Estimation of the Vibration Decrement of an Offshore Wind Turbine Support Structure Caused by its Interaction with Soil

W.G. VERSTEIJLEN¹, A.V. METRIKINE ², J.S. HOVING, E. SMID, W.E. DE VRIES —

Abstract

In today's cutting costs environment in the offshore wind industry, significant achievements can be made with a better assessment of dynamic soil-pile interaction.

Of the main damping mechanisms active at an OWT, least is known about soil damping. The values for this contribution used in the industry today - mostly calculated analogously to a study performed in 1980 [1] - are expected to be on the low side. More research on the topic is recommended.

Presence of more damping than currently assumed, would signify that the (often) design driving fatigue damage accumulation is lower than assumed. This would justify designing more light-weight structures using less construction steel, or allowing for longer (insured) OWT lifetimes then the now applied 20 years. Both these measures significantly decrease costs of offshore wind.

This paper evaluates measured signals of twelve 'rotor stop'- test on an OWT at Dong Energy owned - Burbo Banks wind farm. The vibration decay was measured with an accelerometer and strain gauges along the tower. A simplistic analytical model has been developed enabling analyses of the measured signals.

Two main modal shapes were identified with similar shape, but deviating amplitudes in the soil profile. The large difference in damping that exists between the vibrations of these modes is attributed to the difference in influence that the soil can have on these vibrations. The found effect of soil on the damping of this particular OWT is significantly larger than the order of magnitude used in the industry today.

¹Siemens Wind Power, Prinses Beatrixlaan 800, 2595BN The Hague, The Netherlands. Tel. +31 70 333 6920 / +31 6 175 16 437 email pim.versteijlen@siemens.com
²Delft University of Technology - Faculty of Civil Engineering and Geosciences, Professor at the section of Structural Mechanics, Stevinweg 1, 2628 CN Delft, The Netherlands
1 Introduction

1.1 Background & Motivation

Cutting costs is the main priority in today’s offshore wind industry. In order to at least reach the same levelized costs as coal power, numerous areas exist where costs can be cut. One of these areas is the usage of construction steel. In the design process of support structures for OWT’s the dynamic aspects of the structure - stiffness and damping - are important influencing factors for determining the diameter and wall thickness of the tubular structures, thus determining the amount of steel usage. The currently most commonly applied monopile foundation mounts up to about 20% of the CAPEX of the entire OWT structure. Construction costs and the weight of the applied construction steel have a linear relation.

Damping has a positive influence in decreasing fatigue damage accumulation during the OWT’s lifetime. Each percent extra damping ratio (of critical) incorporated in the loads and design process can have a significant cost saving effect. Several damping mechanisms are active at an OWT: (from top to bottom of the structure) aerodynamic-, tuned sloshing-, structural steel-, hydrodynamic- and damping caused by the influence of soil (‘soil damping’ hereafter). Of these 5 mechanisms, least is known of the magnitude of soil damping.

The major source for determining damping in the industry today is a research performed by M.F. Cook [1], [2] who assessed the sources of damping of different mode shapes of a single piled platform in the Gulf of Mexico in 1980. The magnitudes for soil damping which are estimated on the basis of this paper are expected to be lower than actual and hence result in conservative designs, applying too much steel.

1.2 Description of Research

The basis of this research consists of the measurement of rotor stops of an OWT, and the development of a model, both discussed in the respective sections of this paper. The vibration decrement caused by the rotor stops were measured by an accelerometer in the nacelle and strain gauges at the top and bottom of the tower. The damping of the measured response was identified in both the frequency domain and time domain, and an analytical model was developed to further assess the measurements.

2 Offshore Measurements

2.1 Description of Setup and Obtained Data

For this research it was chosen to perform rotor stop tests to possibly gain more insight in the structural dynamics of an OWT and the influence of the soil. Cost-, and complexity-wise, a rotor stop test is a relatively low threshold option to perform measurements. DONG-Energy was found to be willing to avail their ‘BB16’ OWT of their Burbo Banks wind farm, offshore England’s west coast in the Irish sea. This OWT is equipped with a Power Load Monitoring (PLM) system of which the accelerometer in the nacelle and the strain gauges at tower top and tower bottom were the main sensors used for this research. On the 29th of October 2010, numerous rotor stops were performed of which 12 tests provided useable data. Figure 2.1 gives a schematic view on the measurement setup of BB16 and the power spectra at the 3 measurement locations of the first 6 tests.
Figure 1: Schematic view of the OWT 'BB16' measurement setup and typical measured power spectra at the different measurement locations.

