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Design and Modeling of an Open-Source Baseline Floating Marine Turbine

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Abstract

Marine energy resources such as river, tidal, and ocean currents can provide abundant, predictable, and clean power to both densely populated and remote communities globally. However, marine energy technologies are still in an early stage of development. Recently, features have been added to the National Renewable Energy Laboratory's open-source wind turbine modeling tool OpenFAST to support the simulation of axial-flow marine turbines. These new features enable marine energy developers to predict the performance and safety of their turbines and allow researchers and students to advance the field through the exploration of novel designs. Developing and demonstrating the new capabilities of OpenFAST for marine turbines requires a baseline design that can be used as an example and test case. There are limited open-source turbine models suitable for this purpose. One existing baseline design is the Reference Model 1 (RM1), a fixed-bottom, dual-rotor marine turbine that was published in 2011 as part of the U.S. Department of Energy's Marine Renewable Energy Reference Model program. To test and demonstrate OpenFAST's ability to model floating marine turbines, several modifications were made to the RM1. A floating platform and mooring system were designed to support a single RM1 rotor in a wide range of possible current and wave conditions. The system and model are intended to be a stable reference case and starting point for research efforts. The platform features familiar design elements from the offshore wind industry, including cylindrical members and a mooring system with simple catenary chains. While not optimized for the lowest platform cost, these design elements make the baseline platform robust and relatively simple to analyze. This is a useful starting point for studies to explore new technologies or design methodologies. Additionally, the floating RM1 design enables cross-collaboration among industry, academia, and national lab researchers and serves as an educational platform for newcomers to marine energy. This short paper presents the specifications of the turbine, including its floating support structure and mooring system. The rationale behind the selection of certain design parameters is described. To enable adoption of this baseline case for research and educational efforts, an OpenFAST model of the full system has been made publicly available at https://github.com/OpenFAST/r-test/tree/main/glue-codes/openfast/MHK_RM1_Floating.

Keywords: Marine Turbine; Floating Platform; Reference Model; OpenFAST; Floating RM1 Quad

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1. Context

OpenFAST is an open-source mid-fidelity modeling tool developed by the National Renewable Energy Laboratory (NREL) to predict the performance and loads on wind turbines. The code has been written with a modular approach, including coupled aerodynamic, hydrodynamic, structural, mooring, controls, and turbulence modules [1]. Recent work has adapted OpenFAST to allow the simulation of marine turbines. These changes include the addition of buoyant forces on the blade sections and the ability to model turbines below sea level, which was previously not possible. Buoyancy has also been included for the hub, nacelle, and tower. In order to understand the efficacy of these changes, a floating marine turbine test case is needed. A baseline model and test case called the Floating RM1 Quad is described here.

Marine turbine designs in industry have not converged to any general concept, so it is not possible to represent all devices with a single reference model. An ideal test platform is able to isolate the effects of the new code changes, without introducing additional novel components or instabilities. For this reason, the platform has been designed with components that resemble well-tested offshore wind semisubmersible platforms. All elements, except for a faired tower, are cylindrical, and surface-piercing elements are either vertical or at a large angle from the still free surface. Heave plates are included at the base of the main columns to increase added mass in heave and pitch as well as viscous damping. The mooring lines are simple catenary chains with drag embedment anchors. A design optimized to reduce the platform cost would likely deviate from these standard offshore wind characteristics but would result in a larger step from the systems traditionally modeled in OpenFAST. The Floating RM1 Quad is a robust device, with both physical and numerical stability, to serve as a starting point for marine turbine modeling.

2. Platform Design

The Floating RM1 Quad is an asymmetric semisubmersible with four main columns. The columns each have a heave plate at the base and are connected by a series of smaller diameter braces. Tidal current directions are largely known and fixed. The asymmetric shape provides increased hydrostatic pitch stiffness in the directions of the current, without unnecessarily increasing platform size in the direction perpendicular to the current. The mooring system is also asymmetric, providing the large surge stiffness needed to counter the turbine thrust with six catenary lines.

