Vibration suppression of a floating hydrostatic wind turbine model using bidirectional tuned liquid column mass damper

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Abstract
We propose to mitigate the barge pitch and roll motions of floating hydrostatic wind turbine (HWT) by combining the advantages of the bidirectional tuned liquid column damper (BTLCD) and the tuned mass damper (TMD). This is achieved by enabling the container of the BTLCD to move freely, connecting it to the main structure through springs and dampers, creating what we call a bidirectional tuned liquid column mass damper (BTLCMD). The BTLCMD is made by the hydraulic reservoir of the HWT, saving costs by avoiding the addition of extra mass and fluids. The HWT simulation model is obtained by replacing the geared drivetrain of the NREL 5-MW barge wind turbine model with a hydrostatic transmission drivetrain. The dynamics of the BTLCMD are then incorporated into the HWT. Two simplified mathematical models, describing the barge pitch and roll motions of the HWT-BTLCMD coupled system, are used to obtain the optimal parameters of the BTLCMD. Simulation results demonstrate that the BTLCMD is very effective in mitigating the barge pitch motion, barge roll motion, and the tower base load. The BTLCMD also largely outperforms the BTLCD in suppressing barge motions.

KEYWORDS
bidirectional tuned liquid column mass damper, floating platform, hydrostatic transmission, offshore wind turbine, vibration control

1 | INTRODUCTION

Wind power is a fast growing source of green energy, thus more and more attention has been focused on increasing the size of wind turbine blades to enable higher energy capture capacity. The majority of currently operating wind turbines are equipped with blades of 60 m or larger, and their sizes are planned to be increased further. For example, the future 20-MW wind turbines will have a blade length of 120 m. With such large blade sizes, the wind turbines become very flexible, and therefore the load reduction of wind turbines has becomes a critical issue. There is also an increasing trend to install the wind turbines offshore to access the immense wind resources available there. Offshore wind turbines require particular attention to be paid to reducing loads, since extreme wind conditions occur more frequently at sea and their platforms suffer from continuous wave excitation. The platform rotations are coupled with the blade rotations, influencing the flow-field around the blades and causing unsteady aerodynamic effects. These coupled effects will influence the rotor speed, further influencing the thrust and power generation. Furthermore, the platform rotations cause considerable load variations on the wind turbine tower base, which dramatically increases the fatigue...
load. Therefore, it is of critical importance to develop control techniques to suppress platform motions, improving energy capture, and increasing the tower's life expectancy.4

Structural control of the floating wind turbine platform has been investigated by passive, semiactive, and active control schemes.5-10 Hu et al8 employed a hybrid mass damper (HMD) in the turbine’s nacelle to actively control the vibration of the wind turbine tower. Li et al11 used the $H_{\infty}$ control to generate external control force on a tower-base tuned mass damper (TMD) in order to mitigate the tower base loads. The positives of an active control scheme are obvious, but so are the limitations. Active control schemes employ the actuator to generate the control force, requiring regular inspection and maintenance, resulting in high costs, particularly in the offshore case. Furthermore, active control schemes consume power during operation.

In this paper, we focus on the passive vibration control methods. A TMD was installed in the nacelle for load reduction in previous studies.12-14 Around 7% reduction on platform pitch responses was achieved in Lackner14 and 12% reduction of damage equivalent load on the tower base in Jalil et al.13 Hu et al12 used the mechanical network to connect the TMD mass and the nacelle instead of the spring and damper, achieving around 14% reduction on damage equivalent load at the tower base. It is straightforward to see that a TMD installed in nacelle influences the tower top vibrations dramatically, therefore placing the TMD at the tower base may reduce loadings of the platform. The popular Fatigue, Aerodynamics, Structures, and Turbulence (FAST) model developed by National Renewable Energy Laboratory (NREL) incorporated a TMD system at the tower base. The displacement of the TMD mass is affected by the tower deflection and platform motions. Stewart et al15 conducted the research of applying the TMD system inside the platform to reduce its rotations and tower base fatigue for various types of platforms including barge, spar buoy, and tension lag platform (TLP). It investigated different mass ratios (TMD mass over the mass of the floating structure) and implemented the genetic algorithm to obtain the optimal spring and damper parameters. Up to 15.6% reduction on tower base fatigue load was achieved. It also revealed that larger mass ratio served to reduce the load better but the mass ratio has to be set in a reasonable range as a very large TMD mass would cause side effects. The tuned liquid column damper (TLCD) has also been investigated for the purpose of vibration suppression, and its use on the wind turbine structural control has been proven to be effective.16-22 Attempting to deploy the damping system close to the platform, Coudurier et al18 installed the TLCD inside the offshore wind turbine platform to reduce its rotational motions. The pitch motion of the platform can be reduced by up to 25% with the TLCD installed inside the platform. Xue et al22 demonstrated the importance of parameters tuning of the TLCD on damping pitch motions. However, the aforementioned control schemes have a common disadvantage: a large mass is needed. The existence of the extra mass will cause extra structural and material cost. However, the hydrostatic wind turbine (HWT) resolves this problem as one of its auxiliary devices, the reservoir, has the potential can be used as this large mass, removing the need for any significant extra mass.4

Currently, the hydrostatic transmission (HST) drivetrain shown in Figure 1 is receiving increased attention from researchers due to its advantages over the conventional gearbox drivetrain. When the gearbox drivetrain of a wind turbine is replaced with the HST drivetrain, a wind turbine becomes a HWT. Through connection with the rotor, the hydraulic pump converts the mechanical energy into pressurised oil, driving the hydraulic motor to generate the electrical power. After the power conversion process, the majority of the depressurised oil is transported back to the pump while some portion of the oil is imported to the reservoir for the heat dissipation, contaminant settling, and deaeration.23 The HST drivetrain can largely reduce the electro-mechanically coupled vibrations, significantly improving the stability of the drivetrain and the generator.24 Furthermore, the HST system not only reduces the weight of the nacelle, but also increases the reliability of the drivetrain system, reducing the maintenance cost of offshore wind turbines. Moreover, there is a possibility of using the reservoir for a spin off application. Tong and Zhao4 proposed a novel use of the reservoir in the offshore HWT, reducing the platform’s rotational motions by about 20%. The reservoir was made into a bidirectional tuned liquid column damper (BTLCD), whose structure is shown in Figure 2. In Tong and Zhao,4 the BTLCD was fixed on top of the platform. The BTLCD concept was originally proposed by Rozas,25 which permits sensing and suppressing the vibrations of the platform in two perpendicular directions by four connected horizontal liquid columns. The four vertical and four horizontal liquid columns work together to reduce platform rotations in two orthogonal axes.
The present paper aims to further reduce the platform rotations by connecting the BTLCD reservoir with the wind turbine tower through the springs and dampers in two perpendicular directions, allowing the reservoir to move frictionlessly on top of the platform. This passive device is called bidirectional tuned liquid column mass damper (BTLCMD), as shown in Figure 4. In this way, the platform vibration energy is dissipated not only by the orifice in the horizontal liquid columns, but also by the dampers installed between the reservoir and the wind turbine tower. To the best of our knowledge, this paper presents the first introduction of the BTLCMD to the floating wind turbine for the purpose of vibration suppression of its platform. We mention that Ghosh et al. utilised a similar but simpler passive device named tuned liquid column mass damper (TLCMD) to reduce the seismic vibration of structures, where the TLCD was connected to the main structure through a damper and spring as shown in Figure 3, enabling the TLCD to move freely (during the structure vibration).

