Stabilized Offshore Floating Wind Platform Using a Dual-Function Wave Energy Converter

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***Abstract*— Offshore wind is an attractive source for renewable energy. However, the development and deployment of large scale (>2 MW) offshore wind turbines is hindered by a lack of efficacious methods to develop a stable floating platform in ocean environments at depths greater than 100 m. A stable platform enables direct usage of large scale onshore wind turbines for offshore wind. In this paper, a system of three energy regenerative tuned mass dampers (TMD) is proposed as a means to both mitigate wave-induced structural motion of a floating platform of the DeepCwind 5 MW semisubmersible system and to harvest otherwise inaccessible ocean wave energy. Optimal tuning frequency and electrical damping of the TMD were obtained via the $\mathcal{H}_2$ norm optimization method. When the root mean square of the semisubmersible response was minimized, the TMD was shown to reduce the structural motion by more than 40%. Meanwhile, the harvested power was shown to reach 40~55 kW per significant wave height squared.**

***Keywords*— Offshore wind energy; wave energy conversion; platform stabilization; tuned-mass damper; energy co-generation**

I. Introduction

Offshore wind turbines are considered as one promising means to harvest an abundance of wind energy in offshore areas. However, current fixed-bottom technologies have had limited success, having only achieved deployment in water depths up to 20 m [1]. While a fixed-bottom provides the most stability, deployment in deeper water (>100 m) will exploit further potential of offshore wind energy. For deployment in such a water depth, fixed-bottom technologies are no longer sound strategies. Instead, floating platforms are better alternatives. A stable floating platform would enable direct usage of large scale onshore wind turbines. The floater/buoy must not only support a large payload, but must also minimize the dynamic instability due to wind and wave loads. While a robust design would be beneficial towards the deployment of larger scale wind turbines, the structure weight must be minimal to be economically practical. Accounting for roughly 25% of the initial capital cost of a large offshore wind turbine, the support structure must be designed for both dynamic stability and economic feasibility [2].

Currently, offshore wind turbine platforms fall into three general categories (shown in Fig. 1): ballast stabilized (spar-buoy), mooring line stabilized (tension-leg platform, TLP) and buoyancy stabilized (barge). The spar-buoy, such as the OC3-Hywind spar [3], achieves stability using a ballast weight under the turbine, creating a righting moment for both pitch and roll motions due to its low centre of gravity. The draft is usually very deep to avoid heave motions due to the waves. While this design provides good stability, it's size provides challenges for fabrication and deployment. TLPs, which have been widely used as the floating structure for the offshore production of oil, achieve stability through mooring line tension. While they also have very good stability, the complexity of the mooring installation, coupled with the variations in tension, lead to higher costs. Barge devices achieve stability through the distribution of buoyancy, using the weighted water as a righting moment. Issues with the size of the barge arise, as the weight must be spread out to maintain positive buoyancy. Due to the platform sitting on top of the water, it is also very sensitive to waves. To achieve better stability with a smaller footprint, the combination of multiple stabilization techniques can be used. Semisubmersible devices, such as the DeepCwind [4] and WindFloat [5], use both ballast stabilization and buoyancy stabilization. With the addition of heave plates to "entrap" water, the additional added mass stabilizes the righting moments of the turbine.

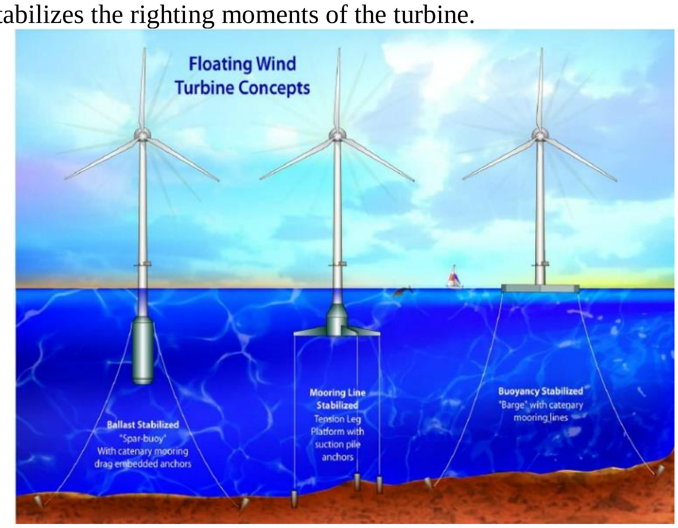

Fig. 1 Concepts for floating offshore wind turbine platforms [NREL 1]

