Time-Varying Dynamic Properties of Offshore Wind Turbines Evaluated by Modal Testing

Étude expérimentale de l'évolution temporelle des propriétés dynamiques d'éoliennes maritimes

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ABSTRACT: Modal frequencies and damping ratios of civil engineering structures are often used as damage-sensitive features, since changes in the dynamic characteristics of the structures may indicate structural damage. For offshore wind turbine structures, the modal parameters are influenced by environmental impacts that change boundary conditions, irreversible soil deformations and inherent structural properties. The excitation frequencies related to the environmental loads and the passage of blades past the tower are so low that a proper estimate of the modal parameters are needed in order to avoid strong resonance of the wind turbine structure. In this paper, free vibration tests and a numerical Winkler type approach are used to evaluate the dynamic properties of a total of 30 offshore wind turbines located in the North Sea. Analyses indicate time-varying eigenfrequencies and damping ratios of the lowest structural eigenmode. Isolating the oscillation oil damper performance, moveable seabed conditions may lead to the observed time dependency.

RÉSUMÉ: Les fréquences modales et les taux d'amortissement des structures de génie civil sont souvent utilisés comme indicateur de dommages car l'évolution de la réponse dynamique des structures peut indiquer des dégâts structuraux. Pour des structures comme les éoliennes maritimes, les paramètres modaux sont influencés par la déformation irréversible des sols, les propriétés structurelles inhérentes et les conditions environnementales qui peuvent changer les conditions aux limites. Les fréquences d'excitations liées aux charges environnementales et aux passages des palles sont si basses qu'une estimation correcte des paramètres modaux est nécessaire pour éviter une forte résonance de la structure de l'éolienne. Dans cet article, des tests vibratoires et une approche numérique du type Winkler sont utilisés afin d'évaluer les propriétés dynamiques de 30 éoliennes maritimes situées en mer du Nord. Les analyses révèlent le changement des fréquences propres et des taux d'amortissement de la plus basse fréquence propre structurelle en fonction du temps. En isolant la performance de l'amortisseur oscillant à huile, les changements de conditions du fond marin peuvent démontrer une dépendance temporelle.

KEYWORDS: Free vibration; modal; offshore wind turbine; *p-y* curve; scour; winkler approach.

1 INTRODUCTION

Recently, offshore wind turbine towers and blades have increased significantly in height and length, respectively, with only a small increase in weight. Therefore, the dynamic response of the wind turbine structure occurs in a frequency range close to the excitation frequencies related to environmental and structural harmonic loads. In this context, sufficient geometrical and material damping in the structure and soil are required to counteract large amplitudes of vibration. Especially for wind parks characterised by a large degree of wind-wave misalignment, a proper estimate of the inherent damping is needed due to low aerodynamic forces out of the rotor plane.

The aim of this paper is to investigate the time-varying eigenfrequency f_1 and inherent modal damping δ_1 of the lowest eigenmode $\mathbf{\Phi}^{(1)}$ for offshore wind turbines installed on a monopile foundation. Experimental modal analysis of offshore wind turbines have been studied by several researchers. Based on free vibration tests, Tarp-Johansen *et al.* 2009 and Damgaard *et al.* 2011 have used "rotor-stop" tests to determine each damping contributor to the measured inherent modal damping δ_1 of an offshore wind turbine. Versteijlen *et al.* 2011 and Devriendt *et al.* 2012 used the same modal approach to obtain reliable damping estimates. In addition, Versteijlen *et al.* 2011 considered operational modal analysis in order to include the aerodynamic effects on the structure. The theory has been widely used for civil engineering structures like bridges and buildings. However, in the last years the application of operational modal analysis on wind turbines has been published in many excellent papers, see for instance Hansen *et al.* 2006 and Tcherniak *et al.* 2010. A thorough data processing of more than 650 free vibration tests on 30 offshore wind turbine structures are presented in the paper. The variation in the dynamic properties is supported by a numerical Winkler approach that estimates the modal parameters for different environmental conditions.

