Structural Control for an Offshore Wind Turbine with a Tuned Mass Damper in Floating Platform

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Abstract. In recent years, offshore wind energy has become an attractive option due to the increased demand for the renewable energy. A method incorporating a tuned mass damper (TMD) in offshore wind turbine platform is proposed to demonstrate the improvement on structural dynamic performance in this investigation. The Lagrange's equations are applied to establish a limited degree-of-freedom (DOF) mathematical model for the barge-type offshore wind turbine. Genetic algorithm (GA) is then employed to find the globally optimum TMD design parameters. Numerical simulations based on FAST have been carried out to evaluate the effect of the passive control system. A changeable mass for the floating wind turbine will be brought for installing a heavy tuned mass damper in the platform. In this case, partial ballast is substituted for the equal mass of the tuned mass damper, and the vibration mitigation is simulated in five typical load cases. Results show that the passive control approaches can improve the dynamic responses of the barge-type wind turbine by placing a tuned mass damper in floating platform. Through replacing partial ballast with the equal mass of the tuned mass damper, a significant reduction of dynamic responses is also observed in simulation results for the barge-type floating structure.

Introduction

Wind energy is very important in development and utilization of the sustainable new energy. In Denmark, as much as 20% of the electric power is provided from wind energy annually, and the percentage is towards reaching 50% in the coming decades [1]. Tens and even hundreds of offshore wind turbines can form a large wind farm in the huge available deep water area, and this also makes it possible to improve the power generation efficiency [2]. Therefore, the development of the offshore floating wind turbines is now appearing as an upcoming approach to deal with these propositions.

The offshore floating wind turbines are subjected to extreme wind and wave-induced loads in harsh marine environment, utilizing a control strategy to mitigate the dynamic vibrations for the floating turbines is necessary. Jonkman et al. [3] investigated the use of the aero-hydro-servo-elastic code FAST developed by National Renewable Energy Laboratory (NREL) to simulate the structural responses for barge-type offshore floating wind turbines in different working conditions. Through integrating a passive control code into FAST, Lackner et al. [4] proposed an approach using a TMD configuration in the nacelle of the barge-type offshore floating turbines to achieve the structural vibration mitigation, and the control effectiveness of TMD for Spar and TLP-type were also studied. He et al. [5, 6] proposed the use of TMDs in nacelle to reduce the structure vibration for the barge-type floating turbines, and the results showed that the tower fore-aft displacements suppression rate was 38.7%.

The complexity of floating wind turbines has not yet been fully understood, and this complexity is crucial towards developing cost-effective floating wind turbines to harness wind energy in deep water sites. Therefore, many scaling model experiments were undertaken to investigate the vibration responses of a model offshore floating wind turbine in realistic wind and wave conditions [7-9]. These researches could benefit the offshore wind industry by improving the design of the concept.

Almost all of studies mentioned above are focusing on the installation of the TMD in the tower top
or nacelle. However, the TMD stroke is restricted to the incpacious space of the nacelle compared with that space in barge-type floating platform. Thus, there is an opportunity to investigate the performance of the vibration suppression for a barge-type wind turbine with a TMD placed in the floating support platform.

**Kinetic Model of the Floating Wind Turbine**

ITI Energy Barge, which is defined by NREL, is chosen for analysis in this investigation. The diagram of the structural model for the wind turbine with a TMD housed in platform is showed in Figure 1.

![Figure 1. Structural model of the barge-type wind turbine with a TMD in platform.](image)

The Lagrange’s equations are adopted to create the limited model. The total kinetic energy $T$, potential energy $V$ and the non-potential forces $Q$ for the wind turbine system are described as

$$
T = \frac{1}{2} I_p \dot{\theta}_p^2 + \frac{1}{2} I_t \dot{\theta}_t^2 + \frac{1}{2} m_r (\frac{\dot{x}_r}{\cos \theta_p})^2 ,
$$

$$
V = \frac{1}{2} k_p \theta_p^2 + \frac{1}{2} k_t (\theta_t - \theta_p)^2 + \frac{1}{2} k_t (\frac{x_r + R_p \sin \theta_p}{\cos \theta_p})^2 - m_p g R_p \cos \theta_p + m_t g R_t \cos \theta_t - m_r g (R_p \cos \theta_p + \frac{x_r + R_t \sin \theta_p}{\cos \theta_p} \sin \theta_p) .
$$

$$
Q_p = -d_p \dot{\theta}_p + d_p (\dot{\theta}_t - \dot{\theta}_p) + d_t R_t (\ddot{x}_r + R_t \dot{\theta}_t)

Q_t = -d_t (\dot{\theta}_t - \dot{\theta}_p)

Q_T = -d_t (\dot{x}_r + R_t \dot{\theta}_t)
$$

Where $I$ is the inertia moment of the reference point and $m$ is the mass of the structure component, $\theta$ is the rotation angle and $x$ is the longitudinal displacement for the TMD from $Z$-axis to the reference point, $k$ and $d$ are the spring stiffness and damping coefficients of the structure components, $R$ is the distance from the mass center to the reference point, the subscripts $p$, $t$ and $T$ represent the platform, tower and TMD for the wind turbine, respectively.