Further, fatigue issues arise with the constant dynamic instability of the turbine induced by both wind and wave. Jonkman and Matha [6] simulated the fatigue loads of the MIT/NREL tension leg platform (MIT/NREL TLP), OC3-Hywind spar, and ITI Energy barge, subjected to Design Load Case 1.2, IEC 61400–3, and showed that the pitch and roll induced tower base fatigue loads are 2.5 times greater than land based wind turbines. While control strategies have been implemented to reduce tower oscillation, it is typically at the expense of absorbed wind energy. Using an estimator based control strategy, Skaare et. al. increased the lifetime of the tower by a factor of 5 – 7; however, power was reduced by roughly 4% [7]. While control strategies such as blade pitch control [8] and drivetrain control [9] have been studied and tested, the increased stability always come at the expense of generated power. In other words, novel vibration strategies that improve the stability without compromising the power should be sought.

In this paper, a mature structural vibration control method, a tuned mass damper (TMD), is reinvented as a means to mitigate wave-induced structural motion of a floating semisubmersible of the OC3-Hywind semisubmersible-buoy system. The TMD, when implemented with a power take-off unit (PTO), is capable of converting the structural motion induced by ocean waves into electricity, resulting in an energy-regeneration vibration control strategy.

TMDs, with a reaction mass attached to the primary structure, have been widely used in many high-rise buildings, such as the Taipei 101 skyscraper [10]. In contrast to typical wind-induced vibration in buildings, ocean wave motions have larger amplitudes and broader spectra. To absorb both ocean wave energy, as well as the gross structural kinetic energy, a tuned mass damper can be implemented onto a floating offshore wind turbine. The stabilized floating wind-wave energy converter (W2SEC), shown in Fig. 2, could not only enable off-shore wind energy implementation in areas of great ocean areas, but could do so in ways that enables additional wave energy extraction through use of the tuned mass damper.

The W2SEC inherently aims to provide a stable “platform” for a wind turbine system. With the platform actively being stabilized – mimicking dry land – more technology and techniques from the already well-established industry of onshore wind can be leveraged, thereby reducing costs for W2SEC development and advancement. Wind thrusting its way through the turbine blades is, of course, how a W2SEC converts air flow into electricity via a generator. However, this thrust enacts a moment about an axis perpendicular to the length of the turbine’s tower thereby inclining it to tilt – the tower will tend to pitch and roll. Concurrently, the semisubmersible or column portions of the W2SEC are not only being subjected to the turbine tower motions (due to wind thrust), but is also directly subjected to the undulating motions of ocean waves and currents. As stated earlier, to counteract this motion – to stabilize the W2SEC – the energy causing such motions is absorbed by a tuned mass damper. Absorption of ocean wave, ocean currents, and wind thrust energy via (1) a wind turbine and (2) a tuned mass damped wave-structural energy converter provides an entirely new concept that enables co-energy generation whilst also enabling a steady platform for a turbine and its tower.

For simplification into the feasibility of this device, in this paper, only wave interactions in heave are considered with the W2SEC.