2 STRUCTURE AND SITE CONDITIONS

A total of 30 Vestas V90-3MW turbines located in the North Sea are considered. Each tower is installed on a monopile connected by a grouted transition piece to the tower base. The tower height is approximately 60 m, the monopile diameter 4.3 m and the water depth 8 m w.r.t. LAT. For each turbine an oscillation damper is placed in the top of the tower. It consists of a pendulum partly immersed in highly viscous oil, capable of oscillating in the horizontal directions. The soil consists mainly of cohesionless soil in the top layers with friction angles φ_k higher than 30° followed by cohesive soils with undrained shear strength c_u higher than 90 kPa.

3 MODAL PARAMETER ESTIMATION

By use of two accelerometers placed in the nacelle, the modal parameters of each wind turbine are experimentally estimated from the acceleration decay when the turbine generator shuts down and the blades pitch out of the wind, see Figure 1. Hence, assuming that the wind turbine structure behaves as a single-degree-of-freedom (SDOF) system, the eigenfrequency f_1 and modal damping δ_1 are determined by least-squares fitting of a linear function to the zero crossings and to the natural logarithm of the rate of decay of the vibration, respectively. It should be noticed that a wind turbine structure has two closely spaced modes occurring at nearly identical frequencies (Damgaard *et al.* 2012), where vibrational energy is transferred from the highest to the lowest damped mode. Hence, for the damping estimation of each free vibration test it is ensured that the acceleration of the structure only takes place in the fore-aft direction *y*.

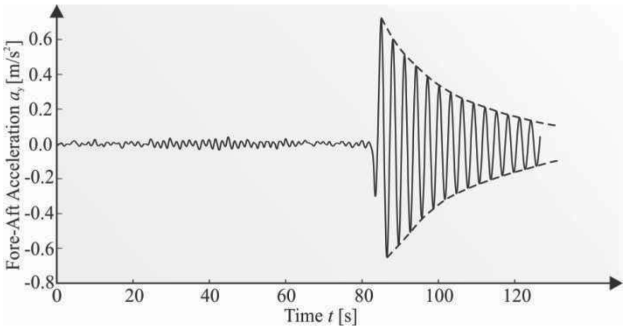

Figure 1. Raw output acceleration signal during a “rotor-stop”.

3.1 Winkler Approach

Offshore wind turbines supported by pile foundations are subjected to lateral cyclic loads. The load-deflection behaviour is often evaluated by a Beam on Nonlinear Winkler Foundation (BNWF) model due to its computationally efficiency and practical versatility. The tower and pile are modelled as Bernoulli-Euler beams and the soil-structure interaction is incorporated via so-called *p-y* curves suggested by DNV 2011, see Fig. 2. The soil consists of a series of independent soil layers with smooth horizontal boundaries, *i.e.* no shearing can be transmitted across the boundaries. Rather than modelling the soil as a number of discrete springs connected to the element nodes, this paper uses a consistent approach, where the soil is modelled as a continuous spring over each element. The nodal forces are then obtained via numerical integration. The reader is referred to Damgaard *et al*. 2011 for more information about the computational model.

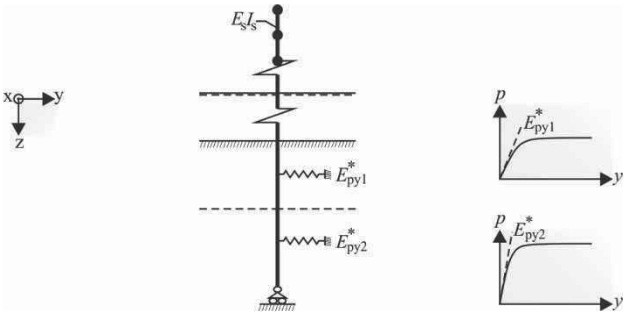

Figure 2. Beam on nonlinear Winkler foundation (BNWF) model.

