Active tuned mass damper control of wind turbine nacelle/tower vibrations with damaged foundations

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Active Tuned Mass Damper Control of Wind Turbine Nacelle/Tower Vibrations with Damaged Foundations

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Abstract. The aim of this paper is to develop an active structural control scheme to control wind turbine nacelle/tower out-of-plane vibration. An active tuned mass damper (ATMD) is designed and placed inside the turbine nacelle. An Euler–Lagrangian wind turbine model based on energy formulation is developed for this purpose, which considers the structural dynamics of the system and the interaction between in-plane and out-of-plane vibrations. Also, the interaction between the blades and the tower including the ATMD is considered. The wind turbine is subjected to gravity and turbulent aerodynamic loadings. A three-dimensional (3D) model of a wind turbine foundation is designed and analysed in the finite element geotechnical code PLAXIS. The rotation of the foundation is measured and used to calculate a rotational spring constant for use in wind turbine models to describe the soil-structure interaction (SSI) between the wind turbine foundation and the underlying soil medium. Damage is induced in the soil medium by a loss in foundation stiffness. The active control scheme is shown to reduce nacelle/tower vibration when damage occurs.

Introduction

The aim of this work is to investigate the effects of damage to a wind turbine foundation on the vibration of the nacelle/tower. 3D models of a wind turbine foundation are designed and analysed in the finite element geotechnical code PLAXIS. The rotation of the foundation is measured and used to calculate a rotational spring constant for use in wind turbine models to describe the SSI between the wind turbine foundation and the underlying flexible soil medium. Usually wind turbine foundations are modeled as fully fixed. In this simple model the soil-foundation system is not considered. Recent studies have attempted to improve on this simplification [1]. This paper attempts to address the problem of foundation damage. Damage to wind turbine foundations can have disastrous effects. Increased nacelle/tower vibrations may decrease the life of vital components; severe damage could also lead to collapse and ultimate failure of the turbine. Mitigating the effects of damage to foundations before failure is crucial. Simulations were run with the model developed. The stiffness of the foundation was reduced to simulate damage. In order to reduce nacelle/tower vibrations due to induced damage an active structural control scheme is proposed. An LQR controlled ATMD is located at the top of the tower to reduce out-of-plane nacelle/tower vibration when damage is simulated. ATMDs for reduction of wind turbine vibrations are of topical interest and have been recently shown to be very effective for blades and towers [2]. A multi degree of freedom (MDOF) model of a wind turbine is developed in this paper. The model is developed using an Euler-Lagrangian approach and leads to a time varying system with the possibility of negative damping. Time domain simulations are performed on the model using turbulent aerodynamic loading. The results have indicated encouraging prospects for the use of ATMDs in the control of vibrations of wind nacelle/towers.

Wind Turbine Model

The dynamic wind turbine model was formulated using the Lagrangian formulation expressed in Eq. 1 below. A schematic of the wind turbine model is shown in Fig. 1.
where $T$ = kinetic energy of the system, $V$ = potential energy of the system, $q_i$ = displacement of the generalized degree of freedom (DOF) $i$ and $Q_i$ = generalized loading for degree of freedom $i$.

Each blade is modelled as a cantilever beam with uniformly distributed parameters as can be observed from the expressions for the kinetic and potential energies in Eq. 2 and Eq. 3. The in-plane and out-of-plane vibrations of the $i^{th}$ blade are modelled by two generalized DOFs, $q_{i,in}(t)$ and $q_{i,out}(t)$. The coupled in-plane and out-of-plane mode shapes, $\phi_{i,in}(x)$ and $\phi_{i,out}(x)$, have been normalized at the tip so that $q_{i,in}(t)$ represents the in-plane tip displacement and $q_{i,out}(t)$ represents the out-of-plane tip displacement. The structural twist of the blade is accounted for in the calculation of the in-plane and out-of-plane mode shapes. Therefore, these mode shapes each have both edgewise and flapwise components.