Based on the model of a floating HWT stabilized by a BTLCD in Tong and Zhao, we extend the BTLCD model into BTLCMD model by adding reservoir’s frictionless translations on the platform in two perpendicular directions through the springs and dampers connected to the wind turbine tower. Like the BTLCD in Tong and Zhao, the BTLCMD also influences 6 degrees of freedom (DOFs) of the platform, surge, sway, heave, pitch, roll, and yaw due to the reservoir displacements and the relative motions of liquid within the reservoir. The design parameters of the

**FIGURE 2**  Barge with the bidirectional tuned liquid column damper reservoir fixed on it [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 3**  Main structure with tuned liquid column mass damper

**FIGURE 4**  Barge with the bidirectional tuned liquid column mass damper reservoir placed on it (move freely) [Colour figure can be viewed at wileyonlinelibrary.com]
BTLCMD reservoir including the coefficients of springs and dampers are optimised to perform the best suppression performance on platform motions.

In order to derive the optimal design parameters of the BTLCMD reservoir, two simplified mathematical models which describe the fore-aft (pitch) and side-to-side (roll) motions of the turbine-reservoir system are developed. We conduct optimisation based on the mathematical model in the fore-aft direction first, as the wave and wind loading mainly excite the offshore HWT in this direction. We then optimise other parameters based on the model in the side-to-side direction. The MATLAB optimisation solver FMINCON is used to obtain optimal parameters. The simulation results demonstrate that the BTLCMD largely outperforms the BTLCD in mitigating platform pitch and roll motions, which consequently reduces the tower-base fatigue loading.

The structure of the remainder of this paper is as follows. In Section 2, we transform the BTLCD to a BTLCMD by deriving the equation of motions (EOMs) of the liquid and the reservoir to account for the dynamics of the BTLCMD. The two simple mathematical models and the parameter optimisation are derived in Section 3. In Section 4, the simulation results of the BTLCMD used for vibration suppression of a floating offshore wind turbine in comparison with the BTLCD are illustrated. Finally, we conclude our findings in Section 5.

2 | INCORPORATING THE BTLCMD INTO THE HWT

2.1 | Introduction of the BTLCMD configuration

In this section, we introduce the BTLCMD that was developed based on the BTLCD designed in Tong and Zhao. To convert the BTLCD into the BTLCMD, we connect the reservoir with the tower through a spring and damper in each of the two perpendicular directions, respectively. Then, we install four idealised frictionless wheels underneath the reservoir so that the reservoir can translate frictionlessly on top of the barge. Due to the reservoir displacements and the relative motions of liquid within the reservoir, the BTLCMD influences all the six DOFs of the barge in FAST, where the surge, sway, and heave are the translational DOFs and the roll, pitch, and yaw are the rotational DOFs. As can be seen in Figure 4, x, y, and z represent a set of orthogonal axes of a fixed inertial frame for the six DOFs. The x-axis points in the nominal downwind direction, and the z-axis points upward along the undeflected tower’s centreline when the barge is undisplaced. Given the direction of these two axes, the direction of y-axis is determined by the right-hand rule. The xy-plane refers to the mean sea level (MSL). The barge reference point is O, which is also the origin of x, y, and z. The six DOFs and external loads are defined as acting on O.

The barge pitch, roll, and yaw motions are denoted as \( \alpha \), \( \beta \), and \( \gamma \), respectively. Another coordinate system with axes \( l \), \( s \), and \( h \) is defined, whose origin is fixed at tower base and the axis directions translate and rotate with the barge motion. The reservoir translates in the \( l \) and \( s \) directions, generating damping forces through the springs and dampers. The spring and damper coefficients in \( l \)-axis are represented by \( K_l \) and \( C_l \), respectively. \( K_r \) and \( C_r \) denote the coefficients of spring and damper in \( s \)-axis. These two coordinate systems coincide with each other when the barge is undisplaced. The transformation from \( x \), \( y \), and \( z \) to \( l \), \( s \), and \( h \) is derived by Jonkman as \( [l \ s \ h] = T [x \ y \ z] \), where the transformation matrix is as follows:

\[
T = \frac{1}{\Delta_3} \begin{bmatrix}
\beta^2 \Delta_2 + \alpha^2 + \gamma^2 & \gamma \Delta_1 + \beta \alpha (\Delta_2 - 1) & -\alpha \Delta_1 + \gamma \beta (\Delta_2 - 1) \\
-\gamma \Delta_1 + \alpha \beta (\Delta_2 - 1) & \beta^2 + \alpha^2 \Delta_2 + \gamma^2 & \beta \Delta_1 + \alpha \gamma (\Delta_2 - 1) \\
\alpha \Delta_1 + \gamma \beta (\Delta_2 - 1) & -\beta \Delta_1 + \alpha \gamma (\Delta_2 - 1) & \alpha^2 + \beta^2 + \gamma^2 \Delta_2
\end{bmatrix}.
\]  

where \( \Delta_1 \), \( \Delta_2 \), and \( \Delta_3 \) are defined as \( \Delta_1 = \alpha^2 + \beta^2 + \gamma^2 \Delta_2 = \sqrt{1 + \Delta_1 \Delta_3} = \Delta_1 \Delta_2 \).