3.1.1 Soil Damping Estimation

In general, attenuation of wave propagation in the soil is determined from geometric damping, *i.e.* the radiation of waves into the subsoil, and material damping caused by the slippage of soil grains with respect to each other. However, extensive studies of wind turbines on a homogeneous or layered ground made by Andersen 2008 show that geometric dissipation is insignificant at frequencies below 1 Hz. From the continuum mechanics it is known that material damping is related to the relative motion of material points, and the energy dissipation is frequency-dependent. For a given frequency and deformation level, the soil material damping can be approximated to an equivalent viscosity. Based on a static deformation analysis, using the Winkler approach, the following procedure is used to determine the soil damping ratio ζ_{soil} of the lowest eigenmode $\mathbf{\Phi}^{(1)}$:

- A 10-minutes time-domain simulation of the wind turbine structure is conducted for a power production situation with a normal turbulence model (IEC 2005) using the aeroelastic code FLEX (Øye 1996). A correct estimate of the structural eigenfrequency f_1 in the FLEX model is ensured by extending the tower until the eigenfrequency f_1 of the Winkler model is reached.
- Based on the maximum overturning moment at the tower/foundation interface from the FLEX simulation and including wave loads, the horizontal pile deformation in each nodal point below the seabed is evaluated.
- Assuming a load-displacement cycle after the generator shuts down, as indicated in Figure 3a, the irreversible soil deformations are a measure of energy dissipation. Hence, the energy dissipation in Figure 3a can be transformed to an equivalent viscous damping model as shown in Figure 3b.
- Using the theory of linear structural dynamics, the soil damping ζ_{soil} of the lowest eigenmode $\mathbf{\Phi}^{(1)}$: is determined from the global damping matrix $\mathbf{C}$, the angular eigenfrequency ω_1, the eigenmode $\mathbf{\Phi}^{(1)}$ and the modal mass M_1 given by

$$\zeta_{\text{soil}} = \frac{\mathbf{\Phi}^{(1)\text{T}}\mathbf{C}\mathbf{\Phi}^{(1)}}{2\omega_1 M_1} \tag{1}$$

The virgin curve in Figure 3a is determined by the *p-y* curve formulation given by DNV 2011. The unloading phase is determined by the initial stiffness E^*_{py}. Assuming separation between the pile and the soil, a shear drag p_{drag} is introduced. For cohesionless soils, the shear drag depends on the vertical effective stress σ'_{v} (Ovesen *et al.* 2006) given by $p_{\text{drag}}=0.6D\,\sigma'_{\text{v}}$, whereas for cohesive soils the undrained shear strength c_{u} must be considered, *i.e.* $p_{\text{drag}}=0.7Dc_{\text{u}}$.

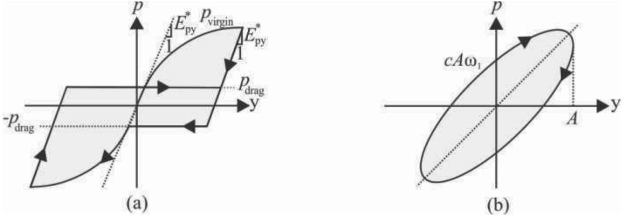

Figure 3. Hysteresis Loop Method (Nielsen 2004): (a) Load-displacement curve after the wind turbine generator shuts down, (b) Hysteresis loop implied by viscous damping in a harmonic motion with the amplitude A and the angular eigenfrequency ω_1.

