MITIGATION OF SPAR PITCH MOTION BY A TWO DEGREE OF FREEDOM TUNED MASS DAMPER

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KEY POINTS

- *The dynamic response of a Spar type wind turbine coupled with a two DOF TMD is investigated.*
- *Numerical analysis is carried out by considering both wind and waves excitations.*
- *The 2DOF TMD frequencies are tuned with the natural frequency of the system at pitch mode and peak frequency of relevant incident waves, respectively.*
- *Results prove the efficiency of the 2DOF TMD in reducing pitch motion with a reduction of its standard deviation that may attain 40%, depending on the environmental states.*

1 INTRODUCTION

In the context of renewables energies, offshore wind energy has received great interest and many research efforts are focused on design techniques optimization of offshore wind systems. One of the main concerns is related with the large vibrations of support structures due environmental loads and interaction with the turbine itself. One of the well-established approach to overcome this issue is that of equipping the structure, either bottom fixed of floating, with tuned mass dampers (TMDs) (Murtagh et al. 2008; Stewart and Lackner 2014; Tong et al. 2017; Ghassempour et al. 2019; Xie et al. 2020; Lackner and Rotea 2011a, 2011 b; Stewart and Lackner 2013; Park et al 2019) located at different positions on the structure and different configurations, depending on the vibration mode to be mitigated. A standard TMD is a mass connected to the primary structure by a linearly-elastic spring and a viscous dashpot. Tuning mass/stiffness of a TMD to a natural frequency of the system provides a reduction of the response at the targeted frequency and optimal performances may be obtained by appropriate selection of the damping coefficient. This paper proposes a summary of the results given by Laface et al. (2021), in which a novel unique two-degree-of-freedom (2-DOF) TMD placed within the nacelle is introduced to mitigate rigid-body motion oscillations. The paper is organized as follows: section 2 briefly describes the analytical model and section 3 shows performances of the new TMD under several environmental states and section 4 gives the conclusions.

2 ANALYTICAL MODEL

A rigid-body model of the system is implemented, where the rotor-nacelle-assembly (RNA) is reverted to a lumped mass. The rotor aerodynamic loads are modelled as a thrust force applied at the tower top (Muskulus, 2015), hydrodynamic loads are represented as Morison forces acting on the floating support. The floating support is the OC3 Hywind spar (Jonkman 2010) and the wind turbine is the NREL 5MW reference floating offshore wind turbine (Jonkman 2009).

The general form of the equation of motion for the considered system takes the form:

$$\mathbf{M}\ddot{\mathbf{d}}(t)+\mathbf{C}\dot{\mathbf{d}}(t)+\mathbf{K}\mathbf{d}(t)=\mathbf{f}(t,\dot{\mathbf{d}},\mathbf{d}) \qquad (1)$$

Where $\mathbf{d}(t)=\left[u_X(t),\varphi(t),u_z(t)\right]^T$, $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively, $\mathbf{f}(t,\dot{\mathbf{d}},\mathbf{d})$ is the vector of the external aerodynamics and hydrodynamic forces. If the system is equipped with the proposed 2-DOF TMD, mass, stiffness and damping matrices in Eq. (1) reads

$$\mathbf{M}=\begin{bmatrix} m+m_a & I_c & 0 & 0 & 0 \\ I_c & I_y+I_{y,a} & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 \\ 0 & 0 & 0 & m_{d1} & 0 \\ 0 & 0 & 0 & 0 & m_{d2} \end{bmatrix} \quad (2)$$

$$\mathbf{K}=\begin{bmatrix} k_s+k_{d1} & k_s(z_k-z_G)+k_{d1}H_T & 0 & -k_{d1} & 0 \\ k_s(z_k-z_G)+k_{d1}H_T & k_p+k_s(z_k-z_G)^2+k_{d1}H_T^2 & 0 & -k_{d1}H_T & 0 \\ 0 & 0 & k_h & 0 & 0 \\ -k_{d1} & -k_{d1}H_T & 0 & k_{d1}+k_{d2} & -k_{d2} \\ 0 & 0 & 0 & -k_{d2} & k_{d2} \end{bmatrix} \quad (3)$$

$$\mathbf{C}=\begin{bmatrix} c_s+c_{d1} & c_{d1}H_T & 0 & -c_{d1} & 0 \\ c_{d1}H_T & c_{d1}H_T^2 & 0 & -c_{d1}H_T & 0 \\ 0 & 0 & c_h & 0 & 0 \\ -c_{d1} & -c_{d1}H_T & 0 & c_{d1}+c_{d2} & -c_{d2} \\ 0 & 0 & 0 & -c_{d2} & c_{d2} \end{bmatrix} \quad (4)$$

where m is the mass of the system, I_y is the mass moment of inertia about the y axis, m_a is the hydrodynamic added mass associated with surge motion, I_c is an hydrodynamic added inertial term coupling surge and pitch motions and $I_{y,a}$ is the hydrodynamic added mass moment of inertia about the y-axis, k_h is the heave stiffness, k_p is the rotational stiffness associated with the stabilizing moment generated by gravity and buoyancy forces. Additionally, k_s is the x-direction stiffness associated with the mooring cables, z_k denotes the position of the mooring cables – spar connection and z_G the position of the centre of mass. Then, in regard with the damping matrix **C**, c_s and c_h are the damping coefficients associated with surge and heave motions, respectively, (as given in Jonkman 2010), m_{d1}, k_{d1} and c_{d1} are related to mass, spring and damper connected to the tower top, while m_{d2}, k_{d2} and c_{d2} are related to mass, spring and damper connected with the mass m_{d1} (as shown in Figure 1), H_T is the vertical distance between the TMD location and the centre of mass of the unprotected system.