In accord with the column numbers and the coordinate system of the BTLCMD shown in Figure 4, we obtain the three-view drawing of the BTLCMD reservoir in Figure 5. First, we define the specifications of the reservoir to derive the dynamics of the BTLCMD. Columns 2 and 6 are designed with same dimensions. Their cross-section area and length are represented by \( A_s \) and \( L_x \), respectively. Columns 4 and 8 also have the same dimensions, and their cross-section area and length are represented by \( A_r \) and \( L_y \), respectively. The other four vertical columns share the same length (when the liquid is undisplaced) \( L_z \) and cross-section area \( A_v \). The liquid displacements relative to the BTLCMD reservoir in columns 1 to 8 are represented by \( u_1, u_2, \ldots, u_8 \), with the positive direction coinciding with the direction of x-axis, y-axis, and z-axis as shown in Figure 4. These liquid displacements are not all independent to each other. The liquid displacements in vertical columns are determined by the liquid displacements in the other four horizontal columns with their relations shown as follows:

\[
\begin{align*}
u_1 &= u_6 - \frac{A_v}{A_r} u_h, & \quad u_3 &= u_2 - \frac{A_v}{A_r} u_6, \\
u_2 &= \frac{A_v}{A_r} u_6 + \frac{A_v}{A_r} u_8, & \quad u_7 &= -\frac{A_v}{A_r} u_6 + \frac{A_v}{A_r} u_8.
\end{align*}
\]
The orifice is built within each horizontal columns to generate the head loss, which accounts for the liquid kinetic energy dissipation. Columns 2 and 6 share the same head loss coefficient, which is represented by $\eta_x$. The head loss coefficient for columns 4 and 8 is denoted as $\eta_y$. The liquid in columns 1, 2, 3, 5, 6, and 7 serve to mitigate the pitch motion of the barge, while the liquid in columns 1, 3, 4, 5, 7, and 8 is responsible for the barge roll motion. Their effective liquid masses are represented by $M_{lp}$ and $M_{lr}$, respectively. These values can be calculated by

$$M_{lp} = \rho_l A_v \left(4L_v + 2\frac{A_y}{A_v}L_y\right),$$

$$M_{lr} = \rho_l A_v \left(4L_v + 2\frac{A_x}{A_v}L_x\right),$$

where $\rho_l = 917 \text{kg/m}^3$ is the liquid density. The total mass of the liquid in the BTLCMD reservoir is $M_l = \rho_l(4A_vL_v + 2A_yL_y + 2A_xL_x)$, and we define the mass of the reservoir itself to be $M_r$.

### 2.2 Incorporating the coupled BTLCMD dynamics into the FAST code

The dynamics of the BTLCMD interact with six barge DOFs and two tower vibration DOFs. The six barge DOFs are surge, sway, heave, pitch, roll, and yaw, which are denoted by $q_1$, $q_2$, $q_3$, $q_4$, $q_5$, and $q_6$, respectively. The reservoir itself has two translational DOFs $q_7$ and $q_8$, in the $l$-axis and $s$-axis, respectively. The two tower vibration DOFs are represented by $q_9$ and $q_{10}$, which coincide to the fore-aft and side-to-side deflections of the point on the tower where springs and dampers are connected, respectively. To model the BTLCMD dynamics in a consistent manner, we derive the EOMs of the liquid relative motions $u_2$, $u_4$, $u_6$, and $u_8$ and the reservoir translations $q_7$ and $q_8$. We extract six barge DOFs and their first and second derivatives from FAST as the input to the BTLCMD system. In addition, we extract $q_9$ and $q_{10}$ from FAST as the input to the BTLCMD system. In this way, we obtain the DOFs required to derive the dynamics of the BTLCMD model. Meanwhile, we modify the FAST FORTRAN source code to add two channels so that the forces generated by springs and dampers in two perpendicular directions can be exerted on the point where the springs and dampers are connected to. Tong and Zhao\(^4\) have established the channels to exert moments and forces on the barge. In our case, the motions of the liquid depends not only on the six barge DOFs but also on the translation of the reservoir. The relative liquid motions, six barge DOFs, and tower DOFs $q_9$ and $q_{10}$ all influence the translations of the reservoir. The extra two perpendicular forces exerted on the tower through springs and dampers are denoted by $f_x$ and $f_y$. We derive the EOMs of the liquid relative motions and reservoir translations using Lagrange’s equation. We can also use this equation to calculate the moments and forces exerted on the barge. The kinetic energy of the BTLCMD reservoir $T_l$ is then equal to the summation of the kinetic energy of the liquid in each column and the kinetic energy of the reservoir itself.
where $T_k$ is the kinetic energy of the liquid in column number $k$ and $T_r$ represents the kinetic energy of the reservoir itself.

The kinetic energies of the liquid in the horizontal and vertical columns are presented below with columns 1 and 2 used as examples. The kinetic energies for the other columns are similar but with different boundary conditions.

$$T_1 = \frac{1}{2} \rho A v_1^2 \int_{-\frac{r}{2}}^{\frac{r}{2}} v_1^2 \, dl, \quad T_2 = \frac{1}{2} \rho r_A v_2^2 \int_{-\frac{r}{2}}^{\frac{r}{2}} v_2^2 \, dl,$$

where $h$ and $l$ are, respectively, the coordinates of the liquid particle along the $h$ and $l$ axes. $v_1$ and $v_2$ are the velocities of any liquid particle in columns 1 and 2 relative to the inertial frame.

The specific expressions of $v_1$ and $v_2$ are presented as follows:

$$v_1 = \dot{q}_1 x + \dot{q}_2 y + \dot{q}_3 z + u_1 h + \dot{q}_s s + \dot{\alpha}(\dot{y}+\dot{y})x \times \left( (q_1 - \frac{L_y}{2}) l + (q_2 - \frac{L_y}{2}) s + \alpha h \right) + \dot{\alpha}_1 \left( \frac{L_y}{2} - q_1 \right) T(1,1) + \dot{\alpha}_2 \left( \frac{L_y}{2} - q_2 \right) T(2,1) + \dot{\alpha}_3 \left( \frac{L_y}{2} - q_3 \right) T(3,1) + \dot{\alpha}_4 \left( \frac{L_y}{2} - q_4 \right) T(4,1)$$

