Modal properties of a modern wind turbine including SSI
Propriétés d’une modale d’aérogénérateur moderne incluant l’interaction sol-structure

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ABSTRACT
The beginning of the 21st century has seen a rapid growth in wind power with a world-wide capacity approaching 100 GW. With this growth, wind turbines are being installed in more sites where seismic loading must be considered. The matter is further motivated by the increase in size and mass of the newer wind turbines, where seismic loading, not wind or fatigue, may control the design of the supporting tower. To predict structural response due to seismic loading it is important to understand the in-situ properties of the wind turbine. This paper presents observed mode shapes and natural frequencies extracted from ambient vibration measurements of a large wind turbine. A finite element (FE) model of the turbine is created, including a full three-dimensional soil mesh to highlight the impact of soil structure interaction (SSI). Similarities and differences between the FE model and the observed results are quantified and discussed to provide insights as relates to SSI for seismic loading conditions.

RÉSUMÉ
Le début du 21ème siècle a vu un rapide développement de champ éolien avec une capacité mondiale approximative de 100 GW. Grâce à ce développement, des aérogénérateurs sont installés dans plus d’emplacements où l’chargement séismique doit être considéré. Le phénomène est de plus, motivé par la grandeur en taille et en masse des nouveaux aérogénérateurs, où l’chargement séismique, pas vent ou fatigue, peut supporter l’architecture de la tour aérogénérateur. Pour prévoir la réponse de la structure du au fait de l’chargement séismique, il est important de comprendre les propriétés des composantes in-situ du aérogénérateur. Ce document présente les modes d’observations et des fréquences extrait a partir des mesures des vibrations ambiantes d’un grand aérogénérateur. Un modèle d’élément fini de l’aérogénérateur est créé, y compris une pleine maille tridimensionnelle qui va aider à comprendre l’impacte de l’interaction sol-structure. Les différences et les similitudes entre le modèle d’élément fini et les résultats observes sont quantifies et discutes pour donner des éclaircissements en rapport avec l’interaction sol-structure au sujet des chargements séismique.

Keywords: renewable energy, seismic design, earthquake, soil structure interaction, testing, wind turbine

1 INTRODUCTION
Installation of wind farms continues to grow rapidly throughout the world with almost 20 GW of capacity erected in 2007 and total production rapidly approaching 100 GW worldwide (DOE 2008). Over one quarter of the turbines installed in 2007 reside in the United States (US), India, and China (DOE 2008), all of which contain regions of high seismic hazard. Regulating bodies in the wind industry have noticed this growth of wind power in seismic regions and have recently added some seismic requirements for the certification of wind turbines (GL 2003; IEC 2005).

The growth of wind turbine installation is leading to an increased interest in addressing the related seismic loading considerations. Early investigations (Bazeos et al. 2002; Lavassas et al. 2003) focused on loading of the tower using models that lump the nacelle and rotor as a point mass (Figure 1). Gradually, interest shifted from these simple models to more refined models that also consider loads for turbine components other than the tower (Ritschel et al. 2003; Witcher 2005; Haenler et al. 2006; Zhao and Maisser 2006). Migration to models that include dynamics of the rotor (Figure 1) is also dictated by industry standard load cases such as the case of an emergency shutdown triggered by an earthquake (IEC 2005). In addition to modeling techniques, effects such as soil structure interaction (SSI) have been investigated through equivalent springs and dampers (Bazeos et al. 2002; Zhao and Maisser 2006).
presented and discussed to provide insights when considering seismic SSI for wind turbine structures.

Figure 2: 900 kW turbine at Oak Creek Energy Systems (OCES).

2 TURBINE AND FOUNDATION DESCRIPTION

A 900 kW turbine (Figure 2) installed at Oak Creek Energy Systems (OCES) in Mojave, California, USA was selected for in-situ measurements. This turbine (Table 1) is characteristic of units installed in the late 1990s (DOE 2008). The turbine was manufactured by NEG Micon, a Danish producer. Being a slender structure with a hub height of 55 meters, this turbine is similar to structures that might experience significant SSI effects (Luco 1986).

Table 1: Main parameters of wind turbine.

