

Translational and rotational responses must be evaluated with their respective units and reference points, because a large value in one motion mode is not directly comparable with a differently normalized value in another. Linear marine hydrodynamics provides a framework for relating wave excitation to these motions through inertia, radiation damping and restoring terms [1].

A moonpool introduces an internal water surface and an opening through the hull. Its water column can undergo a piston mode, in which the surface moves approximately vertically, and sloshing modes with spatially varying surface elevations. The resonance frequencies depend on the moonpool geometry and its interaction with the surrounding water [2]. Consequently, adding an opening is not equivalent to applying a uniform correction to a conventional hull response. The effects can vary with wave frequency, heading, loading condition and vessel speed.

Coupled vessel-moonpool experiments demonstrate that the relative size of the opening matters. Ravinthrakumar et al. [3] found substantial dependence on moonpool volume relative to submerged vessel volume and identified nonlinear behaviour that linear potential-flow predictions did not reproduce adequately near resonance. In a separate drillship investigation, changing moonpool configurations at constant displacement affected motion responses in a mode-dependent manner, including heave near piston-mode resonance [4]. These findings support comparisons that preserve the vessel loading condition and examine individual motion modes.

The offshore Nigerian context motivates evaluating alternative FPSO configurations, but regional relevance does not by itself establish a site-specific design assessment. A moored production vessel and a

vessel advancing at 13.45 knots represent different operating conditions. Furthermore, a response amplitude operator, or RAO, characterizes motion per unit wave input; it is not a hydrodynamic velocity potential or an excitation-force transfer function. Mean added resistance is also distinct from the first-order oscillatory wave force. Maintaining these distinctions is essential when interpreting a comparative seakeeping analysis. Experiments and nonlinear computations at low forward speed further show why wave-induced moonpool resonance must be assessed for the stated flow condition [5].

This paper evaluates how reported heave, pitch and added-resistance levels differ between two FPSO hull configurations at three headings. Its contribution is a reproducible comparison of the available response summaries, together with a consistent governing formulation and an assessment of the conclusions those summaries support. The analysis is restricted to the documented forward-speed cases. It does not estimate mooring-line tensions, extreme response probabilities or operational limits for an identified Escravos sea state.

II. PHYSICAL BASIS OF THE COMPARISON

Moonpool–hull interaction involves both inertia and dissipation. Fluid acceleration inside and around the opening modifies the hydrodynamic reaction, while radiation, flow separation and free-surface effects influence the response near resonance. Faltinsen and Timokha [6] represented vortex-induced losses through a pressure-discharge relation in a model of piston-mode sloshing under forced heave. A single damping value cannot therefore be assumed to describe every opening geometry or excitation amplitude.

Viscous calculations show that vorticity and the opening corner geometry affect moonpool damping under forced heave [7]. The effectiveness of convex appendages also depends on their position and the forcing amplitude [8]. Experiments with grids, flaps, baffles and vertical bulkheads further demonstrate the need to specify the damping arrangement when comparing configurations [9].

Location and entrance geometry are also relevant design variables. A numerical and experimental investigation by Yadav et al. [10] examined moonpool positioning in a floating drilling, production, storage and offloading vessel. A related CFD study considered alternative bottom openings for a conceptual FPSO [11]. These studies support treating the moonpool as an explicitly resolved hydrodynamic feature rather than inferring its behaviour from the external hull outline alone. Experiments on a recessed drilling-vessel moonpool identified coexisting resonant modes, reinforcing the importance of the internal geometry [12]. Potential-flow calculations also show that recess dimensions alter the resonant frequencies and mode shapes [13].

Resistance requires particular care. Yadav et al. [14] investigated a large FPSO with an annular moonpool using CFD and model experiments, and reported increased resistance associated with moonpool oscillations. That finding does not prohibit reductions in a particular wave-added-resistance component for another configuration, but it prevents assuming that a lower reported response ordinate proves lower total resistance. Calm-water resistance, wave-added resistance and propulsion demand must be distinguished.

III. MATERIALS AND METHODS

The comparison covers a hull with a moonpool, denoted M, and a hull without a moonpool, denoted N. Figure 1 reproduces plan and perspective views of the two models. The opening is visible in the moonpool plan view, but the images are not used to infer dimensions or physical scaling. The reported forward speed is 13.45 knots, equivalent to 6.919 m s^{-1} , and the numerical heading labels are 90° , 120° and 150° .