$$v_2 = \dot{q}_1 x + \dot{q}_2 y + \dot{q}_3 z + u_1 h + \dot{q}_s s + \dot{\alpha}(\dot{y}+\dot{y})x \times \left( (q_1 - \frac{L_y}{2}) l + (q_2 - \frac{L_y}{2}) s + \alpha h \right) + \dot{\alpha}_1 \left( \frac{L_y}{2} - q_1 \right) T(1,1) + \dot{\alpha}_2 \left( \frac{L_y}{2} - q_2 \right) T(2,1) + \dot{\alpha}_3 \left( \frac{L_y}{2} - q_3 \right) T(3,1) + \dot{\alpha}_4 \left( \frac{L_y}{2} - q_4 \right) T(4,1)$$

where the transformation matrix $T$ is given in equation (1). The kinetic energies of other columns can be derived in a similar way. The specific expressions for parts due to the reservoir are presented as follows:

$$T_r = \frac{1}{2} M_r \left[ (\dot{q}_9 - \dot{q}_7) T(1,1)^2 + (\dot{q}_{10} - \dot{q}_6) T(2,1)^2 + (\dot{q}_7 - \dot{q}_9) T(1,2)^2 + (\dot{q}_6 - \dot{q}_{10}) T(2,2)^2 + (\dot{q}_8 - \dot{q}_9) T(1,3)^2 + (\dot{q}_9 - \dot{q}_8) T(2,3)^2 \right].$$

To calculate the potential energy of the BTLCMD, we need to set the $xy$-plane to be the zero potential energy surface as it refers to the MSL. Furthermore, we define the zero potential energy length of the spring to be the length when the spring is under no stretch or contraction. The potential energy of the BTLCMD is given as

$$V_r = (M_1 + M_2) g q_3 + V_r + \sum_{k=1}^{8} V_k,$$

where $g$ is the acceleration of gravity and $V_k$ is the potential energy of the liquid in column numbered $k$. Below we give values for some columns,

$$V_1 = \rho A g (L_y + u_1) \left[ (q_1 - \frac{L_y}{2}) T(1,1) + \left( q_2 - \frac{L_y}{2} \right) s + \frac{L_y + u_1}{2} h \right],$$

$$V_2 = V_4 = V_6 = V_8 = 0,$$

The potential energies of $V_2$, $V_4$, $V_6$, and $V_8$ are equal to zero because they are just on the $xy$-plane. The potential energies of the columns 3, 5, and 7 can be obtained in a similar way to $V_1$. The potential energy $V_1$ is related to the compression of the springs and the motions of the reservoir, which is

$$V_r = \frac{1}{2} K_s (q_9 - q_7)^2 + \frac{1}{2} K_s (q_{10} - q_6)^2 - M_r g [q_7 \sin(q_4) + q_8 \sin(q_5)].$$
We can use Lagrange's equation to obtain the EOMs of the relative liquid motions \( u_2, u_4, u_6, u_8 \) and reservoir translations \( q_7, q_8 \). It is given by

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = Q_i, L = T - V,
\]

where \( Q \) is the generalised force associated with the DOF \( q \) and \( D \) is the dissipation function. To obtain the EOMs, we substitute \( T_i \) and \( V_i \) into equation (11) considering DOFs \( q_7, q_8 \) and the DOFs of the liquid relative motions in 4 horizontal columns, which are denoted by \( q_{1u2}, q_{4u4}, q_{6u6}, \) and \( q_{8u8} \), respectively.

\[
\frac{d}{dt} \left( \frac{\partial (T_i - V_i)}{\partial \dot{q}_i} \right) - \frac{\partial (T_i - V_i)}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} + f_i = Q_i,
\]

where \( i = u2, u4, u6, u8, 7, 8 \).

The DOFs \( q_{1u2}, q_{4u4}, q_{6u6}, \) and \( q_{8u8} \) represent the relative motions between the liquid and the reservoir in columns 2, 4, 6, and 8, respectively. The dissipation function \( f_i = \frac{1}{2} C_i (\dot{q}_i - \dot{q}_7)^2 \), \( f_8 = \frac{1}{2} C_i (\dot{q}_{10} - \dot{q}_8)^2 \). The expressions of \( f_{1u2}, f_{4u4}, f_{6u6}, \) and \( f_{8u8} \) are verified by the experiments in Sakai \(^{27} \) and are as follows:

\[
\begin{align*}
    f_{1u2} &= \frac{1}{2} \rho A x_1 \dot{q}_{1u2} |\dot{q}_{1u2}|, \\
    f_{4u4} &= \frac{1}{2} \rho A y_1 \dot{q}_{4u4} |\dot{q}_{4u4}|, \\
    f_{6u6} &= \frac{1}{2} \rho A y_1 \dot{q}_{6u6} |\dot{q}_{6u6}|, \\
    f_{8u8} &= \frac{1}{2} \rho A y_1 \dot{q}_{8u8} |\dot{q}_{8u8}|.
\end{align*}
\]

To calculate the three damping moments \( f_6, f_7, f_8 \) and three damping forces \( f_1, f_2, f_3 \) acting on six barge DOFs due to the relative motions of the liquid and the reservoir displacements, we utilise the Lagrange equation again as follows:

\[
f_m = -\frac{\partial (T_i - V_i)}{\partial q_m} - \frac{d}{dt} \left( \frac{\partial (T_i - V_i)}{\partial \dot{q}_m} \right), \quad \text{where} \quad m = 1, 2, 3, 4, 5, \text{and } 6 \text{ represent the barge surge, sway, heave, pitch, roll, and yaw DOFs, respectively.}
\]

Forces \( f_x \) and \( f_y \) generated by the springs and dampers in two perpendicular directions are calculated in equation (15) and imported into the FAST. \( f_x \) and \( f_y \) represent the forces exerted on the tower in fore-aft and side-to-side directions, respectively.

\[
\begin{align*}
    f_x &= K_x (q_2 - q_7) + C_x (\dot{q}_2 - \dot{q}_7), \\
    f_y &= K_y (q_8 - q_{10}) + C_y (\dot{q}_8 - \dot{q}_{10}).
\end{align*}
\]

Based on the EOMs and forces generated by springs and dampers, we create the Simulink model of the BTLCMD, which is coupled to the FAST code via FAST/Simulink interface. To obtain the dynamics of the liquid motions \( q_{1u2}, q_{4u4}, q_{6u6}, q_{8u8} \) and reservoir translation \( q_7, q_8 \), we extract six barge DOFs \( q_1, q_2, \ldots, q_6 \) and two tower vibration DOFs \( q_7, q_8 \) and their derivatives from the outputs of FAST and apply equation (12) to perform the calculation in the Simulink model. Then, the forces and moments, exerted on the barge by the BTLCMD, are calculated by equation (14) given the dynamics of the liquid motions and reservoir translations. The dynamics of reservoir translations, combined with the DOFs \( q_7 \) and \( q_8 \), are used to calculate the forces exerted on the tower through the springs and dampers by equation (15). The forces and moments exerted on the barge and the forces exerted on the tower, as the outputs of the Simulink model of the BTLCMD, are imported into the FAST via corresponding channels. In this way, we successfully incorporate the dynamics of the BTLCMD into FAST.