4 INTERPRETATION OF RESULTS

Experimental modal testing of 30 offshore wind turbines in the period 2006-2011 is presented in Figure 4a and Figure 4b in terms of the modal damping δ_1 and the eigenperiod T_1 of the lowest eigenmode $\mathbf{\Phi}^{(1)}$, respectively. Using a lognormal probability distribution, the 5% quantile of the modal damping δ_1 and the eigenperiod T_1 are estimated to 0.11 and 2.94 s, respectively. This corresponds to an eigenfrequency f_1 of 0.34 Hz. As indicated in Figure 4a and Figure 4b, the scatter of the estimated parameters is high. Increasing the R-square value from 0.95 to 0.99, meaning that the fit of the acceleration amplitude peaks and zero crossings explains 99% of the total variation in the data about the average, seems to reduce the scatter to a certain extent, see Figure 4c and Figure 4d. Overall, a tendency of decreasing modal damping and eigenfrequency is observed for increasing acceleration level. High structural accelerations induce irreversible soil deformations and thereby soil damping activation. However, the oil damper performance is characterised by optimal damping for low levels of accelerations, which may explain the observed behaviour. In addition, distinct non-linear soil behaviour occurs for high accelerations, which reduces the secant stiffness E_s and thereby the eigenfrequency f_1.

An almost identical mean value and standard deviation of the modal parameters have been observed for each wind turbine. Hence, the variation of the modal parameters in Figure 4c and Figure 4d might be caused by the following conditions:

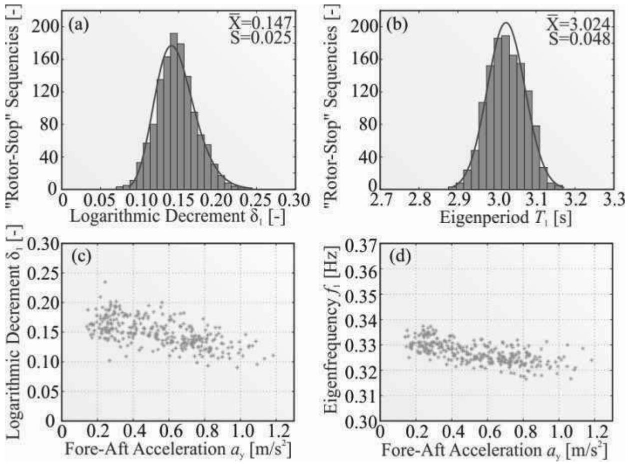

Figure 4. Free vibration tests for a total of 30 offshore wind turbines: (a) Damping histogram, (b) Eigenperiod histogram, (c) Damping vs. acceleration level, (d) Eigenfrequency vs. acceleration level.

- Tower damper performance
- Tidal variation
- Wind variation
- Temperature dependent modal parameters
- Moveable seabed and scour around the foundation

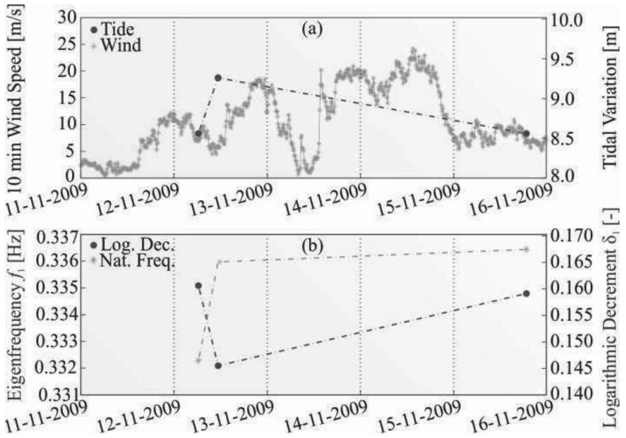

Figure 5. Selected turbine investigation: (a) Tidal and wind variation as a function of time, (b) Modal parameters as a function of time. Data are collected with same acceleration level and slope of generator speed.