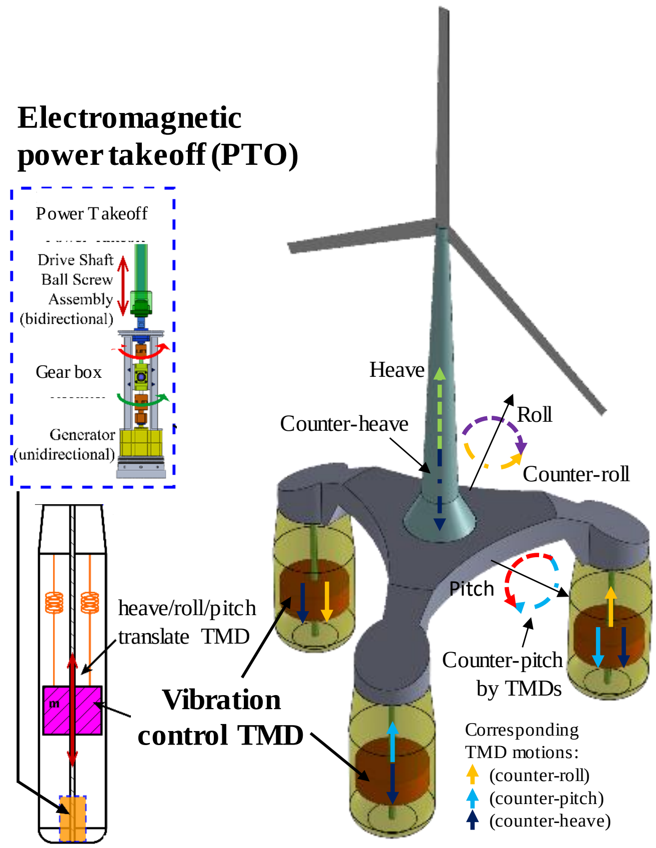

Fig. 2 Concept for platform-stabilizing wind-wave-structure energy converter (W2SEC). Structure not to scale.

II. Semisubmersible-Tuned-mass-damper

The 5 MW scale semisubmersible floating wind turbine developed for the DeepCwind project, which is a US-based project aimed at generating test data for use in validating floating offshore wind turbine modeling tools [4], is used as the floating platform for the offshore wind turbine considered here; see Fig. 2. Strictly speaking, a floating body has six degrees of freedom, i.e., surge, pitch, yaw, roll, sway, and heave. However, here, only pitch motion x_5 is considered. In this regard, the semisubmersible moment of inertia I_{55} is modelled as a harmonic oscillator, subject to hydrodynamic moments due to fluid-structure interaction with the waves (assumed to be linear, i.e. Airy waves), manifested by added inertia A_{55}, hydrodynamic angular stiffness C_{55}^H, and radiation angular damping B_{55}. Furthermore, it is also subjected to external hydrodynamic moment M_e.

Inside each submersed column is installed a tuned-mass-damper (TMD), which consists of a seismic mass m_2, tuning spring k_{PTO}, and damper c_{PTO}, and moves relative to the water surface by displacement x_2. Fig. 3 shows the equivalent dynamic model of the semisubmersible-TMD system. Note that pure pitch motion is assumed. Thus, two TMDs are assumed to move out-of-phase, resulting in two seismic masses $2m_2$ shown in Fig. 3. Also note that moment arm l_p is considered to relate pitch motion x_5 to linear motion x_2.

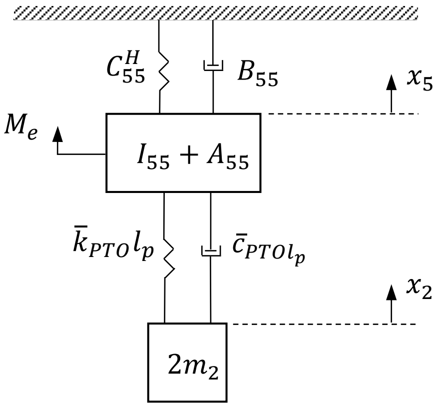

Fig. 3 Equivalent dynamic model of the TMD system.

The TMDs have two functions. First, it counteracts the pitch motion and stabilize the floating semisubmersible, similar to what it would do to high-rise buildings. Second, it absorbs the ocean wave energy and converts it into electricity; in other words, it is also a power take-off (PTO) unit. As a result, the semisubmersible-TMD system can be regarded as a new type of wave ocean converter (WEC), in addition to its original role as a floating platform, which we defined as a wind-wave-structure energy converter (W2SEC). In this paper, the PTO comprises a linear electromagnetic generator which converts the linear relative velocity between the TMD and semisubmersible $l_p\dot{x}_5 - \dot{x}_2$ into electricity, where l_p is the moment arm of the TMD with respect to the center of gravity of the platform. The generator has internal resistance R_i and inductance L. If the electromagnetic generator is shunted with an external resistive electrical load R and the inductance L is small, the force F_{EMF} induced by the back electromotive voltage e_{EMF} will be proportional to the electrical current i and can be modeled as an ideal viscous damping. The viscous damping coefficient is also known as equivalent electrical damping coefficient or c_{PTO}. In other words,

$$F_{EMF} = c_{PTO}(\dot{x}_1 - \dot{x}_2) \tag{1}$$

where $c_{PTO} = k_e^2 F^2/(R + R_i)$ and F is a motion amplification factor.