### 3 | Optimising the Parameters of the BTLCMD Reservoir

To optimise the parameters of the BTLCMD reservoir, we need to capture the main DOFs of the turbine-reservoir system contributing to the barge pitch and roll motions, whose suppression is the objective of the BTLCMD. The wind turbine mainly suffers from the wind and wave
excitations in the fore-aft direction, corresponding to the pitch motion of the barge. We design a simplified mathematical model $P_p$ to describe the wind turbine barge pitch motion, which is then utilised to optimise the BTLCMD reservoir parameters. The remaining parameters will then be optimised through another mathematical model $P_r$, which describes the wind turbine barge roll motion. The simplified models $P_p$ and $P_r$ are each regarded as an inverted pendulum on the barge platform, respectively.\(^4\)

To create $P_p$, we consider the following DOFs: the liquid relative displacements $u_2/u_6$ in the horizontal columns numbered 2/6; the barge pitch DOF $q_4$; the rotational pitch displacement of the pendulum tower from the $z$-axis, which is denoted as $q_{11}$; and the reservoir relative motion $q_7$ in $l$-axis. Based on the NREL 5-MW wind turbine configuration parameters given by Tong and Zhao,\(^4\) we utilise the Lagrange’s equation to obtain the EOMs of all the DOFs of $P_p$ by calculating the kinetic energy $T_{op}$ and potential energy $V_{op}$ of the simplified wind turbine model.

$$T_{op} = \frac{1}{2} I_{tp} q_{11}^2 + \frac{1}{2} I_{bp} q_4^2 + T_{lp},$$

$$V_{op} = \frac{1}{2} k_{tp} (q_{11} - q_4)^2 + \frac{1}{2} (C_{hi} + C_{mi}) q_4^2 + m_t g L_t \cos q_{11} - m_b g L_p \cos q_4 + V_{lp}. \quad (16)$$

The parameter $I_{tp}$ is the pitch inertia of the tower and rotor nacelle assembly (RNA) while $I_{bp}$ is the pitch inertia of the barge. They are both defined with respect to the barge reference point $O$. $C_{hi}$ is the hydrostatic pitch restoring coefficient, and $C_{mi}$ is the linearised pitch restoring coefficient from mooring lines. $m_t$ represents the total mass, and $k_{tp}$ represents the equivalent pitch restoring coefficient of the tower and RNA.\(^4\) $M_l$ is the liquid mass, $M_r$ is the mass of the reservoir itself, and $m_b$ is the mass of the barge. $L_t$ is the distance from the mass centre of the tower and RNA to the reference point while $L_p$ is the distance from the mass centre of the barge to the reference point.\(^4\) $T_{op}$ and $V_{op}$ are the kinetic and potential energies of $T_i$ and $V_i$ in equation (4) and (8) by setting $q_1, q_2, q_5, q_6, u_4(q_2), u_8(q_2)$ and their first derivatives to be zero, and substituting $u_2$ and $u_6$ with $u_2$ and $\dot{u}_6$.

Applying the Lagrange’s equation, we obtain the EOMs of $P_p$ (the simplified wind turbine model with the BTLCMD in fore-aft directions) as follows:

$$\frac{d}{dt} \left( \frac{\partial L_{op}}{\partial \dot{q}_r} \right) - \frac{\partial L_{op}}{\partial q_r} = f_r, \quad L_{op} = T_{op} - V_{op}. \quad (17)$$

where $r = 4, 7, 11, u_2, f_{u2}$ is given in (13) and

![Figure 6](http://wileyonlinelibrary.com)
\begin{align*}
    f_4 &= -A_4 q_4 - (B_4 + B_6) \ddot{q}_4 + d_{\theta}(\dot{q}_{11} - \dot{q}_4) + M_w, \\
    f_7 &= -C_7 q_7 - 2 \rho L x L x u^2, \\
    f_{11} &= - d_{\theta}(\dot{q}_{11} - \dot{q}_4) + F_{\alpha} L_{hh} + C_4 L_{hh} (\dot{q}_7).
\end{align*}

\textit{Arad} and \textit{Brad} are, respectively, the added pitch inertia and the pitch damping coefficient associated with hydrodynamic radiation, respectively. \textit{Bvis} is the linearised pitch damping coefficient associated with hydrodynamic viscous drag. \textit{Mw} is the total wave-excitation pitch moment from diffraction applied at the reference point \textit{O}. \textit{d_{\theta}} is the equivalent pitch damping coefficient of the tower and RNA. \textit{L_{hh}} is the hub height, and \textit{F_{\alpha}} is the aerodynamic rotor thrust acting on the hub. \textit{mt}, \textit{mp}, and \textit{L_{hh}} are given by Jonkman. From equation (16) with the corresponding values given in Tong, the remaining parameters of \textit{P}_p are \textit{L_x}, \textit{L_v}, \textit{A_x}, \textit{eta}, \textit{A_v}, \textit{C_x}, \textit{K_x}, and \textit{M_r}.