The numerical dataset consists of six case descriptions reporting approximate upper response levels and selected frequency ranges. The original frequency-by-frequency RAO exports and numerical hydrodynamic coefficients are not part of this dataset. Table 1 records the reported values. Values described as ranges are retained as intervals; values described as approximately a single number remain approximate point estimates. The term “reported peak” refers to

these described upper response levels, including the low-frequency heave levels at 120° and 150°, rather than to a new search for maxima in the original solver

output. An unquantified moonpool pitch response at 90° is retained as missing rather than assigned zero.

Table 1. Reported response levels used for the comparison at 13.45 knots.

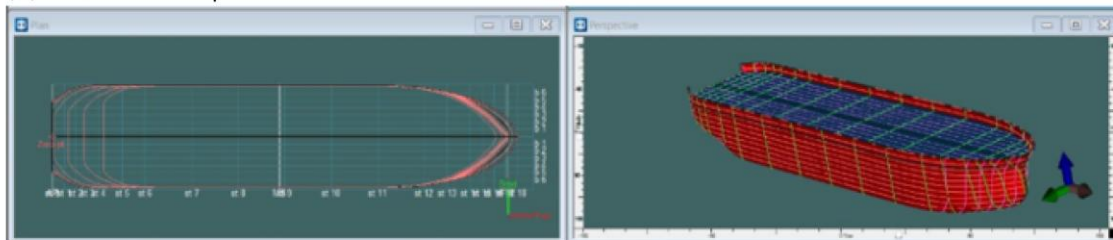
Configuration	Heading	Heave RAO	Pitch RAO	Added-resistance ordinate
With moonpool	90°	1.75–1.80	Not quantified	≈170
Without moonpool	90°	1.30–1.35	0.55–0.60	350–360
With moonpool	120°	1.25–1.30	0.55–0.60	55–75
Without moonpool	120°	≈1.00	≈0.60	≈350
With moonpool	150°	0.80–0.85	0.80–0.85	20–22
Without moonpool	150°	1.05–1.08	≈0.90	330–340

RAOs retain the reported scales. The rotational normalization is not documented. Added-resistance values retain the reported unit kN m^{-2} ; its amplitude or wave-height normalization remains to be confirmed. Approximate point estimates have no stated range, which must not be interpreted as zero uncertainty.

Vessel dimensions, displacement, draft, centre of gravity, radii of gyration, moonpool dimensions, water

depth and solver settings are not quantified in the comparison record. These omissions prevent an independent reproduction of the hydrodynamic solution and a controlled attribution of every difference to the opening alone. The cases are therefore compared as two configurations with a reported common speed, not as an established matched-displacement experiment.

(a) Without moonpool



(b) With moonpool

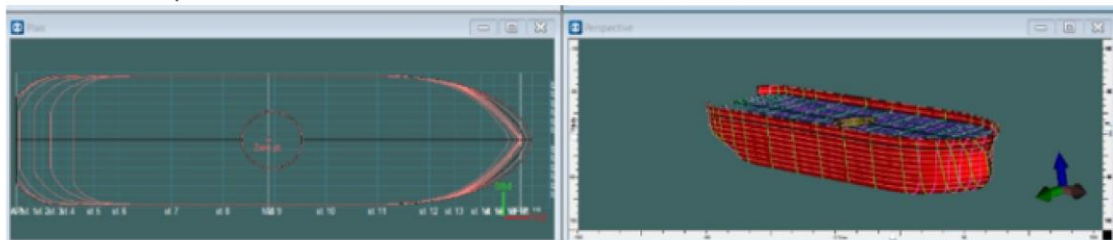


Figure 1. Plan and perspective views of the hull configurations: (a) without a moonpool and (b) with a moonpool. Views are cropped from the original model screenshots. They identify the configurations qualitatively; they do not establish matched dimensions, displacement or inertia.

3.1 Governing motion equations

Let the complex motion vector contain the six rigid-body response amplitudes at a specified reference point. For harmonic excitation, a linear frequency-domain model has the form

$$[-\omega_e^2(M + A) + i\omega_e(B_r + B_v) + C_h + C_m]\hat{\xi} = a f_{\text{exc}}. \quad (1)$$

Here, M is the rigid-body mass and inertia matrix; A is the added-mass matrix; B_r and B_v represent radiation and linearized viscous damping; C_h is hydrostatic restoring stiffness; C_m is an optional linearized mooring stiffness; and f_{exc} is wave-excitation force and moment per unit wave amplitude a . Rotational entries have the corresponding moment units. Hydrodynamic coefficients must be evaluated using a formulation appropriate to the vessel speed. The mooring term is relevant only when such a system is modelled; it is not inferred for the present forward-speed cases.

