Dynamics of Support Structures for Offshore Wind Turbines in Fully-coupled Simulations - Influence of Water Added Mass on Jacket Mode Shapes, Natural Frequencies and Loads

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Abstract

Submerged offshore wind turbine (OWT) substructures, are surrounded by boundary layers of water due to water adhering to the structure. When the submerged structure is excited the boundary layer oscillates with the structure. The adhering boundery layer effects the frequency at which the structure oscillates. By adding a so-called hydrodynamic mass to the mass of the elements of the structure these effects can be taken into account when determining the dynamics of the OWT. The objective of this study is the investigation of the effects of the added hydrodynamic mass on the results when determining the dynamics of an OWT with particular focus on structural responses to the rotor dynamics.

1 Introduction

Most offshore wind parks so far have been realized utilizing monopile or gravity based foundations. As wind turbines grow larger and the water depth at installation locations increases branched support structures gain interest. The water depth at the installation site of the first German offshore wind park Alpha Ventus is between 28 meters and 30 meters, the water depth at the installation site of the DOWNVInD Demonstrator Project (Scotland) is about 45 meters. Branched support structures offer high stiffness at a comparatively low weight (c.f. DeVries (2008)).

At the moment different manufacturers offer various promising branched offshore wind turbine support structure concepts. The jacket substructure, which has been chosen for the DOWNVInD Demonstrator Project in connection with REpower 5M wind turbines and for six of the wind turbines installed at Alpha Ventus, again with REpower 5M wind turbines, is a highly branched concept which shows similarities to support structures as used in the offshore oil and gas industry. Another concept also utilized at Alpha Ventus, in connection with Multibrid M5000 wind turbines, is the tripod. A third concept developed by BARD engineering is the tripile structure, which resembles three monopiles, connected above the water line, with the connection piece carrying the wind turbine.

Like for any other wind turbine support structure a modal analysis is inevitable for branched substructures. It has to be ensured that the wind turbine support structure is not excited by the rotor frequency and the blade passing frequency and that no significant excitations by environmeltal influences like wind and waves occur. Hartnett et al. (1997) showed for the Kinsale Alpha platform in Ireland, an offshore lattice platform, that hydrodynamic mass can affect the structure dynamics in terms of frequencies of the eigenmodes and therefore need to be considered in modal analyses. Since the jacket substructure used for the DOWNVInD Demonstrator Project and at Alpha Ventus is comparable to lattice offshore oil platforms like the Kinsale Alpha platform it seems necessary to investigate the impact of the hydrodynamic added masses on jacket substructures for OWTs. Especially due to the strong dynamic excitations from the rotor dynamics it is of great interest to find out whether hydrodynamic added mass affects the wind turbine eigenfrequencies in a way enabling significant dynamic responses of the support structure to excitations from the rotor-nacelle-assembly (RNA).

According to Seidel (2007) it is furthermore especially important for branched support structures to assess the possiblity of the occurence of local vibration modes.

2 Water Added Mass

The existence of added mass was first realized with pendulums moving in fluids. Dubua studied the phenomenon already in 1776, but it was not before the 19th century when Green in 1833 and Stokes in 1843 formulated an exact mathematical expression for the added mass of a sphere (cf. Korotkin (2009)). A lot of research has been undertaken in the past to determine the exact hydrodynamic added mass for all kinds of structures, mainly structures and shapes associated with ships.

The determination of the exact hydrodynamic mass is not within the scope of this research project but a simplyfied assumption has been made to account for the hydrodynamic added masses. The added hydrodynamic mass has been assumed to equal the mass of the displaced water volume, which is common approach for this sort of applications. It equals a water added mass coefficient of one in the Morison equation which is used for wave load determination on offshore structures.

3 Model

The model consists of a rotor-nacelle assembly (RNA) as defined by Jonkman et al. (2009), and presented as the NREL 5-MW Baseline wind turbine, which is itself based on the Dutch Offshore Wind Energy Converter (DOWEC) (c.f. Kooijman et al. (2003)) and the REpower 5M wind turbine. The turbine is mounted on a common tubular tower and a fictitious, but realistic jacket substructure as shown in Figure 1. The wind turbine is a conventional variable speed, upwind, collective pitch horizontal axis wind turbine. It features:

- a rotor diameter of 126 m,
- blades with a length of 62.5 m,
- a rated power output of 5 MW,
- a tower with a height of 60 m,
- and a jacket with a height of 50 m and a base area of 17 x 17 m.