Figure 2 gives a typical response of - in this case - the bending moment at the tower bottom during the stages of turbine production, blade pitch-out (rotor stop), blade feathering and blade pitch-in. The pitch angle of the blades is plotted in the same graph. The red encircled part of the response was used for frequency analysis and damping identification. Only the linearly decaying oscillations after the rotor stop were considered.

There is a pattern noticeable in the power spectra over the different heights of the tower that are depicted in figure. Each power spectrum contains a first major frequency peak at 0.29 Hz, which corresponds to first natural bending mode shape of the structure. However, in the top section of the structure (nacelle and tower top), a second frequency is present at 0.82 Hz. A check with the aerelastic BHawC model and the developed model for this research (see next section) indicated that this frequency is linked to closely spaced blade modes. It is a rather localized mode: it is hardly measured in the bottom section of the tower.
2.2 Damping Identification

The Quality (Q) factor technique is the main method used for identifying the damping of the 2 main frequencies in the measured signal in the frequency domain. It is a rather fast and accurate technique which allows identification of damping of multiple frequencies in a signal (as opposed to for instance the logarithmic decrement technique on raw time domain signals). The Q-factor is a measure for the skewness of a frequency peak: the higher and narrower they are, the lesser these frequencies are damped. As a check, also the logarithmic decrement technique was applied in the time domain. No window function was used (to minimize energy shifting in the frequency domain), and the raw time samples were zero-padded to produce enough sample points to get smooth power spectra. All 12 tests were assessed, and frequency and damping wise, tests 4 and 5 were closest to the average values of all tests. These tests were extra assessed (as a third check) by fitting their power spectrum with an analytical fit that is derived in an iterative manner. The analytical power spectrum can be described with the equation given under figure 3, in which $A$ is the amplitude, $\omega$ the center frequency, $\Omega$ the running frequency (along the horizontal x-axis), $\zeta$ the damping ratio, and $N$ the amount of periods (cycles) in the time domain sequence that is Fourier transformed to the frequency domain. Figure 3 shows this fit for the first natural bending frequency of the tower of the measured bending moment at tower bottom of test 5. A 3% of critical damping gives the best fit.

Figure 2: Time series of test nr. 6. The red encircled part is of interest for this research: the decaying fore-aft movement of the tower.
Figure 4 depicts the part of the time series which was Fourier transformed to derive the spectrum of figure 3. Different decrement lines have been plotted, and the line with 3% of critical damping decrement seems to have the best correspondence. This signal is clearly dominated by a single frequency: the second (blade induced) frequency is not present in this signal which is measured at the bottom of the tower.

Similar fits as done in figure 3 can also be made on the second frequency peak, as is done in figure 5 in which the tower top bending moment is assessed of test 4. From this graph we can conclude that a 3% of critical damping for the first natural bending frequency and a 1.5% of critical damping for the second blade-induced frequency, are reasonable estimates.

\[
PS = \left| A \cdot \frac{\omega \sqrt{1 - \zeta^2}}{\omega^2 - \Omega^2 + 2i\Omega\omega\zeta} \right|^2 \cdot \left| 1 - e^{-2\pi N\zeta(\zeta + i\Omega)} \right|^2
\]

Figure 3: Measured and analytical fitted power spectrum for first 6 cycles of the bending moment at tower bottom for test 5. Only the first natural frequency is present in this signal at the tower bottom. The fit with 3% damping ratio is found to be the closest fit.

Figure 4: Measured time response of first 6 cycles of the bending moment at tower bottom for test 5. The same fitted damping ratio’s are plotted as logarithmic decrement. Again, the 3% damping ratio is found to be the best fit. The first natural frequency clearly dominates the time response.
A logarithmic decrement check on a signal with two dominant frequencies was not considered to be very sensible, so figure 6 only depicts the time series that was Fourier transformed to derive the spectrum of figure 5 to get an idea of the pattern in the time domain.