Radiation damping and viscous damping are separate mechanisms, and restoring coefficients are stiffness terms rather than forces by themselves. Defining the bracketed dynamic matrix as D , coupled heave and pitch are expressed as

$$\begin{bmatrix} D_{33} & D_{35} \\ D_{53} & D_{55} \end{bmatrix} \begin{bmatrix} \hat{\xi}_3 \\ \hat{\xi}_5 \end{bmatrix} = a \begin{bmatrix} f_3 \\ f_5 \end{bmatrix}, \quad I_{55} = mk_s^2. \quad (2)$$

The off-diagonal terms retain heave–pitch coupling. In the inertia relation, m is vessel mass and k_s is the pitch radius of gyration; the radius must be squared. Decoupled roll can be a useful approximation in selected symmetric conditions, but it is not a general assumption for oblique seas. The present dataset does not contain enough numerical roll information for a separate quantitative comparison.

For a wave propagation direction making an angle β with the vessel velocity, the encounter frequency and finite-depth dispersion relation are

$$\omega_e = \omega - kU\cos\beta, \quad \omega^2 = gk\tanh(kh). \quad (3)$$

Under this stated convention, 0° is following propagation and 180° is opposing propagation. Therefore, 120° and 150° lie on the head-sea side of beam seas, rather than automatically representing stern-quartering seas. Because the original software direction convention is not archived, the comparison graphs retain the numerical heading labels. The heading transformation must be checked before importing the original results into Equation (3). Water depth is also a physical input to the natural-mode problem for moonpools and gaps, rather than only a plotting parameter [15].

For translational response, an amplitude-normalized RAO is

$$H_j = \hat{\xi}_j/a, \quad j = 1, 2, 3; \quad H_\theta = \hat{\theta}/a. \quad (4)$$

An angular RAO may instead be normalized by wave slope, giving $H_\theta^s = \hat{\theta}/(ka)$. These alternatives have different units and require conversion before spectral integration. The comparison retains each mode's reported scale and assumes identical normalization between configurations for the same mode. Heave and pitch ordinate magnitudes are not used to rank their physical severity against each other.

3.2 Moonpool coupling and dissipation

An explicit moonpool model can augment the rigid-body coordinates with a water-column coordinate q . A generic coupled system can be written as

$$\begin{bmatrix} D_{hh} & D_{hq} \\ D_{qh} & D_{qq} \end{bmatrix} \begin{bmatrix} \hat{\xi} \\ \hat{q} \end{bmatrix} = a \begin{bmatrix} f_h \\ f_q \end{bmatrix}. \quad (5)$$

The added coordinate represents an internal free-surface mode and its coupling to hull motion. Coupling to a freely floating body can shift the natural resonance from the uncoupled water-column frequency [16]. Alternatively, a hydrodynamic solver can resolve the internal free surface directly. These approaches must not be superimposed in a way that counts the same water-column inertia twice. Entrance losses and any nonlinear dissipation require calibration or higher-fidelity treatment. Ravinthrakumar et al. [3] demonstrated substantial overprediction near resonance when wave-radiation

damping alone did not capture the dominant dissipation. The present peak data cannot identify the coupling coefficients, damping or an internal resonance mode uniquely.

Related ship-terminal gap experiments identified flow-separation damping as an important control on coupled resonant motion, although that geometry differs from an FPSO moonpool [17]. A domain-decomposition method subsequently combined a local viscous region with an outer potential-flow domain to model gap resonance [18]. For a floating two-dimensional body with a moonpool, nonlinear hybrid calculations improved agreement with measured coupled responses compared with a semi-linear treatment [19].