2.1. Dimensions

Figure 1 shows the Floating RM1 Quad with external dimensions. The blue lines in the figure represent the design still water line (SWL) on all surface-piercing members. All cylindrical members are shown in yellow, and the faired tower is shown in gray, starting from the bottom of the lower braces, 9.0 m below the SWL. Given diameters are outer diameters, and all cylinder thicknesses are 0.02 m.

The bottom left section of the figure shows the mooring layout for the design mean water depth of 50.0 m. Note that the two fairleads each support three mooring lines. The fairleads are located on the top edge of the heave plates, at the upstream/downstream extents. All six mooring lines are made of a single section of chain, with a constant nominal diameter of 0.18 m and a linear mass density of 645 kg/m. The center lines have a length of 152.0 m, and the outer diagonal lines have a length of 160.0 m.

Comparisons to computational fluid dynamics (CFD) models can be useful for verification of mid-fidelity models. Considerations were taken to make the platform friendly to CFD meshing, making these efforts more effective. There is a 0.5 m gap between the lower braces and the heave plates, and a 0.5 m gap between the upper braces and the tops of the columns; this avoids tightly pinched cells tangent to the curve of the braces.

2.2. Mass and Inertia

The system mass and inertia properties were calculated based on thickness of 0.02 m for all members and a material density of 8500 kg/m^3. The lower braces and all heave plates are fully flooded. The potential flow model, which includes the hydrostatic stiffness matrix, includes the full volume of these members, so the platform structure mass is adjusted to include the distributed mass of the permanently flooded water. The columns are intended to have a variable ballast level, which can be used to bring the platform to the design water line during installation. Depending on site wave conditions, this ballast could be purposefully distributed to tune the system pitch inertia. Table 1 gives the mass, center of gravity (COG), and diagonal inertia values, based on an even distribution of ballast weight.

Table 1. System Mass and Inertia

	Platform Structure	Platform Structure + Ballast	Platform Structure + Ballast + Tower & RNA
Mass [kg]	1.050e6	2.525e6	2.588e6
COG [m]	[0.0, 0.0, -5.63]	[0.0, 0.0, -6.09]	[-0.02, 0.0, -6.52]
Ixx [kg-m^2]	8.866e7	1.952e8	2.155e8
Iyy [kg-m^2]	3.408e8	9.194e8	9.403e8
Izz kg-m^2]	3.691e8	1.054e9	1.054e9