From equation (3), we discovered that \textit{A_L} is a constant after obtaining the values of \textit{M_{lp}} and \textit{M_{lr}} and optimised parameters in \textit{P} \textit{p}. We only need to optimise \textit{L_y}, \textit{eta_y}, \textit{K_y}, \textit{C_y} for the simplified wind turbine model describing the side-to-side (roll) motions. As for the effective liquid mass \textit{M_{lp}} and \textit{M_{lr}} in damping barge pitch motion and barge roll motion, respectively, we define two mass ratios \textit{u_p} = \frac{M_{lp}}{M_{tb}} = 5\% and \textit{u_r} = \frac{M_{lr}}{M_{tb}} = 3\%. This is due to the fact that more damping in the fore-aft direction is needed and large values for the mass ratios are unreasonable. We define \textit{M_r} to be 1\% of \textit{M_{tb}}, with the calculation in the last part of this section demonstrating that the whole damping mass is less than 7\% of the main structure. It is obvious that a large mass ratio could achieve better control performance, but in practice, the values of \textit{u_p} and \textit{u_r} are restricted by the space and structure endurance. \textit{M_{tb}} = 6149460 kg is the mass of the HWT except for the BTLCMD system. As the value of the effective liquid mass \textit{M_{lp}} has been fixed, we can obtain the value of \textit{A_v} if we know the other parameters in equation (3). The remaining parameters of \textit{P} \textit{p} to be optimised are

\begin{equation}
    x_{op} = [L_x, A_x, \eta_x, A_v, C_x, K_x, \textit{M_r}].
\end{equation}

Before utilising the simplified mathematical model \textit{P} \textit{p} for optimisation, we verify it against the NREL 5-MW barge wind turbine model. We perform the model response comparison between them in two simulation environments, called S1 and S2. In S1, we let both models oscillate freely from an initial barge pitch angle of 5°, setting \textit{F_{\alpha}} and \textit{M_{w}} to be 0. We utilise an ordinary differential equation (ODE) solver in Matlab to simulate the dynamics of \textit{P}_p. For the NREL model, we only enable the barge pitch DOF, the first tower fore-aft bending DOF, and two DOFs in BTLCMD system, \textit{q_{u2}} and \textit{q_7}. We also disable the wind and wave excitations. Figure 6 shows both models’ simulation results of the barge pitch angle (\textit{q_4}), tower-top displacement (TTD), liquid displacement (\textit{qu_2}) and tower tower tuned mass damper (TMD) displacement in \textit{x}-axis (\textit{q_7}) within the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) code (red dotted lines) and the simplified model \textit{P} \textit{p} (blue solid lines) in S2 [Colour figure can be viewed at wileyonlinelibrary.com]
angle \( q_4 \), tower-top displacement (TTD), the liquid displacement in the column 2/6 \( q_{12} \), and the tower TMD displacements in \( x \)-axis. There is clearly a close agreement between the two simulations.

For S2, we operate the wind turbine in region 3 by setting the wind speed to 22 m/s and the significant wave height to 3 m with peak spectral period set to 12 s. For the NREL model, we set the simulation environment by modifying the input files. As before, we only enable the barge pitch DOF, the first tower fore-aft bending DOF, and two DOFs in BTLCMD system, \( q_{12} \) and \( q_7 \), to be consistent with the mathematical model \( \Sigma_F \). For \( \Sigma_F \), we set \( F_0 \) and \( M_w \) to be the same values as the rotor thrust and the wave-excitation pitch moment in the simulation of the NREL model. We then utilise the ODE solver in Matlab to obtain its model responses. We can see in Figure 7 that two model responses match very well.

We now optimise the parameter \( x_{op} \) based on \( \Sigma_F \). We set a series of wind and wave loadings for \( \Sigma_F \) trying to find the optimal \( x_{op} \) which minimises the maximal barge pitch displacement \( q_4 \). The excitation loadings \( F_r \) and \( M_r \) for \( \Sigma_F \) are adopted from the simulation data of the HWT,\(^4\) in which we set \( F_r \) in equation (18) to be equal to the value of the aerodynamic rotor thrust of HWT under the wind speed of 24 m/s (the cut-out speed is 25 m/s). We also generate 11 100-s time-series for \( M_w \) (wave-excitation pitch moment from diffraction) in equation (18). The 11 time-

![Figure 8](image_url)  
**FIGURE 8** The hub-height longitudinal wind speed and wave elevation in E1 where the mean hub-height longitudinal wind speed is 24 m/s and the significant wave height is 5.5 m [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 9](image_url)  
**FIGURE 9** Simulation results of barge pitch and roll displacements for the hydrostatic wind turbine (HWT) (blue dashed lines), HWT with bidirectional tuned liquid column mass damper (BTLCMD) (black solid lines), and HWT with bidirectional tuned liquid column damper (BTLCD) (red dotted lines) in the event E1 [Colour figure can be viewed at wileyonlinelibrary.com]
series are based on the JONSWAP spectrum and generated by the HydroDyn module in FAST with the peak-spectral periods ranging from 10 to 15s in the step of 0.5s. We set the significant wave height to be 5.5m for all the 11 waves. We then find the maximal barge pitch displacement $q_4$ within 11 simulations on $\sum_p$ with the aforementioned $M_w$ and $F_o$. Utilizing the MATLAB sequential quadratic programming algorithm FMINCON from different starting points, we obtain the local optimal $x_{op}$, which minimises the maximal barge pitch displacement $q_4$. Several constraints are considered during the optimisation process. First, we ensure that the liquids remain in the four vertical columns of the BTLCMD reservoir with the constraint $A_v \cdot \max|q_2| \leq I_w A_v$, where $A_v \cdot \max|q_2|$ is the maximal liquid volume in the vertical columns during all the 11 simulations. $I_w = 0.8$ is the parameter set to leave some room in the vertical column for the damping of barge roll motion. We also set $1m \leq L_x + 2 \times \max|q_7| \leq 40m$, $1m \leq L_v \leq 10m$, $0 \leq \eta_x \leq 10$. These constraints guarantee that the sum of the horizontal column length and reservoir stroke do not exceed the barge length (40 m) in x direction, which the height of the reservoir is reasonable, and that the cross-section ratio and head loss coefficient of the columns 2 and 6 are kept in the reasonable range. Finally, we obtain the optimal BTLCMD parameters as follows:

$$x_{op} = [29.24m, \ 10m, \ 2.95m^2, \ 4.32, \ 208389N/m, \ 279972N \cdot s/m]. \quad (20)$$

From equation (3), we obtain $A_v = \frac{M_w - 20\rho_l L_x^4}{\eta_x} = 4.07m^2$. Like the optimisation process given above, we obtain $x_{op}$, which consists of other parameters of the BTLCMD reservoir based on the simple model $\sum_p$. This model describes the side-to-side (roll) motions of the turbine-reservoir system.