<table>
<thead>
<tr>
<th>Type</th>
<th>Horizontal axis variable speed wind turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>900 kW</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>52 m</td>
</tr>
<tr>
<td>Tower height</td>
<td>54 m</td>
</tr>
<tr>
<td>Hub height</td>
<td>55 m</td>
</tr>
<tr>
<td>Speed regulation</td>
<td>Pitch controlled</td>
</tr>
<tr>
<td>Mass of rotor</td>
<td>23,000 kg</td>
</tr>
<tr>
<td>Mass of tower</td>
<td>69,000 kg</td>
</tr>
</tbody>
</table>

Reports from OCES indicate that the soil profile under this particular turbine consists of an upper 2 meter layer of sandy materials underlain by dense silty sands and clayey sands. The turbine foundation is a hollow cylindrical concrete shell with a 3.5 meter outer diameter that extends 9 meters below ground surface. Outer and inner corrugated metal shells 0.3 m apart constitute the hollow cylinder with concrete poured in between. The inner shell is then backfilled with soil. The turbine tower is attached to the foundation through un-bonded post tensioned bars that extend to the bottom of the foundation.

3 IN-SITU MEASUREMENTS

The turbine tower was instrumented with accelerometers at the base and four equally spaced locations along the tower height. High quality PCB 393C accelerometers were employed, capable of measuring acceleration at a resolution of 0.0001 g. Data was recorded using a four channel National Instruments capture device. For all measurements two orthogonal accelerometers oriented horizontally at the base of the tower were used as reference channels. The other two channels were systematically connected to accelerometers at the other locations on the tower to record the two horizontal directions of vibration. Records were captured for at least 20 minutes in each configuration to provide ample data for analysis.

Throughout the measurement phase, the turbine was operating in low winds. This pattern of loading resulted in clear vibration signals that were easily captured by the employed accelerometers. Over the duration of the data acquisition phase, wind speed was relatively constant and stable in direction. This relative stability facilitates comparison of the data from each measurement. The constant reference base channels allow for employing all measurements within a unified analysis framework.

4 EXPERIMENTAL DATA ANALYSIS

Characterization of structural properties is challenging for situations where input excitation is difficult to measure or quantify. In such cases, output-only system identification procedures may be employed (Ibrahim and Mikulcik 1977; Brown et al. 1979; Vold et al. 1982). Instead of comparing the response of the structure to a known input, output-only system identification methods function without specific knowledge of the excitation. By carefully observing the system vibrations, one is able to infer dynamic properties such as natural frequencies and mode shapes.

A variant of the NExT algorithm (James et al. 1992) termed Multiple Natural Excitation Technique (MNExT) was selected to process the recorded data (He 2008). MNExT uses time series data to create frequency domain cross correlations between each sensor and multiple reference channels. Using multiple references improves identification of modes that might not be apparent with a single reference location (e.g. a reference that coincides with a modal node). The cross correlation, when converted back to the time domain, functions as a surrogate for free vibration data. The NExT algorithm then uses the Eigensystem Realization Algorithm (ERA) (Juang and Pappa 1985) to extract natural frequencies and mode shapes.

Using the approach described above, this paper discusses two extracted modes of interest. The predominant vibration in these modes is longitudinal, parallel to wind direction. From the recorded ambient vibration data, the first longitudinal bending mode was observed at 0.7 Hz (Figure 3). The second observed longitudinal bending mode occurred at 4.0 Hz (Figure 4).

Figure 3: First longitudinal bending mode from observation.
Figure 4: Second longitudinal bending mode from observation.

5 FIXED BASE FE MODEL DESCRIPTION

A simple fixed base FE model was developed that represented the turbine tower, nacelle, and rotor (Figure 1) through beam-column elements. Previous work suggests that a beam-column model can provide results that are consistent with more detailed shell models for towers (Bazeos et al. 2002) as well as turbine blades (Malcolm and Laird 2003). This simple configuration...
represents the predominant approach for numerical modeling of wind turbines for seismic applications (Bazeos et al. 2002; Ritschel et al. 2003; Witcher 2005; Haenler et al. 2006).