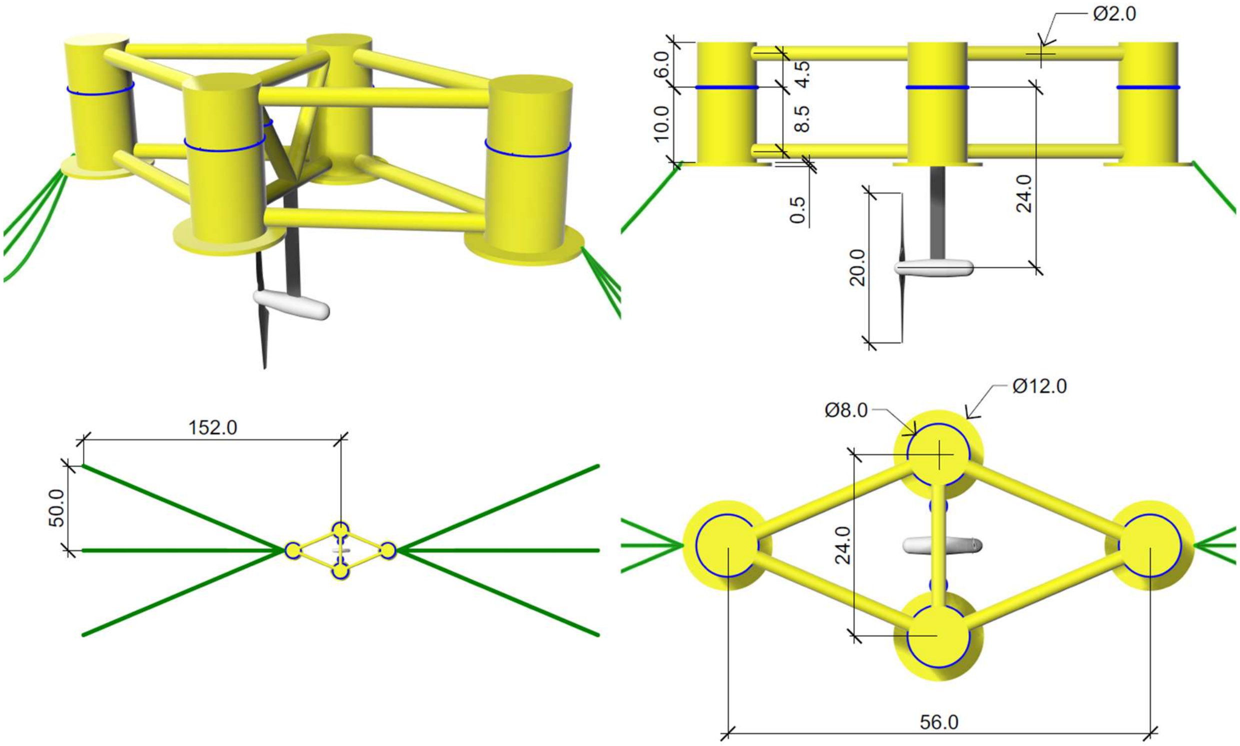

Figure 1. Floating RM1 platform (all dimensions in m).

2.3. Turbine

The turbine is the variable speed and variable pitch RM1 marine turbine developed by NREL in 2011 under the U.S. Department of Energy Marine Renewable Energy Reference Model program [2]. The original RM1 device featured two rotors on a bottom-fixed tower [3]. The RM1 rotors are two-bladed with a 20 m diameter and a rated speed of 1.9 m/s at a rotating speed of 11.5 rpm; the blade profile was optimized using the blade element momentum theory based Harp_Opt code. A detailed description of the blade geometry can be found in the original paper [2]. This optimization also output the operating curves for rotor speed and blade pitch [2]. The original power take-off system was designed to use off-the-shelf components for reduced cost and a more streamlined adaptation [4]. A comprehensive report released by Sandia National Laboratories in 2014 describes all components of the fixed RM1 system [5]. A single turbine with the same rotor nacelle assembly (RNA) and operating profile is used on the Floating RM1 Quad.

3. Example Load Cases

Preliminary OpenFAST simulations were run to test the viability of the system. In the numerical model, the platform is treated as a rigid body with six degrees of freedom, but the tower and blades are able to elastically deform, with displacements calculated using the ElastoDyn module. The catenary mooring lines are dynamically modeled using the MoorDyn module. Currently, either a shear or uniform current flow profile can be specified using the InflowWind module, and the same inflow condition is defined for the platform in the HydroDyn module. The hydrodynamic forces come from a combined potential flow and Morison-element model, accounting for significant forces on both the large volume cylinders and the slender braces. The hydrodynamic excitation forces are due to both waves and current in HydroDyn. The potential flow matrices were calculated using the boundary element method code WAMIT. Selected load cases are meant to test potential limits for environmental conditions but do not correlate to any specific site.

3.1. Free Decay

Free decay tests were performed for each platform degree of freedom to characterize the system rigid body modes. The resulting frequencies are shown in Table 2. The heave, roll, and pitch frequencies could potentially align with the wave frequencies at some tidal energy sites. For these cases, tuning of the mass, inertia, added mass, and added inertia should be performed to avoid wave frequency resonance. Moving the ballast water location and adjusting the size of the heave plates would be a logical starting point for this possible site-specific work.

Table 2. System natural frequencies from free decays

	Surge	Sway	Heave	Roll	Pitch	Yaw
Initial Displacement [m] or [deg]	20.0	10.0	5.0	15.0	15.0	15.0
Frequency [Hz]	0.012	0.005	0.105	0.100	0.105	0.010

3.2. Current Only

Marine turbines produce a relatively large amount of thrust; for a floating turbine platform, this needs to be resisted by the mooring system. Catenary mooring lines are designed so that the anchors only need to take horizontal loading, with some amount of line always touching the seafloor, avoiding vertical forces which drag embedment anchors cannot resist. Figure 2 shows the platform center of gravity surge displacement and the percentage of the mooring lines touching the bottom, for a current-only case with the rated current speed (largest thrust force). Only the upstream lines, which carry the load and risk liftoff, are shown. The system is translated almost 25 m in surge (39% of the platform length), but at least a quarter of each mooring line remains resting on the seafloor. Depending on the load cases for a desired site, the lines could be extended with a larger footprint to ensure that full liftoff never occurs.