A. Equation of motion

After applying Newton's 2nd law to the semisubmersible and TMD, the equations of motion of the system is derived as

$$(I_{55} + A_{55})\ddot{x}_5 + (\bar{c}_{PTO} l_p^2 + B_{55})\dot{x}_5 + \left(\bar{k}_{PTO} l_p^2 + C_{55}^H\right) x_5 - \bar{c}_{PTO} l_p \dot{x}_2 - \bar{k}_{PTO} l_p x_2 = M_e$$

$$m_2\ddot{x}_2 + c_{PTO}\dot{x}_2 + k_{PTO}x_2 - c_{PTO} l_p \dot{x}_5 - k_{PTO} l_p x_5 = 0 \tag{2}$$

where the overhead dot denotes a time derivative. Since pure pitch motion is assumed, two TMDs contribute to vibration control; thus, $\bar{k}_{PTO} = 2k_{PTO}$ and $\bar{c}_{PTO} = 2c_{PTO}$. Under regular wave excitation, the exciting moment can be expressed as the following harmonic function

$$M_e = Me^{j\omega t} \tag{3}$$

and the solutions of Eq. (2) can be expressed as

$$\begin{aligned} x_5(t) &= X_5 e^{j\omega t} \\ x_2(t) &= X_2 e^{j\omega t} \end{aligned} \tag{4}$$

where ω is the excitation frequency. After substituting Eqns. (3) and (4) into Eq. (2), one can obtain the transfer function $H_1(\omega)$ of the semisubmersible pitch and $H_2(\omega)$ of the TMD motion as

$$H_1(\omega) \equiv \left|\frac{X_5}{M}\right| = \sqrt{\frac{\left(-\omega^2 m_2 + k_{pto}\right)^2 + \omega^2 c_{pto}^2}{Re^2 + Im^2}} \tag{5}$$

$$H_2(\omega) \equiv \left|\frac{X_2}{F}\right| = \sqrt{\frac{\left(k_{pto} l_p\right)^2 + \omega^2 c_{pto}^2 l_p^2}{Re^2 + Im^2}} \tag{6}$$

where

$$\begin{aligned} Re = C_{55}^H&(-k_{pto} + \omega^2 m_2) \\ &+ \omega^2\big[B_{55} c_{pto} + \bar{k}_{pto} l_p^2 m_2 \\ &+ (A_{55} + I_{55})(k_{pto} - \omega^2 m_2)\big] \end{aligned} \tag{7a}$$

and

$$\begin{aligned} Im = c_{pto} C_{55}^H \omega &- \bar{c}_{pto} l_p^2 m_2 \omega^3 \\ &+ B_{55}\omega(k_{pto} - \omega^2 m_2) \\ &- (A_{55} + I_{55}) c_{pto} \omega^3 \end{aligned} \tag{7b}$$

III. Platform Stabilization via $\mathcal{H}_2$ Norm Optimization

When the W2SEC system is subjected to irregular wave excitations, one can minimize the semisubmersible pitch motion by tuning the TMD, which is achieved by minimizing the root-mean-square of the time history of the semisubmersible pitch. To this end, let us define the ratio of the pitch height to the wave height, or the response amplitude operator (RAO), as

$$
\begin{aligned}
RAO_1(\omega) &\equiv \frac{X_5(\omega)}{H_w(\omega)} = \frac{H_1(\omega)F(\omega)}{H_w(\omega)} \\
RAO_2(\omega) &\equiv \frac{X_2(\omega)}{H_w(\omega)} = \frac{H_2(\omega)F(\omega)}{H_w(\omega)}
\end{aligned}
\tag{8}
$$

where $H_w(\omega)$ is the wave height. Eqn. (8) can be used to calculate the root-mean-square of the time history of the semisubmersible and TMD displacement; in other words,

