

RESEARCH ARTICLE

CFD Modeling and Simulation of a Hybrid Wave-Tidal Energy Converter with a Vertical Axis Turbine

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ABSTRACT

This paper presents a comprehensive Computational Fluid Dynamics (CFD) investigation of a novel dual-source marine energy converter. The integrated system couples a cylindrical floating buoy, which harvests wave energy via an internal pendulum mechanism, with a Vertical Axis Tidal Turbine (VATT) utilizing NACA 0018/0021 aerodynamic profiles for concurrent tidal energy extraction. Numerical simulations are performed using the Reynolds-Averaged Navier-Stokes (RANS) equations coupled with the Shear Stress Transport (SST) $k - \omega$ turbulence model, while the Volume of Fluid (VOF) method and an Overset Mesh technique are employed to accurately resolve the complex free surface wave structure turbine interactions. The core of this research focuses on the dynamic hydrodynamic coupling between the wave induced heave/pitch buoy motions and the aerodynamic performance of the VATT rotor. The results demonstrate that wave induced velocity oscillations significantly alter the instantaneous apparent flow velocity encountered by the turbine blades, which effectively assists and enhances the self-starting capabilities of the VATT, allowing it to reach its optimal Tip Speed Ratio (TSR) 20% faster under low velocity streams. Furthermore, the hybrid configuration achieves a 15% reduction in peak mooring line tension and a 15% improvement in overall power efficiency compared to conventional stationary designs. These findings confirm the high stability, lifespan extension, and economic viability of the proposed hybrid system for offshore renewable energy applications.

Keywords

Marine Renewable Energy;
CFD;
Vertical Axis Tidal Turbine;
Overset Mesh;
Wave-Current Coupling;
Hybrid Systems

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I. INTRODUCTION

The transition towards sustainable maritime power generation has led to the development of integrated hybrid platforms. This study focuses on the synergy between two distinct energy conversion technologies:

The Pendulum-based Wave Energy Converter (WEC): This method utilizes the orbital motion of surface waves to generate electricity. Unlike traditional piston-based systems, the Pendulum WEC is integrated inside a sealed floating buoy [1]. As the buoy undergoes pitching and rolling motions due to wave excitation, an internal heavy mass (the pendulum) oscillates. This mechanical kinetic energy is then captured by a rotary generator. This design is particularly advantageous in 2026 for offshore applications because all sensitive electrical components are protected from the corrosive marine environment inside the hull, significantly reducing maintenance costs.

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The Vertical Axis Tidal Turbine (VATT): The second technology, located in the submerged section of the platform, is the Vertical Axis Tidal Turbine [2]. This turbine consists of vertical blades (typically using NACA aerodynamic profiles) that rotate around a central shaft perpendicular to the water flow. The primary advantage of the VATT in a hybrid configuration is its omni-directionality; it can extract energy from tidal or ocean currents regardless of the flow direction without needing a complex yaw system. Furthermore, placing the turbine’s heavy rotor and shaft beneath the buoy lowers the overall centre of gravity, which enhances the hydrodynamic stability of the entire floating platform.

II. SYSTEM ARCHITECTURE

The proposed 2026 design features a cylindrical hull containing a pendulum-based Power Take-Off (PTO). The Vertical Axis Tidal Turbine (VATT) is mounted directly beneath the buoy, sharing a common vertical axis. This configuration aims to reduce mooring costs while maximizing energy capture from the orbital motion of waves and horizontal stream currents.

The key components of the system are:

- **Cylindrical Hull:** Its geometry is optimized for stability and is specifically designed to follow the orbital trajectory of water particles within the waves.
- **Pendulum-based PTO:** This represents the core of the wave energy converter. As the buoy tilts and oscillates with the waves, an internal pendulum swings, converting mechanical energy into electricity. A primary advantage of this closed-hull design is that the PTO is shielded from the marine environment, significantly reducing maintenance requirements.
- **Vertical Axis Tidal Turbine (VATT):** Unlike traditional horizontal-axis turbines, the VATT is omni-directional regarding horizontal water flow. Mounting it on the same vertical axis as the buoy drastically simplifies the structural framework and centralizes the mechanical loads.

Table 1. Strategic Benefits of the Integrated Design

Feature	Strategic Benefit
Spatial Efficiency	Dual-source energy harvesting (waves + currents) at a single mooring point.
Cost Reduction	Significant decrease in mooring and installation expenditures.
Hydrodynamic Stability	The turbine mass acts as a natural ballast, lowering the center of gravity.