It has been observed that the mass pendulum of the tower damper in some tests moves exactly with a phase identical to the phase of the wind turbine, resulting in almost no additional damping. To eliminate the variation of the tower damper performance, data for each turbine is investigated for the same slope of generator speed when the blades pitch out of the wind and for the same acceleration level. As an example, Figure 5 shows the comparison of the measured 10-minutes wind speed and tidal variation together with the modal parameters for a selected turbine. One one-year measurements of the tidal levels at the wind park show only a maximum difference between highest and lowest astronomical tide of 2 m. It might then be assumed that the tidal variation at the wind park has negligible impact on the magnitude of the modal parameters. The same conclusion can be drawn regarding the variation in the wind speed and temperature during the tests. The aerodynamic damping is very low, when the blades pitch out of the wind, and a temperature change from -73° to 93° only changes the Young's modulus of elasticity E_{steel} with 5% (Nielsen 2004). Based on a Winkler model this corresponds to a change in the eigenfrequency f_1 of only 0.5%. In conclusion, assuming that the tower damper contributes with the same damping value in Figure 5b, the time-dependent modal parameters might be caused by erosion of soil particles near the monopile foundation.

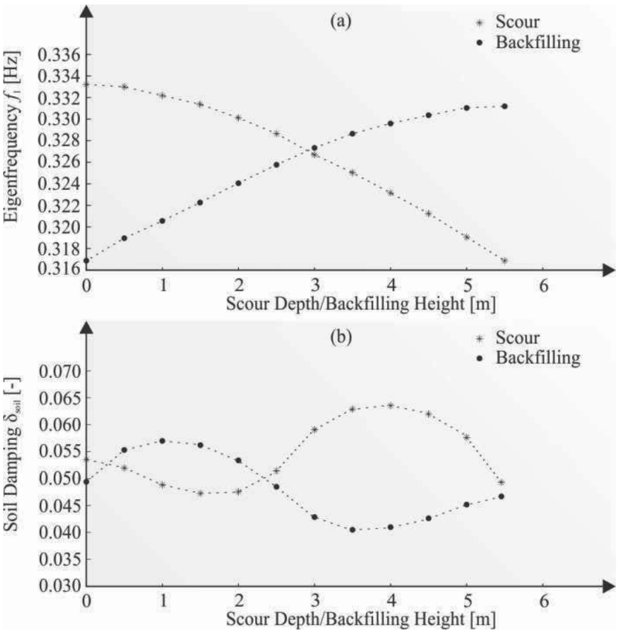

Figure 6. Scour and backfilling analysis based on a Beam on Nonlinear Winkler Foundation model: (a) Eigenfrequency f_1 as a function of scour depth and backfilling height, (b) Soil damping δ_{soil} as a function of scour depth and backfilling height.

1.1 *Scour and Backfilling*

When a pile is installed in a loose sedimentary bed, a scour hole will form around the pile. The phenomenon is of high importance, since the structural eigenfrequency and soil damping contribution will change and in worst case lead to fatigue damage and, eventually, failure. Based on experimental tests, Sumer *et al.* 1992 stated that the mean value of the equilibrium scour depth for a vertical cylinder in steady current is given by 1.3D, where D is the diameter of the cylinder. However, for combined current and wave conditions the scour depth is difficult to determine, since wave action tends to reduce the scour depth (Høgedal and Hald 2005).

As no scour protection is present for the investigated wind turbine structures in this paper, the variation of the eigenfrequency f_1 and soil damping δ_{soil}, caused by sediment transportation at seabed, is estimated using a Winkler approach. Different scour depths and backfill heights are considered for a wind speed of 13 m/s with maximum depth and height equal to 1.3D, respectively. The vertical effective stress p_0 is reduced linearly with depth to a depth equal to 3D below the base of the current scour hole. As expected, Figure 6a shows a decreasing eigenfrequency f_1 for increasing scour depth. Assuming cohesionless backfill material with a friction angle φ_k of 28°, the eigenfrequency f_1 tends to increase for increasing backfill height. The material soil damping δ_{soil} highly depends on the pile deflection and the initial stiffness E^*_{py} for each soil layer, see Figure 3. However, the pile deflection at the base of the scour hole only increases to a certain scour depth, and the initial stiffness E^*_{py} depends on the strength of each soil layer and the scour depth. Hence, for increasing scour depth the pile deflection and initial soil stiffness might increase or decrease relative to each other. This may in turn explain the observed behaviour of the soil damping δ_{soil} in Figure 6b.