3.3 Spectral response formulation

JONSWAP provides a wind-wave spectral representation, but its parameters must come from the relevant sea-state characterization rather than from the vessel RAOs. A global assessment found substantial spatial variation in the suitability of standard JONSWAP parameter choices, supporting site-specific calibration [20]. For angular frequency ω , a convenient normalized implementation is

$$S_{\eta}(\omega) = \frac{H_s^2}{16} \frac{\tilde{S}(\omega)}{\int_0^{\infty} \tilde{S}(\omega) d\omega},$$

$$\tilde{S}(\omega) = g^2 \omega^{-5} \exp \left[-\frac{5}{4} \left(\frac{\omega_p}{\omega} \right)^4 \right] \gamma^{\exp[-(\omega - \omega_p)^2 / (2\sigma^2 \omega_p^2)]}.$$
(6)

Here, H_s is significant wave height, $\omega_p = 2\pi/T_p$ is peak angular frequency, γ controls peak enhancement, and the conventional JONSWAP width parameter is $\sigma = 0.07$ below the peak and 0.09 above it. Normalizing the spectrum enforces its variance as $H_s^2/16$. A mixed wind-sea and swell state may require separate spectral partitions rather than a single fitted peak.

For a directional wave spectrum and an amplitude-normalized transfer function, response variance can be evaluated in the incident-frequency domain as

$$m_{0,j} \int_0^{\infty} \int_0^{2\pi} |H_j(\omega, \beta, U)|^2 S_{\eta}(\omega, \beta) d\beta d\omega, \text{ RMS}_j = \sqrt{m_{0,j}}.$$
(7)

The transfer function in Equation (7) is evaluated with the appropriate encounter-frequency mapping. Working in the incident-frequency domain avoids combining a wave-frequency spectrum directly with an unmatched encounter-frequency axis. If an encounter-frequency spectrum is used instead, the transformation must conserve variance and account for the frequency mapping. No numerical spectra or RMS responses are calculated here because H_s , T_p , directional spreading and complete RAO arrays are not specified. Long-crested waves are not assumed to be uniformly conservative or unconservative; the effect depends on the directional distribution and vessel response.

3.4 Added resistance and comparative metrics

Added resistance in waves is the increase in mean resistance relative to calm water at the same speed and loading condition, consistent with the ITTC definition [21]:

$$R_{AW} = \bar{R}_{\text{waves}} - \bar{R}_{\text{calm}}, \quad Q_R = R_{AW}/a^2. \quad (8)$$

The second expression illustrates a possible amplitude-squared normalization: force divided by amplitude squared has units N m^{-2} . This unit does not make the ordinate a local pressure measurement. A wave-height-squared definition would differ by a factor of four because wave height is $2a$. The reported added-resistance ordinate is denoted A^R until its exact definition is recovered. Percentage comparisons assume the same definition and scaling for both configurations. They do not provide fuel-consumption or delivered-power savings; these require further resistance and propulsion information [22].

For a reported interval $[L, U]$, the representative value is its midpoint, $x_c = (L + U)/2$. The relative difference uses the configuration without a moonpool as the reference:

$$\Delta_x = 100 \left(\frac{x_M}{x_N} - 1 \right),$$

$$\Delta_{\min} = 100 \left(\frac{L_M}{L_N} - 1 \right), \quad \Delta_{\max} = 100 \left(\frac{U_M}{U_N} - 1 \right).$$
(9)

All denominators in this dataset are positive. Approximate point estimates are entered with identical numerical lower and upper values solely to evaluate this arithmetic; this convention does not assign zero measurement uncertainty. The propagated ranges describe sensitivity to the stated source ranges and are not confidence intervals. Missing values remain missing. The reproducible calculation sorts the three headings, plots midpoint markers and range whiskers, and computes Equation (9) independently for heave, pitch and added resistance. Connecting lines are visual guides between the documented headings, not predictions at untested headings or reconstructed RAO curves.

IV. RESULTS

Figure 2a shows a decrease in the reported heave level of configuration M as the heading changes from 90° to 150°. Its representative values are 1.775, 1.275 and 0.825, compared with 1.325, 1.000 and 1.065 for configuration N. These midpoints carry no greater experimental precision than the ranges in Table 1. At 90°, both case descriptions place the prominent heave response near 0.50–0.55 rad s⁻¹ encounter frequency. This corresponds to an encounter-period range of approximately 11.4–12.6 s; it does not by itself identify a moonpool natural period.