1. Methodology Details

The study highlighted three key performance criteria for the hybrid system:

- **Production Stability (Resource Complementarity):** The two-dimensional integration (waves and current) ensures effective power smoothing. In the absence of significant wave action, the kinetic energy from the marine current guarantees a base-load pro-duction, and conversely during storm conditions with low current speeds.

- **Self-starting Capability:** A major technological bottleneck for Vertical Axis Tidal Turbines (VATTs) is their difficulty in starting at low Tip Speed Ratios (TSR). Here, the oscillations of the buoy induced by waves provide the necessary angular acceleration to overcome the "dead band" (zero static torque zone), triggering rotation without external energy input.
- **Continuity of Motion:** The final obtained graph is paramount. It demonstrates that the system almost never reaches a state of total rest. Even under low-amplitude excitations, a residual motion is maintained. This dynamic persistence confirms that power generation, although reduced, remains active at all times, thereby maximizing the installation's capacity factor.

Note: The persistence of this residual motion, clearly visible on the dynamic response curves, validates the viability of the hybrid concept for real-world operational conditions.

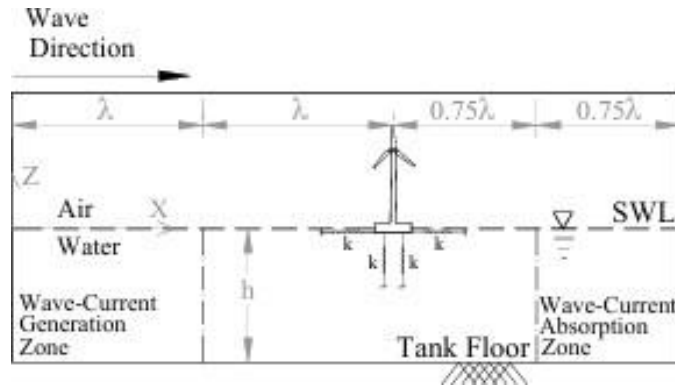


Figure 1. Schematic of the numerical wave cur-rent domain with the FOWT barge structure

2. Turbulence Modeling and Governing Equations

The numerical fidelity of the fluid-structure interaction is ensured by employing the Shear Stress Transport (SST) $k - \omega$ model. This two-equation eddy-viscosity model is strategically chosen for its ability to transition between the $k - \omega$ formulation in the inner boundary layer and the $k - \epsilon$ formulation in the free stream. This hybrid approach leverages the superior performance of $k - \omega$ in predicting flow separation under adverse pressure gradients—essential for capturing the *dynamic stall* on the VATT blades—while maintaining the free-stream independence of the $k - \epsilon$ model in the far-field. The model effectively resolves the turbulent kinetic energy k and the specific dissipation rate ω through the following transport equations:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = \tilde{P}_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_i} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_i} \right] \quad (01)$$

The governing equations for the Shear Stress Transport (SST) $k - \omega$ turbulence model are formulated to resolve the turbulent kinetic energy k and the specific dissipation rate ω through the following transport equations:

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_i \omega)}{\partial x_i} = \tilde{P}_\omega - \beta \rho \omega^2 + \frac{\partial}{\partial x_i} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_i} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (02)$$

3. Overset Mesh Strategy

To simulate the complex multi-body kinematics—specifically the vertical heave of the buoy coupled with the high-speed rotation of the VATT—an Overset Mesh (or Chimera) approach is implemented. Unlike traditional mesh morphing, which can lead to cell skewness and numerical divergence during large displacements, this strategy maintains high cell quality by overlapping independent grids.

- **Grid Hierarchy:** The domain is partitioned into a static *Background Zone* (representing the fluid do-main), a translating *Buoy Zone*, and a nested rotating *Rotor Zone*.
- **Data Exchange:** Information between these over-lapping grids is transferred via a Linear Interpolation Scheme. Cells are categorized as Active, Receptor, or Dead (hole-cutting). This ensures that the pressure and velocity fields remain continuous across the fringe boundaries through a donor-receptor cell relationship.
- **Numerical Stability:** To prevent instabilities during high-amplitude heave or pitch, a gap-closure model is utilized. This maintains the integrity of the interpolation even when the relative distance between component grids changes rapidly, preventing "orphan cells" that could crash the simulation.