The above FE model was implemented using the computational platform OpenSees (Mazzoni et al. 2006). The tower (Figure 1) was divided into 51 beam-column elements with a flexural stiffness based on the cross section of the tower at the center of each element. The model used 20 beam-column elements per blade to simulate the mass and stiffness of the rotor (Figure 1). A hinge was added to account for the free rotational configuration of the rotor. The blade mass and stiffness distribution were approximated by scaling published values from a similar unit (Jonkman and Buhl 2005) to match the NEG Micon blade proportions. Unlike the tower where the bending stiffness at the base is only 10 times that at the top, the blade is over 3,000 times stiffer at the root compared to the tip.

With a Young’s Modulus for steel of 200 GPa the above simple model was calibrated to match the first observed natural frequency at 0.7 Hz by increasing the tower wall thickness by 24%. The second longitudinal cantilever type mode occurred at 4.0 Hz in this fixed base model. The experimentally observed mode shapes (Figure 3 and Figure 4) closely match the predicted mode shape (Figure 5 and Figure 6). This similarity in mode shape and natural frequency is expected given the stiff soil profile of the turbine tested at OCES.

Figure 7 shows the scale of the mesh in comparison to the size of the turbine. Other meshes were evaluated to verify that the reported results were not influenced by the soil model geometry.

When modeled with the soil mesh, the first natural frequency occurred at 0.7 Hz. This matches the observed and fixed base frequency. Observing the mode shape (Figure 8) shows little influence from the soil mesh on base rotation. The second bending mode was predicted at 3.9 Hz, which closely matches the frequency of the fixed base model and the experimentally observed mode. Again, the mode shape (Figure 9) shows little base rotation.

To numerically consider the impact of SSI for a wind turbine, the fixed base model was extended using OpenSeesPL (Lu et al. 2006) to include a soil domain and a foundation model. The soil is modeled by a 2 meter layer of medium density sand underlain by stiff clay (Table 2). The foundation, described earlier, was modeled as a hollow cylinder of elastic material. In this modal analysis model, the foundation and adjacent soil remain in perfect contact.

To minimize boundary effects, the soil was modeled to a depth of over 200 meters and a horizontal distance of over 400 meters. The total model consisted of over 1,300 soil elements.

The impact of SSI for the three soil stiffness scenarios is shown in Table 3. Medium stiffness did not affect the resonant frequencies appreciably. The resulting mode shapes were similar to those of the stiff soil model (Figure 8 and Figure 9). When the stiffness of the soil mesh is further reduced to the soft scenario, the first natural frequencies were lowered to 0.65 Hz and 3.4 Hz for the first and second longitudinal modes (Figure 10 and Figure 11). The second mode in particular clearly shows a pronounced influence from the soil mesh, observable mainly as a rotation of the foundation within the soil.

6 SSI MODEL DEVELOPMENT

Previous investigations have considered SSI for wind turbines by using equivalent springs and dampers (Bazeos et al. 2002; Zhao and Maisser 2006). Theory exists to make these springs and dampers frequency independent, but large errors may occur in the soil-structure system response at resonance (Ghafar-Zadeh and Chapel 1983).

This investigation chose instead to use a full soil mesh to avoid this source of possible error. Given the continued proliferation of computational power, this approach may prove to be simpler in certain respects. In addition, it is more adaptable to sites where the soil profile is layered.

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Figure 7: Full three-dimensional model of soil and turbine.
8 CONCLUSION

An experimental and numerical investigation of the resonant characteristics of a 900 kW wind turbine was presented. In-situ data was recorded and analyzed to provide a basis for model calibration. Numerical modeling showed the relatively stiff soil found at OCES produced little SSI influence on the first and second longitudinal modes. In contrast, when softer soils were investigated, a more significant influence was apparent. The second longitudinal bending mode behavior was clearly impacted, showing a reduction in frequency and increased foundation rotation.

Wind turbines are installed in all soil types throughout the world. This investigation found that for this particular 900 kW turbine at OCES, SSI influence on the first and second longitudinal bending modal parameters may not be significant. In soft soil, the influence is observable and may dictate design changes. With current trends toward taller and more massive turbines (DOE 2008), it is imperative to conduct further SSI research as an integral component of seismic response studies.

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