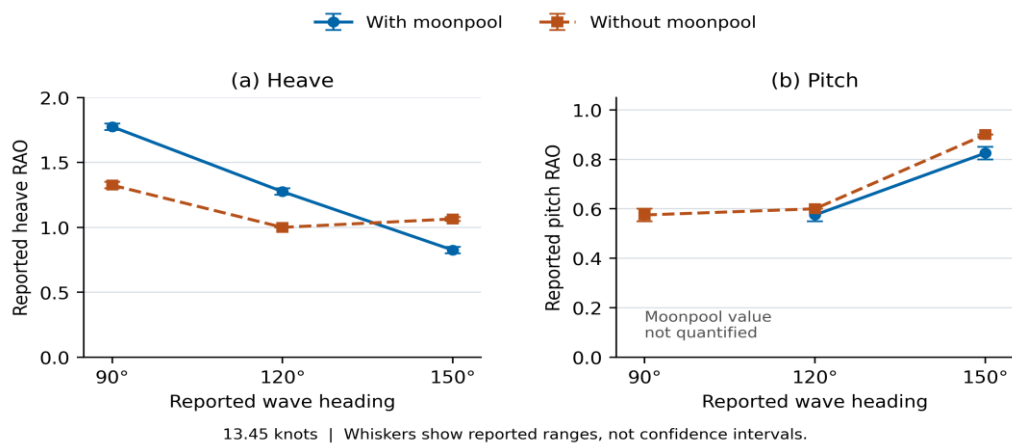


Figure 2. Comparison of reported heave and pitch response levels at 13.45 knots. Markers show midpoints of stated ranges or approximate point estimates; whiskers show only the stated ranges, not statistical uncertainty. Lines connect documented headings. The moonpool pitch value at 90° is unquantified and is not plotted. RAO normalization is retained from the source descriptions and must be checked against the original export.

The midpoint heave increase for configuration M is approximately 34.0% at 90°, with source-range arithmetic spanning 29.6–38.5%. At 120°, the increase is approximately 27.5%, with a 25.0–30.0% range conditional on the approximate reference value of 1.00. The sign reverses at 150°: configuration M is approximately 22.5% lower, with a propagated range of 19.0–25.9% lower. The heave intervals do not overlap between configurations at any of these

headings. This establishes the sign of the comparison within the reported ranges, although it does not account for unreported modelling or measurement errors.

Figure 2b presents pitch separately. At 120°, the moonpool range of 0.55–0.60 includes the approximate non-moonpool value of 0.60; the midpoint decrease of 4.2% is therefore weak evidence of a difference. At 150°, the moonpool range of 0.80–0.85 is below the approximate reference value of 0.90, corresponding to a midpoint decrease of 8.3%. A pitch comparison at 90° cannot be quantified because the moonpool description provides no numerical peak. Similarly, the available descriptions do not support comparative peak estimates for surge, sway, roll and yaw across all six cases.

4.1 Added resistance comparison

The reported added-resistance ordinate for configuration M falls from approximately 170 at 90° to 55–75 at 120° and 20–22 at 150°. Configuration N remains within approximately 330–360 across the

three headings. Figure 3 shows this pronounced separation on the source-reported scale. The midpoint differences are approximately –52.1%, –81.4% and –93.7%, respectively.

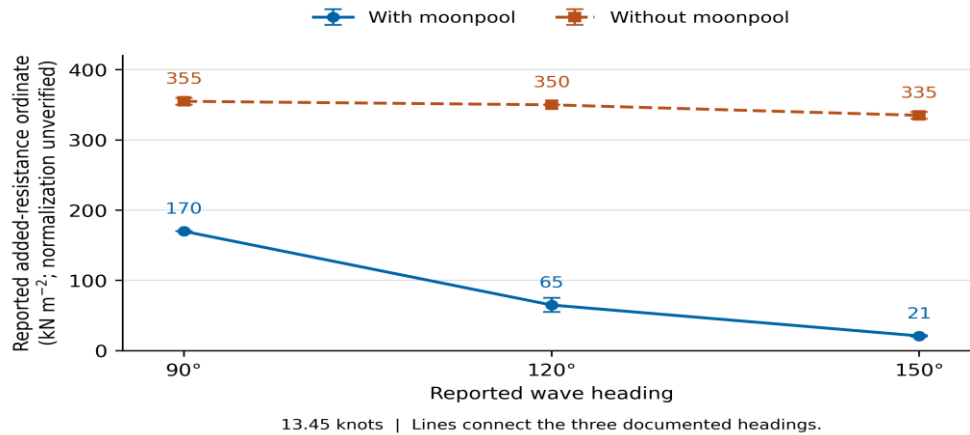


Figure 3. Comparison of the reported added-resistance ordinate. The source unit kN m^{-2} is retained; a common normalization must be confirmed before treating the ordinate as a validated transfer quantity. Whiskers represent stated ranges only. A missing whisker indicates that no numerical range was provided, not that the estimate is exact.