The kinetic and potential energies of the model are derived including the motion of the nacelle/tower and are stated respectively in Eq. 2 and Eq. 3. These expressions are then substituted back into the Lagrangian formulation in equation (1) to allow the equations of motion to be determined.

\[
T = \frac{1}{2} \sum_{i=1}^{3} \int_0^L \mu(x) \nu_i^2 \, dx + \frac{1}{2} M_n q_{n,in}^2 + \frac{1}{2} I_{f,in} \theta_{f,in}^2 + \frac{1}{2} M_n q_{n,out}^2 + \frac{1}{2} I_{f,out} \theta_{f,out}^2
\]  

\[
V = \frac{1}{2} \sum_{i=1}^{3} \int_0^L \left[ E I_{in}(x) \left( \frac{\partial \theta_{i,in}}{\partial x} \right)^2 + E I_{out}(x) \left( \frac{\partial \theta_{i,out}}{\partial x} \right)^2 + 2 E I_{in,out}(x) \left( \frac{\partial \theta_{i,in}}{\partial x} \right) \left( \frac{\partial \theta_{i,out}}{\partial x} \right) \right] \, dx + \frac{1}{2} K_{n,in} q_{n,in}^2 + \frac{1}{2} K_{\theta,in} \theta_{f,in}^2 + \frac{1}{2} K_{n,out} q_{n,out}^2 + \frac{1}{2} K_{\theta,out} \theta_{f,out}^2
\]  

where $\mu(x)$ = mass of blade, $L$ = length of the blade, $\nu_i$ = absolute velocity of the $i^{th}$ blade, $M_n$ = mass of nacelle and $I_{f,in}$ and $I_{f,out}$ are the in-plane and out-of-plane mass moments of inertia of the foundation respectively, these values are obtained from a finite element analysis of the turbine foundation. $\theta_{f,in}$ and $\theta_{f,out}$ are the in-plane and out-of-plane foundation rotational degrees of freedom. The displacement of the tower in the rotor plane (side-to-side) is modelled by the degree
of freedom, $q_{n,in}(t)$ and the displacement of the tower out of the rotor plane (fore-aft) is modelled by the degree of freedom, $q_{n,out}(t)$. $E$ is the modulus of elasticity of the blade. The parameters $I_{n,in}(x)$, $I_{n,out}(x)$, and $I_{inout}(x)$ are the second area moments of inertia and the second area products of inertia of a cross section of the blade respectively. The effect of the blade structural pre-twist is therefore accounted for in this model following Zhu [3]. The term $K_{n,in}$ is the in-plane modal stiffness of the tower/nacelle and $K_{n,out}$ is the out-of-plane modal stiffness of the tower/nacelle. $K_{a,in}$ and $K_{a,out}$ are the in-plane and out-of-plane rotational stiffness of the foundation respectively. The rotation of the blade leads to a centrifugal stiffening effect, $N(x)$ denotes the centrifugal force that gives rise to this stiffening. The gravity force acting on the blade will also contribute to the stiffness of the blade. The term $G(x)$ denotes the gravity force. In Eq. 3, $\theta_{i,in} = \left( \frac{\partial w_{i,in}}{\partial x} \right)$, $\theta_{i,out} = \left( \frac{\partial w_{i,out}}{\partial x} \right)$, $N(x) = \Omega^2 \int_x^L \mu(\xi) \xi d\xi$ and $G(x) = -\frac{1}{2} g \cos \psi_i \int_x^L \mu(\xi) d\xi$ where $\psi_i$ is the azimuthal angle of the $i^{th}$ blade.

Substituting Eq. 2 and Eq. 3 back into Eq. 1 gives the equations of motion for the coupled wind turbine with foundation. The equations of motion are of the form described in Eq. 4.

$$[M(t)][\ddot{q}] + [C(t)][\dot{q}] + [K(t)][q] = [Q] + [U_m]$$

where $[M(t)]$, $[C(t)]$ and $[K(t)]$ are the time dependent mass, damping and stiffness matrices of the system respectively. $\{\ddot{q}\}$, $\{\dot{q}\}$ and $\{q\}$ are the acceleration, velocity and displacement vectors and $\{Q\}$ is the loading, including turbulent aerodynamics loading and gravity loading. $\{U_m\}$ is the active control force vector which is defined later. Structural damping included in the system was assumed to be in the form of stiffness proportional damping.