The mean sea level (MSL) is 30 m, hence the transition between jacket and tower is 20 above MSL. Considering the transition piece and the nacelle the hub height is 89 m above MSL.

The NREL 5-MW Baseline wind turbine has been used for numerous studies and research projects.

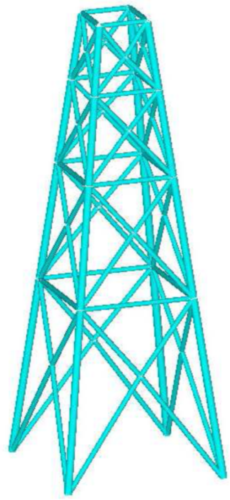

Figure 1: *Jacket as used for the study*

4 Modal Analysis

Wind turbine substructures, as used in this project, feature different kind of mode shapes. There are global mode shapes, concerning the entire substructure, local mode shapes concerning only parts of the substructure and coupled mode shapes which are combinations of local and global mode shapes.

4.1 Approach

The modal analysis has been performed using the finite element analysis software ANSYS. The above presented model has been adopted for the modal analysis in order to decrease the complexicity. The substructure and the tower are defined using beam elements, a common approach for this kind of analyses. The RNA is strongly simplified and is represented by point masses with appropriate mass moments of inertia to account for the mass distribution of the actual RNA.

Two different cases have been investigated and compared

1. Neclecting water added mass.
2. Considering water added mass.

4.2 Results

The comparison of the results of the modal analysis incorporating and neglecting water added mass led to several findings, which are detailed in the following section. All natural frequencies have been normalized to the first natural frequency of the structure neglecting water added mass.

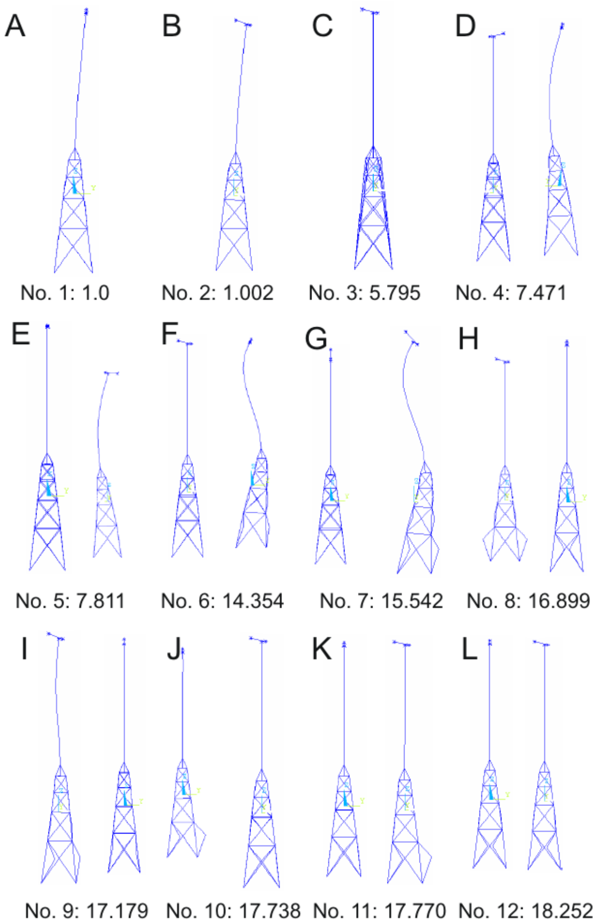

Figure 2: *Mode shapes No. 1 to No. 12, ordered by normalized frequency, neglecting water added mass.*

Figure 2 depicts the Mode shapes of the substructure neglecting water added mass. The mode shapes are ordered by normalized frequency and each mode shape is labelled with a letter. Using this illustration it is possible to identify global, local and coupled mode shapes:

- Global mode shapes: A, B, C, D, E
- Local mode shapes: H, J, K, L
- Coupled mode shapes: F, G, I

Figure 3 illustrates the mode shapes considering water added mass. The mode shapes are ordered by normalized frequency. The natural frequencies of the mode shapes D to L are lower considering water added mass.