As a summary, table 1 sums up the named damping magnitudes. A noticeable difference in damping value of 1.5% exists between the two modal frequencies.

It is believed that the main reason for the large difference in identified damping can be found in the different possible influence the soil can have on these two modes. The motions after the rotor stops seem to be dominated by two main frequencies: a global bending mode over the entire length of the structure, and a localized mode at the top of the structure which is associated with blade modes. These two modes have similar shapes over the vertical height of the structure. However, the horizontal amplitudes of the blade-induced mode in the lower part of the structure
Table 1: Damping values of rectangular windowed initial vibration cycles of tests 4 and 5.

<table>
<thead>
<tr>
<th>Test</th>
<th>Frequency [Hz]</th>
<th>Damp ratio [%] of crit.</th>
<th>Log decr [%]</th>
<th>Test</th>
<th>Frequency [Hz]</th>
<th>Damp ratio [%] of crit.</th>
<th>Log decr [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mtop 1st</td>
<td>0.253</td>
<td>3</td>
<td>18.85</td>
<td>Mtop 1st</td>
<td>0.292</td>
<td>3</td>
<td>18.86</td>
</tr>
<tr>
<td>Mbot 1st</td>
<td>0.253</td>
<td>4</td>
<td>25.15</td>
<td>Mbot 2nd</td>
<td>0.877</td>
<td>1.5</td>
<td>18.86</td>
</tr>
<tr>
<td>Difference in damping between two main frequencies: Δ = 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.05</td>
</tr>
</tbody>
</table>

The damping values are expected to be much smaller than those of the first global bending mode. The global mode is damped twice as much as the localized mode. As this global mode does mobilize soil reactions and the localized mode does not, the difference in identified damping - 1.5 % of critical - is believed to be a measure for the magnitude of soil damping that is mobilized during the vibration amplitudes occurring after a rotor stop. To put these numbers into perspective: the design value for the total experienced damping by the structure incorporated in the design of BB16 was 2.5 % log, decr.

3 Model Development

In order to further analyze the measured responses of the BB16 structure, an analytical model has been developed. The 'Euler-Bernoulli' beam bending approach is used to derive the equation of motion and boundary conditions. Figure 7 displays a symbolic representation of the model and part of its governing equations (equation of motion and boundary conditions) to give an idea of the analytical way of solving. The model is further described by initial conditions and interface conditions at waterline ($x = x_{\text{wl}} = 12.5\text{ m}$) and mudline ($x = x_{\text{ml}} = 0\text{ m}$), which are not printed here but can be found in [3].

![Figure 7: Graphical representation of the analytical model developed to simulate the response after the performed rotor stops. $x_{\text{wl}} = 12.5\text{ m}$ meter was the mean sealevel (waterline) during the tests. On the right side, some of the governing equations are given: the equation of motion and the 5 boundary conditions.](image-url)
3.1 Parameter Discussion

The role of most of the parameters in the model can be deducted by looking at figure 7. The here presented model is the end-result of a streak of enhancement steps. In the simplistic way of modeling the soil, the research of P. Wegener was incorporated for modeling the soil stiffness [4]. In his assessment on the applicability of the currently used PY-curves - which were developed for slender piles (high length over diameter (L/D) ratio) - he suggested to link the stiffness $k_s$ of the distributed soil springs with a factor (dependent on the L/D ratio) to the elastic Young’s modulus of the saturated soil. As a second parameter to reach somewhat more realistic modeling of the currently used rigid (low L/D ratio) behaving monopile, he also suggested a pile-tip correction factor which is also dependent on the L/D ratio. For the L/D ratio of BB16, these two factors are $k_s = 1.48E_s$ and a pile tip correction factor of 11.5, which means that the spring at the end of the pile, $k_t$, is a factor 11.5 as stiff as the other distributed springs. These two values are linked to the L/D ratio, and for BB16 this is L/D≈5. The values were derived with a comparison study between two models: the standard FEM 1 dimensional model of a beam on a Winkler foundation with distributed springs (used in the industry), and a 3D elastic FEM model which was assumed to be a more realistic representation of the SPI process. The soil damping, $c_s$ was linked to the distributed spring stiffness $k_t$ as a factor. The SPI process is thus governed by a three-play of parameters: $c_s$, $k_t$ and $k_s$ and therefore also $E_s$. This latter was taken to be constant with depth and equal to 130 MPa. Determining the proper Young’s modulus of offshore saturated soil is not entirely straightforward. This value is a conservative (not very stiff) estimate for saturated sand (the main soil type present at the BB16 location).