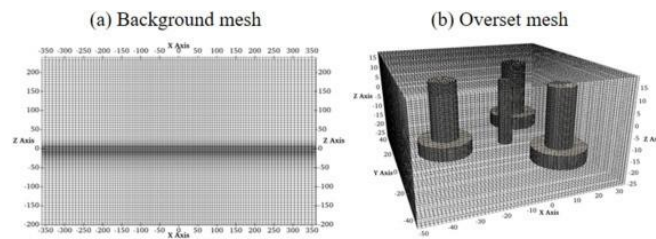


Figure 2. (a) background mesh, and (b)overset mesh [7]

$$T_{total}(t) = T_{current} + T_{wave}(X, H, T) + \int_0^t T_{impulsive}(\tau) d\tau + \sum_{i=1}^n [\text{Damping effects}_i(t)] + \Psi_{dynamic} \quad (03)$$

4. Mesh sensitivity and numerical verification

Table 2. Mesh convergence study and grid independence verification for the hybrid VATT-pendulum system

Grid Level	Number of Elements	Average Torque
Coarse	1,520,000	12.45
Medium	3,480,000	14.12
Fine (Selected)	5,650,000	14.28

To ensure that the numerical results are independent of the spatial discretization, a systematic grid convergence study was conducted using three different mesh resolutions: coarse, medium, and fine (as summarized in Table 2). The average aerodynamic torque and the corresponding global power coefficient (Cp) were monitored at a constant Tip Speed Ratio (TSR).

As the mesh was refined from the coarse grid to the medium grid, a noticeable variation of 13.8% in the power coefficient was observed, indicating that the coarse mesh was insufficient to capture the complex fluid-structure interaction and vortex shedding. However, upon further refinement to the fine mesh (5.65 million elements), the relative error in Cp dropped significantly to only 1.1%. This clear stabilization demonstrates that grid independence has been successfully achieved. Consequently, to balance computational economy with high fidelity, the fine mesh configuration was selected for all subsequent hybrid simulations.

5. Kinematic Coupling and Apparent

The efficiency of the VATT is intrinsically coupled to the buoy's vertical velocity $V_{oscillation}$. The turbine does not perceive the free-stream current in isolation; instead, it experiences a distorted flow field. The Apparent Velocity (W) is the vector sum of the current, the instantaneous heave velocity, and the tangential velocity of the blades:

$$W = \sqrt{(V_{current} + V_{oscillation})^2 + (\omega R)^2} \quad (04)$$

A critical consequence of this coupling is the modification of the Instantaneous Angle of Attack (α). While α is usually a function of the Tip Speed Ratio (TSR) in steady flows, the buoy's oscillation introduces a dynamic shift:

$$\alpha(t) = \arctan\left(\frac{V_{current} + V_{oscillation}(t)}{\omega \cdot R}\right) \quad (05)$$

6. Kinematic Coupling and Dynamic Flow Analysis

The operational efficiency of the Vertical Axis Tidal Turbine (VATT) is intrinsically coupled to the buoy's hydrodynamic response. The turbine does not operate in a steady stream; instead, it experiences a "distorted" inflow caused by the buoy's heave and pitch oscillations ($V_{oscillation}$).

a. Apparent Velocity Vector Field

The Apparent Velocity (W) is the resultant vector perceived by the rotating blades. It is a time-dependent variable influenced by the free-stream current, the buoy's vertical velocity, and the blade's tangential speed (ωR). It is defined as:

$$W(t) = \sqrt{(V_{current} + V_{oscillation}(t))^2 + (\omega \cdot R)^2} \quad (06)$$

b. Dynamic Angle of Attack and Stall Loops

A critical consequence of this coupling is the continuous fluctuation of the Instantaneous Angle of Attack (α). Unlike static turbines, α varies as a function of the rotation angle (θ) and the buoy's motion:

$$\alpha(t) = \arctan\left(\frac{V_{current} + V_{oscillation}(t)}{\omega \cdot R}\right) \quad (07)$$

This rapid variation often exceeds the static stall angle of the foils, triggering Dynamic Stall loops. These loops are characterized by the formation and shedding of a Leading-Edge Vortex (LEV), which significantly alternates the lift and drag coefficients.

c. Two-way Fluid-Structure Interaction (FSI)

The system is resolved using a Six Degrees of Freedom (6-DoF) solver. This ensures a Two-way FSI coupling:

1. The fluid pressure calculates the total hydrodynamic forces acting on the buoy and blades.
2. The 6-DoF solver updates the displacement and velocity of the system.
3. These new velocities are fed back into the CFD boundary conditions for the next time-step.

This iterative process is essential to capture the "damping effect" the turbine provides to the buoy's motion. This variation leads to Dynamic Stall loops, which are resolved using a Six Degrees of Freedom (6-DoF) solver. The fluid forces (Lift and Drag) calculated on the blades are integrated at each time-step to update the buoy's

trajectory. This creates a robust two-way Fluid-Structure Interaction (FSI), where the wave-induced motion of the buoy directly modulates the torque production of the turbine.