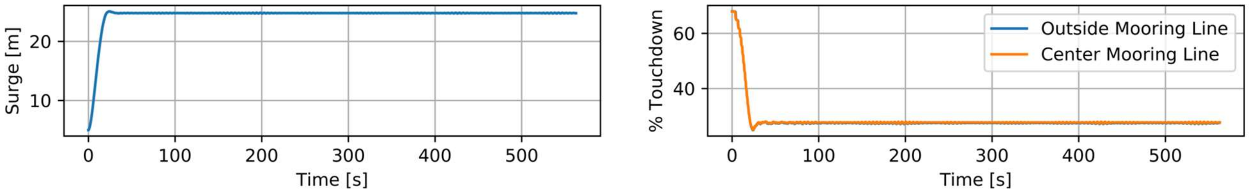

Figure 2. Surge offset and mooring line touchdown percentage for rated current-only load case (current = 1.9 m/s)

3.3. Combined Current and Waves

Figure 3 shows an example combined wave and current load case. It is noted that the inflow condition for the rotor does not include the wave velocities. The current velocity is the design cutout speed for the turbine of 3.0 m/s. The wave is an irregular wave based on a JONSWAP spectrum with a significant wave height of 3.0 m (extreme for most tidal sites) and a peak period that coincides with the natural pitch and heave period of the system; the time series and power spectral density of the surface elevation are shown on the first row. Even with the potential resonance, the maximum heave cycle is only 2.2 m, and the maximum pitch cycle is only 4.2°, shown in the third and fourth rows.

This demonstrates the stability advantage of this overbuilt platform. The second row shows the power and thrust coefficients – both reduced from their design maxima to decrease loads in this post-rated condition, but with relatively stable values given the large wave condition. The mean surge offset is similar to the rated condition shown in Figure 2, as the increased platform drag counters the decreased turbine thrust. Both in physical stability and in numerical stability, the Floating RM1 Quad is robust, allowing for streamlined optimization of individual features.