3.2 Model Output

As most interesting output of the model, power spectra of the moment at tower top and bottom, and a time-domain response comparison are presented here below. Figure 8, indicates that the second blade induced frequency is most present at the top of the structure, and damps out towards the bottom.

Besides comparing the power spectra of measured and modeled responses, it is also interesting to compare a modeled time-domain response with a measured one. This is done in figure 9. The signals are the bending moments at the tower top, which is why they are clearly double frequency dominated responses. The resemblance is considered to be satisfactory for this simplistic model.
The attenuation is roughly the same, except for the last part, where the 'real' structure is probably subject to some external excitation, lowering the mean bending moment.

4 Conclusions

This research was aimed at finding the effect of soil on the vibrational decrement of an offshore wind turbine support structure. Based on measurements at 3 different vertical locations performed after 12 consecutive rotor stops on the 'BB16' OWT in Burbo Banks, the following conclusions were drawn:

1. The estimation of the order of magnitude of vibration decrement caused by equivalent linear viscous damping generated by soil-pile interaction of the 'BB16' test turbine support structure lies in the range of 9.5 % logarithmic decrement, which equals 1.5 % ratio of critical damping of the first bending mode.

2. Considering the fact that the average magnitude of the total identified damping in the measurements of the 'BB16' OWT is
   - 19 % logarithmic decrement (3 % ratio of critical) for the first natural bending frequency of 0.296
   - 9.5 % log. decr. (1.5 % ratio) for the second main present frequency of 0.825 Hz

   it is concluded that, compared to the design value for BB16 of 2.5 % log. decr. (0.4 % ratio) of damping for the first natural frequency, the identified value in the measurements is relatively high.

3. In this research, a tool has been developed to simplistically assess the influence of soil on the damping of an OWT. A difference in displacement in the soil profile between the vibrations of two different frequencies allows for identifying the influence of soil on these vibrations.
The mode shapes that correspond to the first and second measured frequencies have been identified via a combination of analyses of power spectra of signals at different measurement locations, the development of an analytical model, and a confirmation with the Siemens-design model BHawC. A difference in displacements of these mode shapes in the soil profile and a difference in damping of the vibrations of these two modes was identified. This allowed for assessing the influence of the structure's interaction with soil on the total damping of the structure. The second frequency in the signal is associated with a localized mode in the top of the structure caused by the closely spaced natural modal frequencies of the blades. The amplitudes in the soil profile of this modal shape are smaller than those of the first bending mode shape. Because of the varying amplitudes of the vibrations of these two modes in the soil profile, the difference in identified damping is attributed to the difference in possible influence that the soil can have on this damping.

Caution should be taken in generalizing the above stated order of magnitude for the damping caused by soil-pile interaction. Generalization of the results of this research is limited by some factors of which some are discussed here.

The research is based on 12 rotor stops on a specific turbine during one day. Except for changing soil conditions, also changing environmental conditions (in particular wind speed) have influence on the magnitude of damping. For instance, displacement dependent damping is expected to be active in the soil-pile interaction process, the initial amplitude of vibration after a rotor stop has an important influence on the experienced damping of the structure. In this respect, the damping associated with vibrations induced by a rotor stop, might not be representative for the damping experienced during most of the lifetime of the OWT: the damping occurring during vibrations while the turbine is in production, during which vibration amplitudes are usually smaller than those after a rotor stop.

Another factor which needs more investigation is the unknown effect of the sloshing damper on the damping of vibrations after a rotor stop. A part of the identified difference in damping between the two dominant modes can possibly be attributed to a difference in sloshing damping influence on the vibrations of these modes.

References