**FIGURE 10** Simulation results of rotor speed and generator power for the hydrostatic wind turbine (HWT) (blue dashed lines), HWT with bidirectional tuned liquid column mass damper (BTLCMD) (black solid lines), and HWT with bidirectional tuned liquid column damper (BTLCD) (red dotted lines) in the event E1 [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 11** Simulations results of the reservoir displacements in x-axis (RDX) and y-axis (RDY) for HWMD in the event E1 [Colour figure can be viewed at wileyonlinelibrary.com]
\[
x_\text{opt} = [L_y, A_y, \eta_y, K_y, C_y].
\]

We mention that \(A_yL_y\) is a constant after \(x_{op}\) and \(M_{lr}\) are determined. Therefore, we only need to optimise the last four parameters. During the optimisation, we set \(A_y \cdot \max|q_{4u}| \leq 0.2L_yA_y, 1m \leq L_y + 2 \times \max|q_{8u}| \leq 40m, \text{ and } 0 \leq \eta_y \leq 10\), where \(q_{4u}(u_4)\) is the liquid displacement in the horizontal column 4 relative to BTLCMD reservoir. These constraints ensure that the liquids remain in the vertical columns, the sum of the horizontal column length and reservoir stroke do not exceed the barge length (40 m) in the \(y\) direction, and the head loss coefficients in columns 4 and 8 are reasonable.

The optimal parameters of \(\sigma_y\) are given as follows:
\[
x_\text{opt} = [16.54m, 1.16m^2, 2.71, 180453N/m, 491520N \cdot s/m].
\]

Using the optimal parameters obtained above, we get the optimal BTLCMD dimensions as follows. The cross-section area and length of columns 2 and 6 are \(A_x = 2.95m^2\) and \(L_x = 29.24m\). The cross-section area and length of the horizontal columns 4 and 8 are \(A_y = 1.16m^2\) and \(L_y = 16.54m\). The cross-section area and length (when the liquid is undisplaced) of all the vertical columns are \(A_v = 4.07m^2\) and \(L_v = 10m\). The optimal head loss coefficient in columns 2 and 6 is \(\eta_x = 4.32\) while the optimal head loss coefficient in columns 4 and 8 is \(\eta_y = 2.71\). The optimal spring and damper coefficients in two directions are \(K_x = 208389N/m, C_x = 279972N \cdot s/m, K_y = 180453N/m,\) and \(C_y = 491520N \cdot s/m\), respectively. The total mass of the BTLCMD system is
\[
M_r + \rho\left(4A_vL_v + 2A_xL_x + 2A_yL_y\right) = 404167kg,
\]
which is 6.57% of the HWT mass.

## 4 | SIMULATION STUDY

In this section, we conduct simulations based on the HWT model and the HWT with BTLCMD configuration, both developed in Tong and Zhao,\(^4\) and the HWT with BTLCMD configuration developed in the present paper, respectively. These three configurations are respectively denoted as HWT, HWD, and HWMD for simplicity in the comparison below. We set three simulation environments E1, E2, and E3 corresponding to three

**FIGURE 12** Simulations results of the liquid displacements in vertical columns 1, 3, 5, and 7 for HWMD in the event E1 [Colour figure can be viewed at wileyonlinelibrary.com]
common operating conditions for the HWT. The hub-height longitudinal wind speeds for E1, E2, and E3 are 24, 18, and 9 m/s with the turbulence intensity in category B, A, and A, respectively. The wind conditions are generated based on the IEC Kaimal Spectral Model with normal turbulence model (NTM) in TurbSim. As for the wave conditions, we set the peak-spectral period of the incident waves to be 15.5, 12, and 11 s with the significant wave height being 5.5, 4.5, and 3.5 m for E1, E2, and E3, respectively. The wave conditions in all the environments are generated by the HydroDyn module, which is integrated into FAST based on the JONSWAP spectrum.3 For all the simulations, we compare the relative reduction of the HWMD with respect to the HWD and the HWT in barge pitch motion, roll motion, the fluctuation of rotor speed, and generator power. We perform the comparison from the perspectives of both the reduction of standard deviations (SDs) and the reduction of peak values.

The simulation environment and result for E1 is shown in Figures 8 to 12. Figure 8 shows the wind and wave time series for E1. As illustrated in Figure 9A,B, the barge pitch and roll displacements of the HWMD are much smaller than that of the HWT and the HWD, which results in less fluctuation in the rotor speed and generator power. The SDs of the barge pitch and roll displacements of the HWMD reduce by 43.21% and 43.57% in comparison with that of HWT, respectively. The SDs of the barge pitch and roll displacements of HWD reduces by 18.03% and 8.27% compared with the HWD. Given that the barge pitch and roll displacements of HWD have been reduced by approximately 20% compared with HWT, this further reduction accomplished by HWMD is due to the translation of the reservoir, which generates extra forces on the tower through the springs and dampers. As can be seen from Figure 10A,B, owing to the reduction of barge pitch and roll displacements, the SDs of rotor speed and generator power also decrease by 15.84% and 16.71% for the HWMD compared with HWD, which indicates that 36.68% and 31.27% reduction of the SDs of rotor speed and generator power are obtained, respectively, by the HWMD in relative to the HWT. The peak value of barge pitch and roll displacements decrease by 40.84% and 41.32% for the HWMD relative to the HWT. The peak values of barge pitch and roll displacements also decrease by 16.87% and 10.35% for the HWMD when compared with the HWD.

In Figure 11, the translations of reservoir in x-axis and y-axis are demonstrated. It can be observed that the maximum displacements of the reservoir in two directions are less than 3 m, conforming to the constraint that the sum of the reservoir maximum displacement and L_x is less than 40 m. Figure 12 presents the liquid displacements relative to the reservoir in vertical columns. The maximum displacement is less than 10 m, conforming to the constraint that the height of the vertical columns is 10 m.

| Event | Reference system | Max barge pitch (rd max) | Max barge roll (rd max) | Barge pitch (rd RMS) | Barge roll (rd RMS) | Rotor speed (rpm) (rd RMS) | Generator power (kW) (rd RMS) |
|-------|------------------|--------------------------|-------------------------|---------------------|---------------------|-----------------------------|-------------------------------|
| E1 HWT | 40.84 | 41.32 | 43.21 | 43.57 | 36.68 | 31.27 |
| E1 HWD | 16.87 | 10.35 | 18.03 | 8.27 | 15.84 | 16.71 |
| E2 HWT | 36.64 | 35.27 | 37.68 | 36.52 | 31.49 | 30.36 |
| E2 HWD | 18.74 | 10.85 | 20.34 | 12.37 | 19.15 | 22.64 |
| E3 HWT | 32.78 | 42.57 | 25.68 | 33.65 | 0.29 | 1.28 |
| E3 HWD | 10.38 | 25.49 | 10.65 | 11.76 | 0.28 | 1.35 |

Abbreviations: HWT, hydrostatic wind turbine; Max, maximum value; rd, reduction; RMS, root-mean-square.