These differences compare the reported upper response levels of each configuration. They are not differences evaluated at a common frequency unless the two peak frequencies coincide. The case descriptions indicate substantial low-frequency response, but they do not establish the complete peak locations or the area under each resistance curve.

Consequently, a larger percentage difference between peak ordinates need not imply an equally large difference in irregular-wave mean resistance.

4.2 Combined comparison

Table 2 and Figure 4 summarize the percentage differences. At 90° and 120°, the reported reduction in the resistance ordinate is accompanied by increased heave response. At 150°, the reported heave, pitch and resistance ordinates are all lower for configuration M, within the quantities that are numerically described. This is a three-point heading comparison and does not identify an optimum operating heading.

Table 2. Percentage differences for the moonpool configuration relative to the configuration without a moonpool.

Heading	Heave difference	Pitch difference	Added-resistance difference
90°	+34.0% [29.6, 38.5]	Not quantified	–52.1% [–52.8, –51.4]
120°	+27.5% [25.0, 30.0]	–4.2% [–8.3, 0.0]	–81.4% [–84.3, –78.6]
150°	–22.5% [–25.9, –19.0]	–8.3% [–11.1, –5.6]	–93.7% [–94.1, –93.3]

Square brackets give the arithmetic bounds from the reported ranges, not confidence intervals. Positive values denote an increase; negative values denote a

decrease. Bounds involving an approximate point estimate omit its unreported uncertainty.

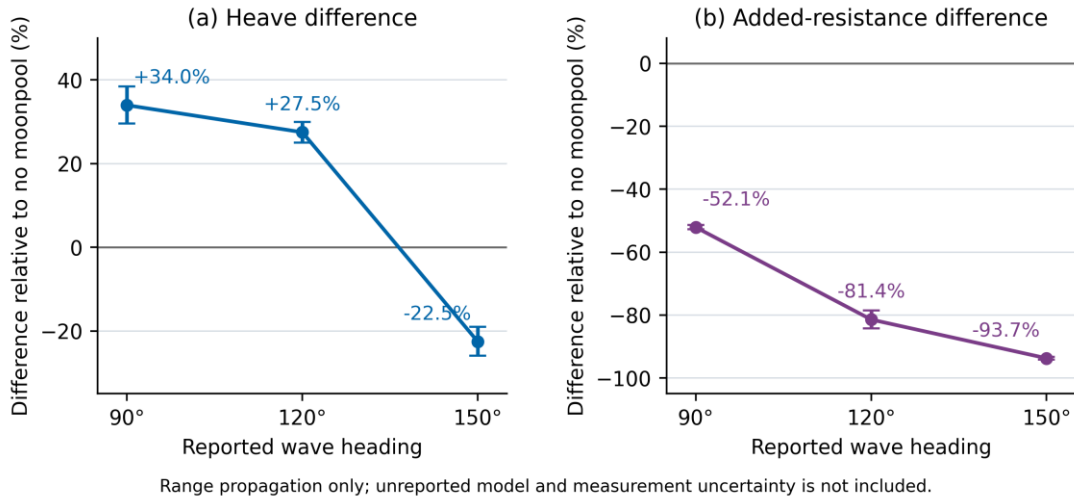


Figure 4. Relative differences in reported response levels, calculated using Equation (9). The zero line represents equal ordinates for the two configurations. The plots summarize individual reported levels rather than frequency-resolved differences or operational risk.

4.3 Discussion

The reversal of the heave comparison between 120° and 150° is inconsistent with a simple claim that adding a moonpool always increases or always suppresses vessel motion. A plausible explanation is that the opening changes the coupled dynamic impedance and its interaction with heading-dependent excitation. This is an interpretation, not a mechanism identified by the available data. Confirming it requires the complex RAOs, excitation coefficients, hydrodynamic coefficients and internal water-surface response for both configurations.