$$
\begin{aligned}
\sigma_1 &= \sqrt{\int_0^\infty |RAO(\omega)|^2 S(\omega) d\omega} \\
\sigma_2 &= \sqrt{\int_0^\infty |RAO_2(\omega)|^2 S(\omega) d\omega}
\end{aligned}
\tag{9}
$$

where $S(\omega)$ is the wave spectrum density. Note that Eq. (9) represents an "average" sense of semisubmersible and TMD response under a type of irregular wave excitation. Depending on the wave spectrum density, Eq. (9) can lead to different responses. In this paper, the JONSWAP wave spectrum [11] is considered, i.e.,

$$
\begin{aligned}
S(\omega) &= 320 H_s^2 \frac{\omega_m^4}{\omega^5} \exp\left(-1950 \frac{\omega_m^4}{\omega^4}\right) \gamma\alpha \\
\alpha &= \exp\left(-\frac{\left(\frac{\omega}{\omega_m} - 1\right)^2}{2\sigma^2}\right) \\
\sigma &= \begin{cases} 0.07 \text{ if } \omega < \omega_m \\ 0.09 \text{ otherwise} \end{cases}
\end{aligned}
\tag{10}
$$

where ω_m is the modal (most likely) frequency and H_s is the significant wave height. Note that $\gamma = 2.87$ is used in this paper, which is consistent with Load Case (LC) 3.2 in the Offshore Code Comparison Collaboration, Continuation (OC4) projects [12]. With Eqns. (8) and (9), one can define the platform stabilization problem as

$$
\min_{\{k_{pto}, c_{pto}\}} \sigma_1 \tag{11}
$$

Solutions k_{pto}^{opt} and c_{pto}^{opt} of Eq. (11) lead to an optimal design of the spring stiffness and damping coefficient of the TMD such that the semisubmersible response is minimized; thus, stabilization of the floating semisubmersible can be achieved by the TMD.

IV. Irregular Wave Power Generation

As was done for Eq. (8), Eq. (9) can be used to calculate the root-mean-square of the time history of the power generated;

$$
P_{irr} = \int_0^\infty \bar{P}(\omega)\, S(\omega) d\omega \tag{12}
$$

where $\bar{P}(\omega)$ is the regular wave power generated by the power dissipating term, c_{PTO}, defined as

$$
\bar{P}(\omega) = \frac{1}{2}\omega^2 c_{PTO} |RAO_1(\omega) - RAO_2(\omega)|^2 \tag{13}
$$

P_{irr} represents an "average" sense of power generated under a type of irregular wave excitation. Similar to the optimization of the semisubmersible response, one can maximize power generation through the maximization problem as

$$
\max_{\{k_{pto}, c_{pto}\}} P_{irr} \tag{14}
$$

Solutions k_{pto}^{opt} and c_{pto}^{opt} of Eq. (14) lead to an optimal design of the spring stiffness and damping coefficient of the TMD such that the power extraction is maximized. In this way, the W2SEC structure acts strictly as a wave energy converter, with the goal to increase the relative velocity of the two masses.

V. Results and Discussion

In this section, a benchmark semisubmersible system, adapted from the DeepCwind project, which is commonly used in 5 MW scale offshore wind turbines, will be used to demonstrate how the proposed W2SEC system will achieve optimal vibration control or power generation via numerical simulation. The parameters of the system are provided in Table I.

TABLE I
W2SEC Parameters

Item	Unit	Value
Platform pitch inertia I_{55}	kg m^2	6.827E9
Moment arm l_p	m	25
Draft	m	20
Platform mass m	kg	1.347E7
CG below SWL	m	13.46

First, an optimal design that stabilizes the semisubmersible motion is sought. A typical significant wave height $H_s = 6$ m and two dominant wave periods $T_e = 10$ sec and 9 sec are substituted into Eq. (10) to generate two irregular wave excitations. These two wave periods are considered because they are sufficiently lower than the structural fundamental period of the semisubmersible. As a result, the response of the semisubmersible in the frequency domain is dominated by the wave spectrum instead of the structural resonance, which will have a single dominant peak in the frequency domain. One advantage of such consideration is that the semisubmersible system behaves like a single-degree-of-freedom (SDOF) oscillator. Vibration control of SDOF systems using a TMD has yielded fruitful results in the literature which will serve as good references for the current study.