Over a period of time the relative density I_d of the backfill material might be increased due to the presence of waves inducing depth compaction (Sørensen *et al.* 2010). Hansson *et al.* 2005 have reported friction angles above 40° for Frederikshavn sand. Figure 7 shows the eigenfrequency f_1 and soil damping δ_{soil} as a function of the strength of the backfill material after the scour hole is replaced by the backfill material.

In conclusion, the Winkler approach shows a variation of the eigenfrequency f_1 caused by sediment transportation at the seabed level of 8%. The model indicates a soil damping δ_{soil} in the range of 0.05-0.08 logarithmic decrement. Hence, comparing these results with the experimental findings in Figure 5, the time-varying modal parameters of the investigated offshore wind turbines might be caused by sediment transportation at seabed.

2 CONCLUSION

Wind energy is a rapidly growing interdisciplinary field that involves many different disciplines within civil engineering. The dynamic behaviour of the wind turbine structure is determined by a complex interaction of components and sub-systems. A full understanding of the structural modal parameters is crucial in order to assess the fatigue damage accumulation during the lifetime of the wind turbine structure.

Experimental and numerical investigations of the dynamic properties of offshore wind turbine structures installed on a monopile foundation have been presented in this paper. Based on a total of 665 free vibration tests, time-varying modal parameters are observed, which is supported by a Winkler approach. Several interesting observations can be made:

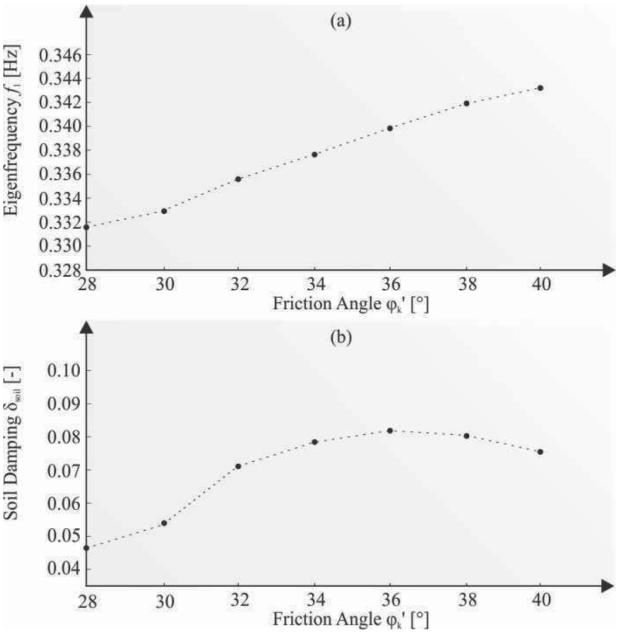

Figure 7. Strength of backfilled material based on a Beam on Nonlinear Winkler Foundation model: (a) Eigenfrequency f_1 as a function of the friction angle φ_k' of the backfill material, (b) Soil damping δ_{soil} as a function of the friction angle φ_k' of the backfill material.

- Experimental testing indicates a high variation in the eigenfrequency f_1 and the modal damping δ_1. A 5% quantile of 0.11 logarithmic decrement is observed, which corresponds very well with the findings for each considered turbine.
- Eliminating the tower damper performance tends to reduce the large variation of the modal parameters. However, distinctly time-varying eigenfrequencies f_1 and modal damping values δ_1 are still obtained.
- A Beam on a Winkler foundation model indicates that the observed time-dependencies might be caused by sediment transportation at seabed. Scour development and backfilling change the eigenfrequency f_1 with 8%, and the soil damping δ_{soil} varies in the range 0.05-0.08.

3 ACKNOWLEDGEMENTS

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