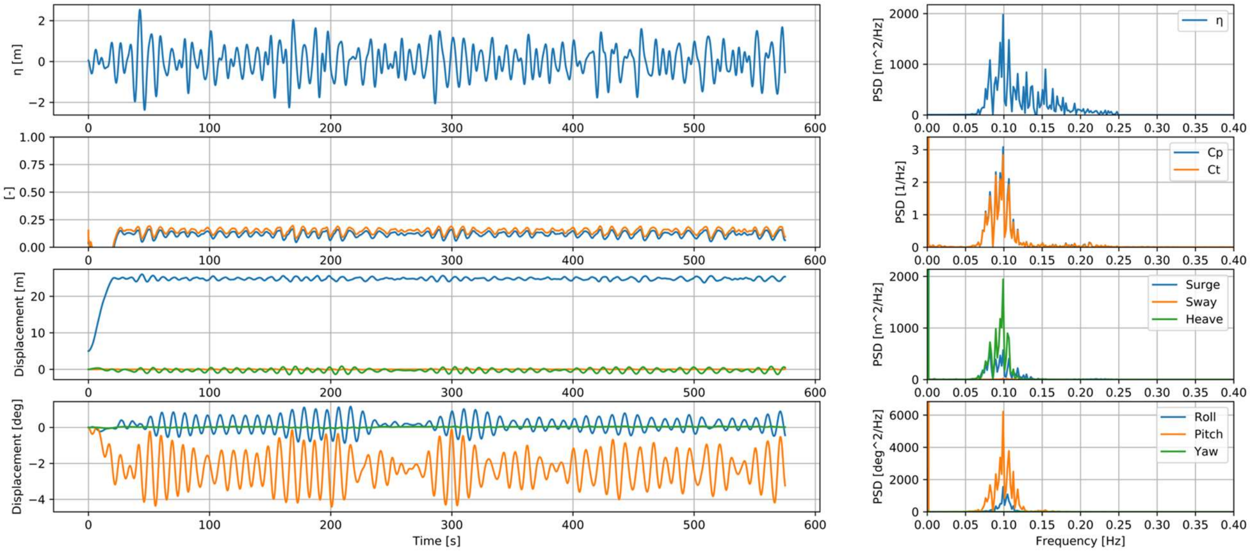

Figure 3. System response to combined wave and current load case (Hs = 3.0 m, Tp = 10.0 s, current = 3.0 m/s, tide elevation = 0.0 m)

4. Initial Optimization

The Floating RM1 Quad is meant to serve as a publicly available starting point for studies focusing on varying one or more aspects of the system. An example of an initial use of the platform is an optimization of the controls strategy.

ROSCO [6] is a reference open-source controller developed by NREL for wind turbines, and it has been adapted for use with the Floating RM1 Quad. The two primary control variables for this model are the generator torque and the blade pitch. The values of these variables are determined by proportional-integral-based feedback controllers with a feedback signal of generator speed. In the below-rated region, the generator torque is varied to track the generator speed that provides the optimal TSR. In the rated region, the generator torque is held at the constant rated value, and the blade pitch is varied to maintain the rated generator speed. For the floating system, an additional control loop is included in the rated region, where the tower-top velocity is proportionally fed back to the blade pitch controller to counteract a known negative-damping problem [7].

5. Conclusions

The Floating RM1 Quad is a robust open-source floating marine turbine that can be used by the research, industry design, and academic communities both as a reference benchmark and a launching point for further investigations. The design is intentionally overbuilt, resulting in strong stability, but also an increased platform cost. Possible logical starting points for platform optimization would include streamlined members instead of cylinders and reduced sized members.

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References

[1] National Renewable Energy Laboratory, 9 August 2023. [Online]. Available: https://openfast.readthedocs.io/en/main/source/user/index.html.

[2] M. Lawson, Y. Li and D. Sale, "Development and Verification of a Computational Fluid Dynamics Model of a Horizontal-Axis Tidal Current Turbine," in *International Conference on Ocean, Offshore, and Arctic Engineering*, Rotterdam, Netherlands, 2011.

[3] G. Bir, M. Lawson and Y. Li, "Structural Design of a Horizontal-Axis Tidal Current Turbine Composite Blade," in *International Conference on Ocean, Offshore, and Arctic Engineering*, Rotterdam, Netherlands, 2011.

[4] M. Beam, B. Kline, W. Straka, A. Fontaine, M. Lawson, Y. Li, R. Thresher and M. Previsic, "Marine Hydrokinetic Turbine Power-Take-Off Design for Optimal Performance and Low Impact on Cost-of-Energy," in *International Conference on Ocean, Offshore, and Arctic Engineering*, Rio de Janeiro, Brazil, 2012.

[5] V. Neary, M. Previsic, R. Jepsen, M. Lawson, Y.-H. Yu, A. Copping, A. Fontaine, K. Hallett and D. Murray, "Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies," Sandia National Laboratories, Albuguerque, NM, 2014.

[6] N. Abbas, D. Zalkind, L. Pao and A. Wright, "A Reference Open-Source Controller for Fixed and Floating Offshore Wind Turbines," *Wind Energy Science,* 2022.

[7] J. Jonkman, "Influence of Control on the Pitch Damping of a Floating Wind Turbine," in *ASME Wind Energy Symposium*, Reno, Nevada, 2008.

[8] M. Lawson, G. Bir, Y. Li and R. Thresher, "The Development of a Preliminary Design for a Horizontal Axis Tidal Current Turbine," National Renewable Energy Laboratory, Boulder, CO, 2012.

[9] R. Murray, R. Thresher and J. Jonkman, "Added-Mass Effects on a Horizontal-Axis Tidal Turbine using FAST v8," *Renewable Energy,* vol. 126, pp. 987-1002, 2018.