Wind Turbine Loading

Aerodynamic Loading

In order to have a realistic estimate of the aerodynamic loading to which the rotor is subjected, models based on the Blade Element Momentum (BEM) theory have been adopted according to a method developed by Hansen [4]. The rotor blade is discretized into smaller elements. Each element is located at a radial distance of $r$ from the hub and has a chord length of $c = c(r)$ and width $dr$. These elements are analysed in sections along their length and the forces are summed over all sections to get the total force on the rotor [4]. The rotor has a radius $L$ and angular velocity $\Omega$. For more detail about the specifics of implementation of Hansen’s modified BEM method see [4].

Turbulence Model

A rotationally sampled turbulence model has been assumed in this paper. A rotating blade is subject to an atypical fluctuating wind velocity spectrum, known as a rotationally sampled spectrum [5]. The spectral energy distribution is altered due to the rotation of the blades. The variance shifts from the lower frequencies to peaks located at integer multiples of the rotational frequency [6]. The turbulent component of the wind velocity is quantified and included in the modified BEM method. This results in turbulent aerodynamic loading. The in-plane and out-of-plane loads are coupled for the model used in this paper.

Gravity Loading
The loading effect of gravity has been considered. The gravity force causes a harmonic in-plane load on the blade. Resolving the gravity force leads to two forces, one normal to the blade as can be seen in Fig. 2.

The main sources of loading experienced by wind turbines; aerodynamic loading and gravity loading have been accounted for in this study.

**Wind Turbine Foundation Model**

A 20x20x1m³ concrete foundation is designed and analysed in PLAXIS [7]. The purpose of this analysis is to obtain rotational stiffness values, \( k_\theta \), for use in the wind turbine models derived. As the foundation is square and Mohr-Coulomb soil models are considered the foundation rotational stiffness values are the same for both in-plane (side-to-side) and out-of-plane (fore-aft) motion, i.e. \( k_{\theta,in} = k_{\theta,out} = k_\theta \) and \( l_{f,in} = l_{f,out} = l_f \).

The foundation is tested at an embedment depth of 2m. The depth of the soil layer is taken as 50m and the phreatic level as 2m below the ground surface. A dense sand is considered in this paper, Table 1 outlines the properties of the soil.

<table>
<thead>
<tr>
<th>Mohr Coulomb soil parameters</th>
<th>Dense sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_{un} )</td>
<td>17</td>
</tr>
<tr>
<td>( \gamma_{sat} )</td>
<td>20</td>
</tr>
<tr>
<td>( E )</td>
<td>5000</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.3</td>
</tr>
<tr>
<td>( c )</td>
<td>0.1</td>
</tr>
<tr>
<td>( \phi )</td>
<td>35</td>
</tr>
<tr>
<td>( E' ) (increment)</td>
<td>2000</td>
</tr>
<tr>
<td>( c' ) (increment)</td>
<td>0</td>
</tr>
<tr>
<td>( K_0 )</td>
<td>0.5</td>
</tr>
<tr>
<td>( R_{inter} )</td>
<td>0.65</td>
</tr>
</tbody>
</table>

The foundation is modelled in 3D. The 3D foundation considered is a square concrete foundation 20m² and 1m deep. The concrete foundation itself is modelled by a linear isotropic plate of thickness 1m with Young's modulus value of 30x106kN/m², a unit weight value of 24kN/m³ and Poisson's ratio value of 0.15. The mesh is set to Medium and the mesh around the plate is refined to a fineness factor of 0.25. The 3D model is shown in Fig. 3.
The foundation is subject to a static gravity load and also a dynamic load due to the moment arising from the aerodynamic torque. This is applied to the foundation in PLAXIS. The in-plane and out-of-plane rotations of the foundation, $\theta_{f,\text{in}}$ and $\theta_{f,\text{out}}$, are measured in PLAXIS. From these values the rotational stiffness, $k_\theta$, can be calculated using Eq. 5

$$k_\theta = \frac{M_{\text{applied}}}{\theta_f}$$  \hfill (5)

where $M_{\text{applied}}$ is the moment applied to the foundation (in-plane or out-of-plane) and $\theta_f$ is the rotation of the foundation (in-plane or out-of-plane) measured by PLAXIS.