To obtain ROAs in Eq. (8), all FSI-related parameters, including added inertia A_{55}, hydrodynamic angular stiffness C_{55}^H, and radiation angular damping B_{55}, and external hydrodynamic moment M_e, must be determined a priori. These parameters are determined by numerically solving Eq. (2) under frequency-sweeping regular wave excitations using the boundary element method software WAMIT [13]. Note that due to FSI, these parameters are frequency dependent, e.g., added mass $A_{55}(\omega)$ is a function of excitation frequency.

A MATLAB [14] routine is developed to solve the minimization problem in Eq. (11). The optimal designs with respect to different mass ratios are plotted in Fig. 4. Note that mass ratio $\mu = \frac{m_2}{m_2+m}$, where m is the mass of the platform.

As seen in Fig. 4, the optimal electrical damping coefficient c_{pto} increases with mass ratio, which shares the same trend with the prediction of the classical TMD optimization of SDOF systems provided by Den Hartog [12]. Furthermore, the optimal tuning frequency $\omega_2 = \sqrt{k_{PTO}/m_2}$ of the TMD falls within 0.70 and 0.74 rad/s for $T_e = 10$ sec (0.63 rad/s) and 0.75 and 0.78 rad/s for $T_e = 9$ sec (0.70 rad/s). These results roughly agree with the prediction provided by Den Hartog which indicates that the optimal tuning frequency of the classical TMD optimization of SDOF systems decreases with mass ratio.

To examine the efficacy of the proposed W2SEC system, the root-mean-square responses of the system are compared with the semisubmersible system without TMD. The results are shown in Fig. 5. As seen in Fig. 5, without TMD, the semisubmersible response is around 0.45 degrees. After TMD is included, the semisubmersible response is reduced. Furthermore, the reduction is proportional to mass ratio. Specifically, when $\mu = 1$, the response is reduced by over 40%. Lastly, the responses of the W2SEC system for $T_e = 10$ sec with three mass ratios are also compared with the semisubmersible system without TMD in the frequency domain, as shown in Fig. 6. As seen, without TMD, the semisubmersible response is dominated by a single peak which is contributed mostly by the wave spectrum. After TMD is included, the peak is split into two peaks, which is similar to what is commonly observed when a TMD is added to a SDOF system.

Another MATLAB routine is developed to calculate the power regenerated by the TMDs. The optimal designs plotted in Fig. 4 with respect to different mass ratios are used to calculate the power. The results are plotted in Fig. 7.

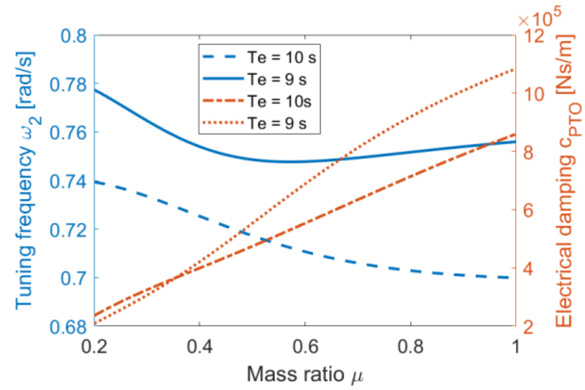

Fig. 4 Optimal PTO natural frequencies and electrical damping coefficients which minimize the root-mean-square response of the semisubmersible.

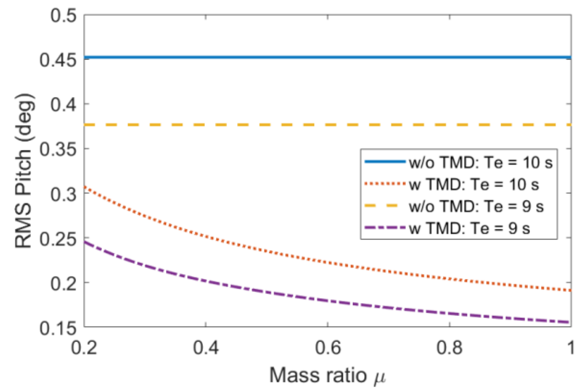

Fig. 5 Root-mean-square (rms) responses of the W2SEC system optimized for minimal semisubmersible displacement and semisubmersible system without TMD. $T_e = 15$ sec.