Liu et al. [4] demonstrated that moonpool geometry can affect coupled heave, pitch and roll responses under controlled displacement conditions. The present comparison is compatible with the general possibility of mode-dependent effects, but it does not reproduce that controlled experiment. Changes in draft, mass distribution or hydrostatic stiffness between the two FPSO models could also contribute to their different response levels. Matching only forward speed is insufficient to isolate a moonpool effect. Experiments under combined wave and current excitation also show that pitch and internal water motion depend on the forcing conditions and damping arrangement [23].

Nor should a visually dominant peak be used alone to judge offshore operability. A narrow resonance

outside the energetic part of a sea spectrum may contribute less to variance than a broader, lower response within it. Relative motions, accelerations and equipment tolerances may be more relevant than centre-of-gravity displacement for a particular operation. These quantities require the complete transfer functions and consistent motion reference points.

4.3.1 Assessment of the resistance result

The reported 52–94% reductions in the added-resistance ordinate are large enough to require verification of case labels, speed, loading condition, hull scale, wave normalization and result selection. They should not be converted directly into percentage fuel savings. In particular, lower wave-added resistance does not establish lower total resistance if the moonpool also changes calm-water drag.

The direction of the reported trend also differs from the resistance augmentation associated with moonpool oscillations in the experimental FPSO configuration examined by Yadav et al. [14]. The vessels, moonpool arrangements and resistance measures need not be identical, so this difference is not proof that the present data are wrong. It is a reason to verify the definitions and modelling assumptions before asserting a general resistance benefit.

A decisive comparison would recover the full resistance transfer curves on a common incident-frequency grid and apply the same directional sea spectrum to both. It would also report calm-water resistance separately. That approach would establish whether the apparent peak reduction persists after spectral weighting and whether it affects total resistance or propulsion demand. The present peak summaries cannot answer those questions.

4.3.2 Reproducibility and application limits

The comparison is reproducible at the level of the reported numerical summaries: the source ranges, midpoint calculations and plotting routine accompany the manuscript. Reproduction of the underlying hydrodynamic predictions requires substantially more information. The essential record includes dimensions and displacement for each hull, loading condition and inertia, moonpool geometry, solver version and method, mesh or panel resolution, frequency and heading grids, wave convention, damping treatment and normalization of every exported response.

Validation must also address the limits of linearization. In forced-heave tests of recessed moonpools, potential-flow predictions overestimated resonant response, while calculations using linearized free-surface conditions did not reproduce observed Duffing-type behaviour [24].

Near a possible moonpool resonance, independent verification should include resolution sensitivity and evidence that the internal free surface and relevant loss mechanisms are represented. Model tests or a separately verified viscous calculation can provide a useful check. Seakeeping test guidance also emphasizes documenting model properties, test conditions and uncertainty [21]. No such verification is established by the summary dataset, and range whiskers in the comparison figures must not be mistaken for an uncertainty budget.

Finally, extension to a stationary FPSO offshore Nigeria requires zero-speed or otherwise appropriate operating cases, site-specific wave and current information, loading variations, and a defined mooring and riser system. Wind-sea and swell contributions should be represented according to the measured or

hindcast environment. The present forward-speed comparison provides a basis for identifying cases to investigate, rather than evidence of site-specific operability or structural safety. A site assessment should document environmental conditions and loads within an established offshore engineering framework [25].

V. CONCLUSIONS

At 13.45 knots, the reported heave comparison is heading dependent. The moonpool configuration has approximately 34.0% and 27.5% higher representative heave RAOs at 90° and 120°, respectively, and approximately 22.5% lower heave RAO at 150°. These signs persist over the stated source ranges. Pitch is approximately 8.3% lower at 150°; the small difference at 120° is not well resolved, and the 90° moonpool pitch value is unquantified.

The moonpool configuration also has lower reported added-resistance ordinates at all three headings, with midpoint differences of approximately -52.1%, -81.4% and -93.7%. These remain comparisons of approximate reported ordinates under an assumed common normalization. They do not demonstrate equivalent reductions in total resistance, power demand or fuel use.

The principal finding is therefore a preliminary motion-resistance trade-off that changes with heading. A controlled assessment of moonpool influence requires matched vessel properties, full numerical response curves, verified damping and independent validation. Until those conditions are established, the configurations cannot be ranked as universally superior or transferred directly to a moored Escravos operating case. The accompanying supplementary files contain the response values and source ranges used in Tables 1 and 2, the derived percentage differences, the comparison figures and a MATLAB plotting routine. Original hydrodynamic solver exports and vessel model files are not included in the numerical dataset analysed here.

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