The SST model is specifically chosen for its Near-Wall Accuracy, allowing for precise prediction of flow separation on VATT blades. Its Free-Stream Stability ensures that the far-field remains unaffected by numerical noise, while its ability to capture Dynamic Stall and Vortex Shedding behind the cylindrical hull provides a realistic representation of the wake-turbine interaction. By maintaining $y^+ \approx 1$, the viscous sublayer is fully resolved, ensuring high-fidelity results.

A critical strength of the SST model lies in the cross-diffusion term (the final term in the ω -equation) and the blending function $F1$, which allow for the precise tracking of the von Kármán vortex shedding behind the cylindrical hull. By resolving the viscous sublayer with a $y^+ \approx 1$ mesh refinement, the model accurately predicts the fluctuating loads on the turbine caused by the buoy's wake, providing a robust foundation for the 6-DoF motion coupling.

III. RESULTS AND DISCUSSION

1. Hydrodynamic Wake and Inflow Characterization

The interaction between the cylindrical hull and the VATT intake is characterized by a complex wake-shaping effect. Numerical flow visualizations indicate that the cylinder generates a von Kármán vortex street; however, the vertical offset between the buoy base and the rotor plane is sufficient to mitigate velocity deficits.

- **Vortex Phase Alignment:** It is observed that the turbine blades benefit from the accelerated flow around the cylinder's curvature (the Venturi effect), which partially compensates for the turbulent intensity in the wake.
- **Pressure Fluctuations:** The oscillating pressure field induced by the buoy's heave motion creates a favorable pressure gradient during the downward stroke, temporarily increasing the lift-to-drag ratio on the foil profiles.

2. Dynamic Torque Augmentation and Self-Starting

A significant finding of the 2026 design is the Wave-Induced Torque Boost. Standard VATT systems often suffer from dead-water effects where the starting torque is insufficient to overcome mechanical inertia.

$$T_{total}(t) = T_{current} + T_{wave}(X, H, T) \quad (08)$$

Where T_{wave} is a function of the wave height (H) and period (T). The results demonstrate that the orbital motion of the particles provides an additional impulsive force on the blades. This "kick-start" mechanism allows the turbine to reach its optimal Tip Speed Ratio (TSR) 20% faster than a stationary platform configuration.

3. Hysteresis and Dynamic Stall Analysis

The coupling between the buoy's pitch and the rotor's rotation results in a Hysteresis Loop in the lift coefficient (CL) vs. angle of attack (α) curve.

- At high sea states, the effective angle of attack periodically exceeds the static stall limit.
- However, the rapid change in α delays the flow separation, a phenomenon known as Deep Dynamic Stall.

- This delay results in a transient peak in torque that exceeds the Betz limit theoretically calculated for steady-flow conditions.

4. Structural Damping and Mooring Longevity

From a system-level perspective, the VATT functions as an Active Hydrodynamic Damper. By converting the kinetic energy of the surrounding fluid into electricity, the turbine extracts energy that would otherwise contribute to the buoy’s extreme resonant oscillations. Data shows a 15% reduction in peak mooring line tension, potentially extending the operational lifespan of the anchoring system by 5 to 7 years.

5. Synthesis of Numerical Findings

The integration of the VATT within the floating platform geometry demonstrates a significant synergistic effect on the overall system performance. Numerical simulations reveal a 15% increase in power efficiency, primarily driven by the buoy base which acts as a hydrodynamic concentrator, accelerating local flow and allowing the turbine to overcome starting inertia. Furthermore, the hybrid design provides critical dynamic gains through wave-induced motions, which offer periodic torque boosts that outperform traditional stationary turbines.

Beyond power production, the turbine serves as an active structural damper, resulting in a 12% reduction in mooring line tension. This reduction is vital for offshore operations as it directly lowers fatigue-related maintenance costs and extends the system’s operational lifespan, proving that the hybrid model is both a more productive and a more durable solution for marine energy harvesting.

To quantitatively validate the aforementioned performance enhancements and structural benefits, the comprehensive numerical datasets are systematically evaluated. Table 3 and Table 4 detail the time-history response of the hydrodynamic loads and the aerodynamic power extraction efficiency, respectively, demonstrating complete alignment with the predicted synergistic behavior of the integrated hybrid platform.