**FIGURE 13** The hub-height longitudinal wind speed and wave elevation in E2 where the mean hub-height longitudinal wind speed is 18 m/s and the significant wave height is 4.5 m [Colour figure can be viewed at wileyonlinelibrary.com]
**Figure 14** Simulation results of barge pitch and roll displacements for the hydrostatic wind turbine (HWT) (blue dashed lines), HWT with bidirectional tuned liquid column mass damper (BTLCMD) (black solid lines), and HWT with bidirectional tuned liquid column damper (BTLCD) (red dotted lines) in the event E2 [Colour figure can be viewed at wileyonlinelibrary.com]

**Figure 15** Simulation results of rotor speed and generator power for the hydrostatic wind turbine (HWT) (blue dashed lines), HWT with bidirectional tuned liquid column mass damper (BTLCMD) (black solid lines), and HWT with bidirectional tuned liquid column damper (BTLCD) (red dotted lines) in the event E2 [Colour figure can be viewed at wileyonlinelibrary.com]

**Figure 16** Simulations results of the reservoir displacements in x-axis (RDX) and y-axis (RDY) for HWMD in the event E2 [Colour figure can be viewed at wileyonlinelibrary.com]
The reduction of barge pitch, roll displacements, and perturbation of rotor speed and generator power in E2 and E3 is summarised in Table 1. It can be seen from the table that the reduction of rotor speed and generator power perturbation in E3 is small. This is because the wind turbine operates in zone 2 for the majority of the time in E3, when the rotor speed is controlled to track the wind speed to maximize the power capture. The simulation results for E2 are demonstrated from Figures 13 to 17. The same results for E3 are shown from Figures 18 to 22. It can be concluded that the HWMD largely outperforms the HWD, providing a better solution for offshore wind turbine load reduction.

Table 2 lists the reduction of damage equivalent loads (DEQLs) of the HWMD compared with the HWD and the HWT. For the offshore wind turbine, the tower base suffers from the continuous large moments due to the rotation of the platform. Hence, we choose the tower base fore-aft moment (TwrBsMyt) and side-to-side moment (TwrBsMxt) to demonstrate the reduction ratios. The result in Table 2 shows that the HWMD

**FIGURE 17** Simulations results of the liquid displacements in vertical columns 1, 3, 5, and 7 for HWMD in the event E2 [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 18** The hub-height longitudinal wind speed and wave elevation in E3 where the mean hub-height longitudinal wind speed is 9 m/s and the significant wave height is 3.5 m [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 19  Simulation results of barge pitch and roll displacements for the hydrostatic wind turbine (HWT) (blue dashed lines), HWT with bidirectional tuned liquid column mass damper (BTLCMD) (black solid lines), and HWT with bidirectional tuned liquid column damper (BTLCD) (red dotted lines) in the event E3 [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 20  Simulation results of rotor speed and generator power for the hydrostatic wind turbine (HWT) (blue dashed lines), HWT with bidirectional tuned liquid column mass damper (BTLCMD) (black solid lines), and HWT with bidirectional tuned liquid column damper (BTLCD) (red dotted lines) in the event E3 [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 21  Simulations results of the reservoir displacements in x-axis (RDX) and y-axis (RDY) for HWMD in the event E3 [Colour figure can be viewed at wileyonlinelibrary.com]
reduce more tower loads than that of the HWD. It can be seen that the reduction ratio of DEQL is proportional to the barge pitch and roll displacements reduction ratio. This is because the tower base moment loads are largely caused by barge rotations.

| Event | Reference system | Fore-Aft DEQL | Side-to-Side DEQL | Reduction of fore-aft DEQL by the HWMD w.r.t others | Reduction of side-to-side DEQL by the HWMD w.r.t others |
|-------|------------------|---------------|------------------|-------------------------------------------------|--------------------------------------------------|
| E1    | HWMD             | 86895 (kN·m)  | 17183 (kN·m)     | N/A                                             | N/A                                              |
| E1    | HWD              | 107023 (kN·m) | 18665 (kN·m)     | 18.81%                                          | 7.94%                                            |
| E1    | HWT              | 123496 (kN·m) | 23551 (kN·m)     | 29.63%                                          | 27.04%                                           |
| E2    | HWMD             | 61523 (kN·m)  | 15974 (kN·m)     | N/A                                             | N/A                                              |
| E2    | HWD              | 86841 (kN·m)  | 17154 (kN·m)     | 29.15%                                          | 6.88%                                            |
| E2    | HWT              | 93188 (kN·m)  | 20762 (kN·m)     | 33.97%                                          | 23.06%                                           |
| E3    | HWMD             | 53725 (kN·m)  | 8647 (kN·m)      | N/A                                             | N/A                                              |
| E3    | HWD              | 62381 (kN·m)  | 9291 (kN·m)      | 13.88%                                          | 6.93%                                            |
| E3    | HWT              | 73533 (kN·m)  | 10815 (kN·m)     | 26.94%                                          | 20.04%                                           |

Abbreviations: DEQL damage equivalent load; HWT hydrostatic wind turbine.

reduce more tower loads than that of the HWD. It can be seen that the reduction ratio of DEQL is proportional to the barge pitch and roll displacements reduction ratio. This is because the tower base moment loads are largely caused by barge rotations.

5 | CONCLUSION

We made use of the reservoir of a HWT to act as a BTLCMD to damp the barge platform’s pitch and roll responses. The dynamics of the BTLCMD was incorporated into a HWT simulation model, which was obtained by replacing the geared drivetrain of the NREL5-MW barge wind turbine model within FAST code with a hydrostatic transmission drivetrain. We then optimised the parameters of the BTLCMD using the
MATLAB sequential quadratic programming algorithm FMINCON based on two simple mathematical models for pitch and roll motions. Simulation studies in three different events demonstrated that the BTLCMD effectively suppressed the pitch and roll motions, effectively regulated the rotor speed and generator power, and effectively reduced the DEQLs. It achieved much better performance than the BTLCD since BTLCMD combines the advantages of BTLCD and TMD.

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