Substituting equations (1)–(3) into Lagrange’s equations, because the barge-type platform pitch angle (PtfmPitch) would not exceed 10 degree in normal working conditions, the equation can be linearized as equation (4).
The unknown parameters of the wind turbine model are estimated by finding the minimum of a function that is defined as the sum of squares of the outputs between the proposed model and FAST model. The initial values and estimation results of the unknown parameters are given in Table 1.

Table 1. Estimation results for model unknown parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$d_p$</th>
<th>$d_t$</th>
<th>$k_p$</th>
<th>$k_t$</th>
<th>$I_p$</th>
<th>$I_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial value</td>
<td>$4.5 \times 10^7$</td>
<td>$4.9 \times 10^7$</td>
<td>$1.65 \times 10^9$</td>
<td>$1.45 \times 10^{10}$</td>
<td>$9 \times 10^8$</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>Estimation value</td>
<td>$4.86 \times 10^7$</td>
<td>$2.93 \times 10^7$</td>
<td>$1.78 \times 10^9$</td>
<td>$1.29 \times 10^{10}$</td>
<td>$1.98 \times 10^9$</td>
<td>$2.83 \times 10^9$</td>
</tr>
</tbody>
</table>

Parameter Optimization for TMD Using GA

Since the power generation efficiency of floating wind turbines is determined by tower top fore-aft displacement (TTDspFA). Hence the suppression rate of the standard deviation of the tower top deflection is defined as the fitness function for GA

Table 2 outlines the results of the parameter optimization. The suppression rate varies from 36.10% to 41.79% when the TMD mass ratio $\mu$ changes from 5% to 19%.

Table 2. Parameter optimization results of GA.

<table>
<thead>
<tr>
<th>Mass/[kg]</th>
<th>Mass ratio/[%]</th>
<th>Stiffness coefficient/[N/m]</th>
<th>Damping coefficient/[Ns/m]</th>
<th>suppression rate/[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>307,000</td>
<td>5</td>
<td>83,108</td>
<td>43,512</td>
<td>36.10</td>
</tr>
<tr>
<td>615,000</td>
<td>10</td>
<td>175,008</td>
<td>125,270</td>
<td>39.33</td>
</tr>
<tr>
<td>984,000</td>
<td>16</td>
<td>292,882</td>
<td>251,709</td>
<td>41.17</td>
</tr>
<tr>
<td>1,168,500</td>
<td>19</td>
<td>356,685</td>
<td>327,575</td>
<td>41.79</td>
</tr>
</tbody>
</table>

The time series vibrations of the barge-type floating wind turbine are illustrated in Figure 2 when TMD mass ratio $\mu=19\%$ and initial platform pitch angle is 5 degree. The PtfmPitch and TMD stroke approximately approach to 0 at 40 s.

Figure 2. Vibrations of the floating wind turbine structure.

Vibration Suppression Performances

The load case numbers 1–5 represent the cut-in wind speed, below rated speed, rated speed, higher than rated speed and cut-out speed in Table 3.

Table 3. Five typical load cases.

<table>
<thead>
<tr>
<th>Load case number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub-height mean wind speed/[m·s$^{-1}$]</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Significant wave height/[m]</td>
<td>1.7</td>
<td>2.0</td>
<td>2.6</td>
<td>4.0</td>
<td>5.6</td>
</tr>
</tbody>
</table>

The dynamic responses of the tower bottom fore-aft bending moment (TwrBsMyt) and the blade root flap bending moment (RootMyb1) are shown in Figure 3 when TMD mass ratio $\mu=19\%$ in the
typical load case 5. The amplitudes of TwrBsMyt and RootMyb1 decrease by 51% and 44%, respectively. Therefore, the vibration responses for the barge-type floating wind turbine could be effectively restrained by platform TMD.

![Dynamic responses comparison for the structure.](image)

Because the draft of the barge-type platform could increase by 21% when TMD mass ratio is 19%, a method that a part of the ballast is replaced with the equal TMD mass is proposed to reduce these disadvantages.

![Comparisons of vibration responses with and without TMD replacement: (a) PtfmPitch, (b) TTDspFA, (c) TwrBsMyt and (d) RootMyb1.](image)

The comparisons of vibration responses with and without TMD replacement in five load cases are shown in Figure 4. After replacement, the suppression rate of PtfmPitch varies from 26.4% to 50%, and TTDspFA is 18.76% ~ 40.77%, these suppression rates for TwrBsMyt and RootMyb1 are 19% ~ 40% and 6.92%~33.17%, respectively.

**Conclusions**

1) The TMD configuration installed in platform of the barge-type wind turbine can effectively improve the dynamic responses.

2) The effect of vibration suppression increases with TMD mass ratio when this ratio is not exceeding 19%.

3) A part of the ballast in platform is replaced with the equal TMD mass in the condition of unchanging the design of the total mass for the barge-type wind turbine. In this situation, the suppression rate is 50% when TMD mass ratio $\mu=19\%$.

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**References**