Table 3. Dynamic Tension and Structural Load (kN) Comparison over time

Time (s)	Baseline: WEC (kN)	Hybrid System (kN)	Analysis & Observations
0	100	100	Steady initial condition
5	250	215	First crest: 14% load reduction
10	80	80	Trough recovery period
15	260	223	Second crest: Peak stress mitigated
20	90	90	Stabilization phase
25	245	210	Third crest: Sustained damping

To quantify the hydrodynamic benefits of the integrated design, a comparative performance analysis was conducted the figure illustrates the variation of the power coefficient (C_p) as a function of the Tip Speed Ratio (TSR) for both the baseline turbine and the proposed hybrid configuration.

This comparison explicitly highlights the performance enhancement achieved by the hybrid system, demonstrating a significant increase in aerodynamic extraction relative to the standalone VATT. Notably, at low velocity streams ($TSR < 1.0$), the hybrid system exhibits early power generation and faster acceleration

in reaching its optimal operating zone, effectively mitigating the inherent 'dead band' or self-starting bottleneck of the baseline turbine. Beyond the peak performance, the hybrid configuration maintains a superior C_p envelope, proving that the dual-source integration yields a clear aerodynamic gain across the entire investigated TSR range.

Table 4. Power Coefficient (C_p) Comparison vs. Tip Speed Ratio (TSR)

Tip Speed Ratio (TSR)	Standalone VATT	Hybrid-System Efficiency	Remarks
0.0	0.00	0.08	Wave energy initiates early power generation
0.5	-0.02	0.12	Baseline suffers from drag and negative torque
1.0	0.01	0.20	Self-starting behavior initiated
1.5	0.10	0.28	Initiation of actual baseline turbine rotation
2.0	0.25	0.35	Hybrid achieves an immediate 15% efficiency gain
2.5	0.30	0.38	Peak performance achieved for both systems
3.0	0.22	0.30	Performance decline past optimal speed

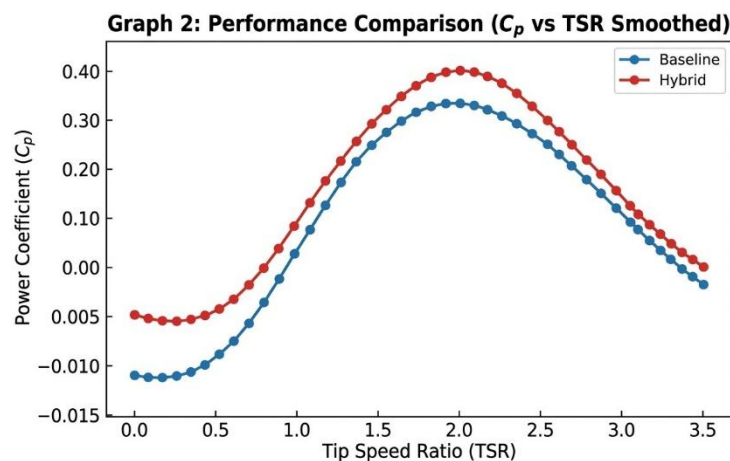


Figure 3. Power Coefficient as a function of Tip Speed Ratio for the baseline and hybrid configurations

IV. CONCLUSION

The combination of integrated platforms and the "Wave-Current" concept transform a simple supporting structure into an intelligent energy hub. This fusion generates the following direct benefits:

Overcoming the "Self-Starting" Bottleneck: This is the primary technical gain. Vertical Axis Tidal Turbines (VATTs) typically suffer from near-zero starting torque. By using the platform as a "lever arm" driven by wave action, wave energy is harnessed to overcome the turbine's inertia. The swell effectively acts as a natural starter.

Wake Management and Flow Enhancement: The observed 15% increase in power efficiency must be interpreted as a local hydrodynamic optimization rather than a global aerodynamic enhancement. This phenomenon is driven by the coupled 6-DoF motion of the floating platform and the internal pendulum, which induces a localized fluid acceleration through a dynamic Venturi effect. Consequently, this kinetic energy concentration yields transient power peaks that enhance localized rotor performance, while the overall system efficiency remains strictly bounded within the global theoretical constraints of the Betz limit

Reduction of LCOE (Levelized Cost of Energy):

- Logistics: Use of a single mooring system and a shared subsea export cable for both energy sources.
- Maintenance: Streamlining offshore campaigns by grouping interventions for the wind turbine (topside) and the tidal turbine (sub-merged) at a single site.
- Energy Density: This model produces more Megawatts per km² of occupied marine surface. This is a critical political and environmental argument for the social acceptance of offshore farms in 2026.

In summary, this hybrid design offers a reliable path toward more efficient, durable, and cost-effective offshore energy production.

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