**Controller Design**

The active control algorithm examined in this paper is the Linear Quadratic Regulator (LQR). LQR is used as it is a well known method for calculation of optimal control gains. The LQR is a feedback controller used to operate a dynamic system at minimum cost. The LQR proposed here uses full state feedback. LQR is used to obtain the generalized control force vector $\{U_m\}$. The linear state feedback is given by Eq. 6.

$$U_a = [G_{LQR}] \{\{q\}\}$$  \hfill (6)

where $U_a$ is the control force on the actuator connected to the out-of-plane damper located at the top of the tower and $[G_{LQR}]$ is the feedback gain. The value for $[G_{LQR}]$ is optimized such that the following performance criterion is minimized

$$J = \min_{U_a} \int_{t_0}^{t_f} \left[q^\top Q_{LQR} q + U_a^\top R_{LQR} U_a\right] dt$$  \hfill (7)

Appropriate choice of the weighting matrices is crucial when performing LQR control. In this study the LQR cost function consists of applying weights to individual state and input values separately (i.e. all non-diagonal $[Q_{LQR}]$ and $[R_{LQR}]$ matrix elements are set to zero). Importance is placed on maintaining small values for nacelle/tower displacement thus their weighting factors are chosen to be large. Additionally, because each ATMD has a limited range of motion similar importance is placed on reducing the motion of the ATMD, and this weighting factor is chosen to be large as well. After the gain matrix, $[G_{LQR}]$, is obtained by the LQR method the control input is then calculated and incorporated into the equations of motion. The coupled wind turbine with foundation and
ATMD has a total of 11 DOFs. The LQR weighting matrices chosen are thus $Q_{LQR} = [I]_{22 \times 22}$ and $R_{LQR} = 10^{-12} [I]_{1 \times 1}$.

**Numerical Simulations**

Numerical simulations are now performed to demonstrate the effectiveness of the active control scheme designed. The National Renewable Energy Laboratory (NREL) offshore 5-MW baseline wind turbine [8] has been used to develop and test the model. The proposed model and control strategies were implemented in MATLAB [9]. The blade considered is the LM61.5 P2 (manufactured by LM Wind Power, LM Wind Power Group, Kolding, Denmark), which is 61.5m long and has a total mass of 17,740 kg. The in-plane and out-of-plane mode shapes considered have been computed from blade structural data by using the Modes [10] finite element code.

The wind turbine is assumed to be operating at rated speed (12m/s) with a turbulence intensity of 20%. Fig.4 shows the blade loading in-plane and out-of-plane respectively.

![Figure 4 Blade loads](image1)

Fig.5 shows the nacelle/tower loading in-plane and out-of-plane respectively.

![Figure 5 Nacelle loads](image2)

A loss of stiffness in the soil medium of 20% is simulated. The effect of this damage on the out-of-plane vibration of the uncontrolled nacelle/tower is illustrated in Fig. 6. It is clear that the damage induced in the foundation by a reduction in stiffness causes the nacelle/tower vibrations to increase. Peak-to-peak vibration increases of up to 45% are observed after damage occurs.
The active control scheme is now tested to see if it can reduce the nacelle/tower vibration when damage occurs. It is clear that the LQR controlled ATMD shows excellent performance. Nacelle/tower vibrations are greatly reduced, mitigating the effect of foundation damage. Peak-to-peak vibration reductions of up to 52% are achieved by using the active control scheme.

Conclusion
An active control strategy has been developed for a coupled wind turbine model with a foundation. An LQR controlled ATMD placed at the top of the tower has been designed to reduce nacelle/tower out-of-plane vibration. Damage has been simulated by a loss in foundation stiffness. It has been shown that the active control scheme designed is very effective at reducing nacelle/tower vibration when damage occurs. In the uncontrolled case foundation damage increases the nacelle/tower
vibration; however the actively controlled model achieves vibration reductions and mitigates the effects of damage. Peak-to-peak reductions of up to 52% were achieved.

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