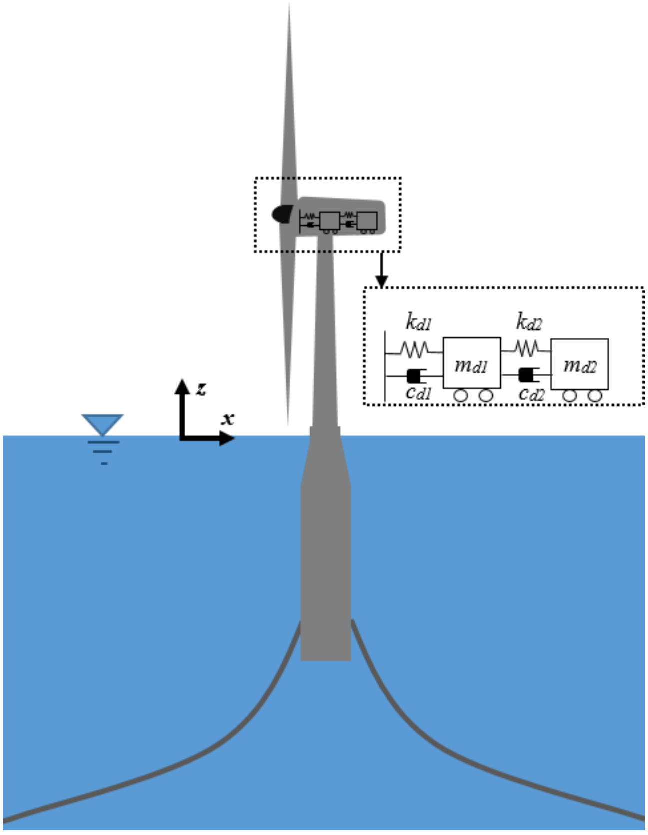

Figure 1. Spar floating wind turbine equipped 2-DOF TMDs located in the nacelle.

3 NUMERICAL INVESTIGATIONS

This section shows results of numerical investigations carried out starting from an optimized configuration of the two DOF TMD. Specifically, Laface et al. (2021) showed that the novel TMD is more efficient than a classical single DOF TMD for a fixed mass ratio μ (percentage ratio between TMD mass and total mass of the system, which is 7.466×10^{6} Kg), but the performances of the two DOF TMD could be further improved by selecting appropriate mass ratio μ^* between the two masses m_{d1} and m_{d2}, for which a value of 2 has been identified as optimal choice for most of environmental states. In the following, results of the numerical analyses conducted assuming $\mu=6\%$ and $\mu^*=2$ are proposed. With the purpose of mitigating oscillations at pitch frequency, the first tuning frequency is chosen as the pitch natural frequency of the system, while the second one is selected as a frequency characterizing the system response to wave loads and is assumed as an average of the peak frequencies characterizing the investigated sea states (see Table 1 for TMD parameters). For the analysis irregular waves to the Stokes' first order, are simulated accordingly to a mean Jonswap spectrum (Hasselmann et al., 1973). A turbulent wind field is simulated adopting the the Kaimal turbulence model in accordance with the IEC prescriptions (International Electrotechnical Commission, 2015). The load condition involved in this analysis cover all the possible combinations of significant wave heights in the within the range of 3-12 m with a step of 3m and the wind speed in the range 5-20 m/s with a step of 5 m/s.

m_{d1} [kg]	m_{d2}[kg]	k_{d1} [N/m]	k_{d2} [N/m]	c_{d2} [Ns/m]	c_{d2}[Ns/m]	ω_1 [rad/s]	ω_2 [rad/s]
$0.04M_{system}$	$0.02M_{system}$	112000	3500	70000	11000	0.197	0.6

Table 1. Mass, stiffness, damping and frequencies of the two DOF TMD.

For each load condition two simulations are performed: the first assuming the system uncontrolled (without TMD) and the latter considering the system equipped with the two DOF TMD. The efficiency of the proposed TMD is evaluated starting from the time histories of the pitch responses in the two configurations, by calculating the following variation of pitch standard deviation $\Delta\sigma$:

$$\Delta\sigma[\%] = \frac{\sigma_{without\ TMD} - \sigma_{with\ TMD}}{\sigma_{without\ TMD}} \cdot 100 \quad (5)$$

where $\sigma_{without\ TMD}$ is the pitch standard deviation in absence of the TMD and σ_{TMD} is that of the system equipped with the TMD.