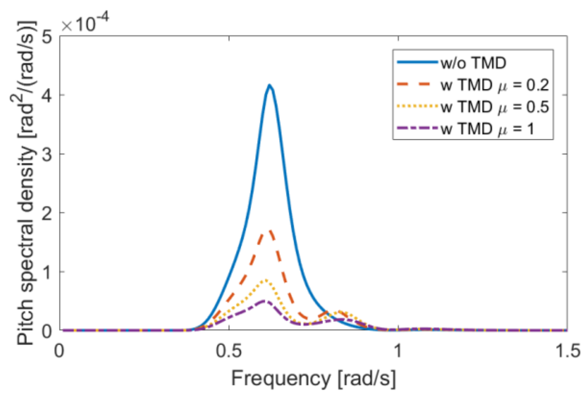

Fig. 6 Responses in the frequency domain of the W2SEC system and semisubmersible system without TMD. $T_e = 10$ sec.

As seen in Fig. 7, power densities around 40~55 kW per significant wave height squared can be reached by the W2SEC when optimized for minimal semisubmersible displacement. A weighted $\mathcal{H}_2$ norm optimization for both semisubmersible rms response and absorbed power can be used to increase power from the TMD while still maintaining control of the semisubmersible response.

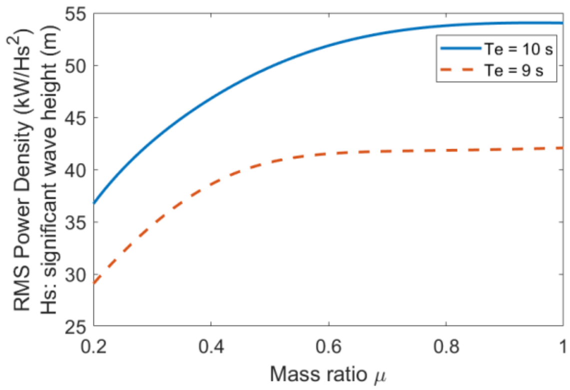

Fig. 7 Irregular wave power of the W2SEC, optimized to minimize the platform pitch motion.

VI. Conclusions

To absorb both ocean wave energy, as well as the gross structural kinetic energy, a tuned mass damper can be implemented onto a floating offshore wind turbine. The platform stabilizing wind-wave energy converter (W2SEC) could not only be capable of harvesting wind energy in areas of great ocean depths, but could do so in ways that enables additional wave energy extraction through use of the tuned mass damper.

The W2SEC inherently aims to provide a stable "platform" for a wind turbine system. With the platform actively being stabilized – mimicking dry land – more technology and techniques from the already well-established industry of onshore wind can be leveraged, thereby reducing costs for W2SEC development and advancement. A benchmark semisubmersible system, adapted from the DeepCwind semisubmersible, which is commonly used in 5 MW scale offshore wind turbines, was used to demonstrate how the proposed W2SEC system would achieve optimal vibration control or power generation. For a mass ratio of 1 (evenly distributed weight between the semisubmersible and TMD mass), the rms response of the semisubmersible was nearly halved, while generating upwards of 55 kW per significant wave height squared.

Concurrently, the semisubmersible of the W2SEC is not only subjected to the undulating motions of ocean waves, but is directly subjected to the turbine tower motions (due to wind thrust) and ocean currents. To counteract this motion – to stabilize the W2SEC – the energy causing such motion is absorbed by a tuned mass damper. Absorption of ocean wave, ocean currents, and wind thrust energy via (1) a wind turbine and (2) a tuned mass damped wave-structural energy converter provides an entirely new concept that enables co-energy generation whilst also enabling a steady platform for a turbine and its tower. Future work in modelling the 6DOF system and including both the wave-structure and wind-structure interactions will be necessary, as well as a weighted $\mathcal{H}_2$ norm optimization strategy for both semisubmersible rms response and absorbed power to increase power from the TMD while still maintaining control of the semisubmersible response.

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