Note that the wind thrust force is calculated assuming a constant thrust coefficient, whatever the wind speed is, and equal to the maximum value for the considered turbine which is about 0.8. This assumption leads to an overestimation of the thrust force for wind speed within the full load region of the turbine power curve. In this regard, for more accurate results the thrust coefficient should be estimated calculating the value of the thrust coefficient for any value of wind speed within the full load region of the turbine power curve. If so, the calculated efficiency of the system will show a further increase. Figure 2 shows $\Delta\sigma$ for all the load conditions investigated in the proposed analysis. Results show that the efficiency of the considered TMD varies with the environmental conditions and increases as wind speed and wave height grow and may exceed the 30-40%. Figure 3 shows the comparison between power spectral densities of pitch response for the simple system and the equipped with TMD one for significant wave height of 7 m and average wind speed at hub height of 8 m/s. From the figure it is evident the capability of the two DOF TMD to reduce the peaks in the range of the two tuning frequencies.

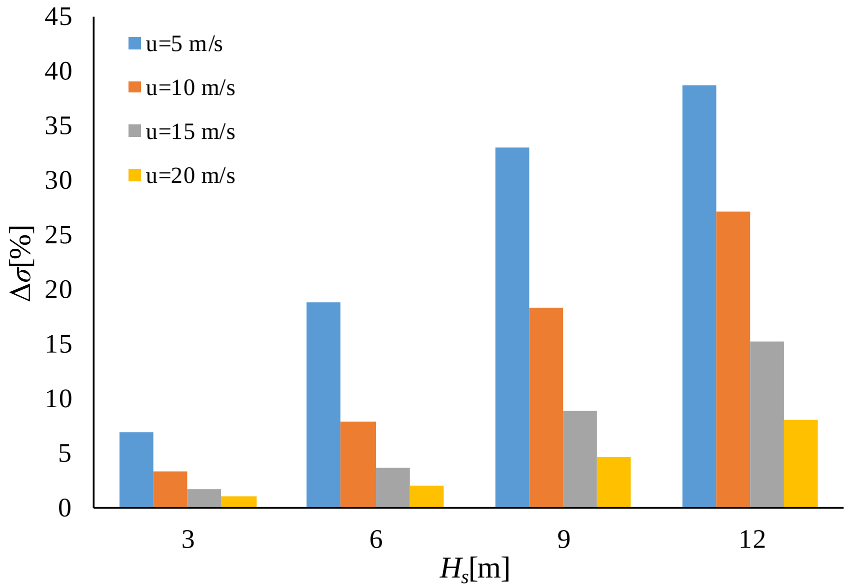

Figura 2. $\Delta\sigma$ achieved by a two DOF TMD with μ*=2 and mass ratio μ= 6% under several environmental conditions.

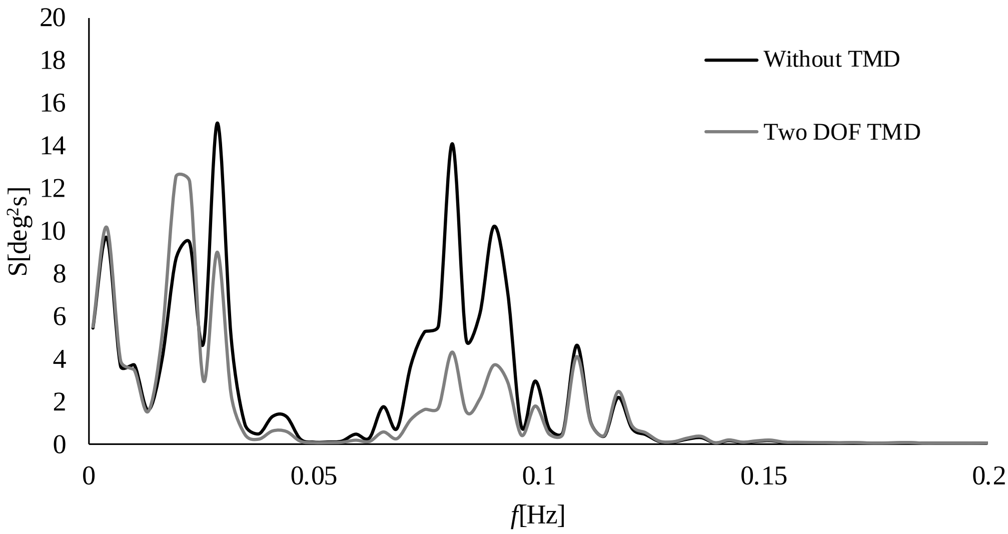

Figura 3. Spar pitch power spectral densities under wind (8 m/s) and waves *(H_s*=7m) excitations without TMDs (continuous line) and with two DOF TMD (dotted line).

4 CONCLUDING REMARKS

This paper has shown the performance of a new concept TMD, which consists of a two DOF unique TMD, designed for mitigating pitch motion of spar offshore wind turbines, under simultaneous wind and wave excitations. The results have shown as this kind of device is able to cut down the peaks of pitch response power spectral density of the system with a reduction pitch response standard deviation that may exceeds the 30-40%.

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