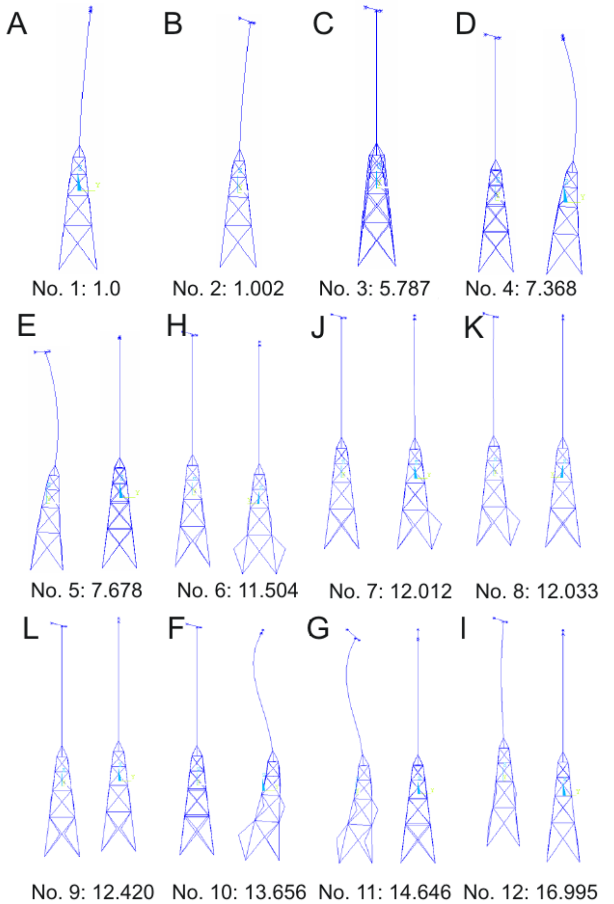

Figure 3: *Mode shapes No. 1 to No. 12, ordered by normalized frequency, incorporating water added mass.*

The effect of the water added mass on the natural frequencies of the global mode shapes is very small, it ranges from 0% (A, B, C) to about 2% (E). The effect of the water added mass on the coupled mode shapes is in average bigger, it ranges from about 1% (I) to about 6% (G). The effect on the local mode shapes is significantly higher, it ranges from about 47% (H) to about 48% (J,K) - the increase in frequency for all four local mode shapes is withhin a range of less than one percent. Since these mode shapes are very similar this could be expected.

Furthermore the mode shapes are permuted in their order when sorted by frequency.

Figure 4 gives an overview of the changes in natural frequencies for the mode shapes A to L.

The fact that water added mass has a greater effect

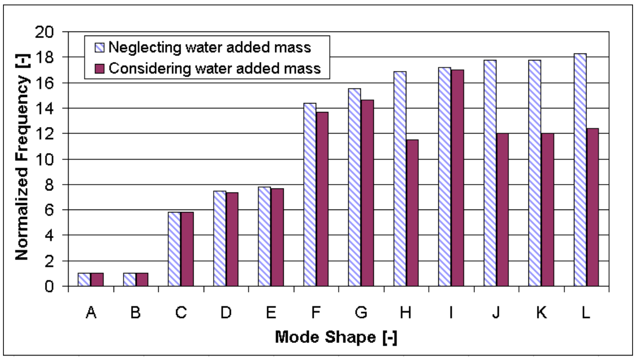

Figure 4: *Comparison of natural frequencies of the first twelve mode shapes considering and neglecting water added mass.*

on local oscillations in the jacket than on global mode shapes is owed to the fact that global oscillations, contrary to the local vibrations, are dominated by the tower head mass from the RNA.

Normally the risk of excitations of the modes of a wind turbine is bigger for lower natural frequencies, thereafter the decrease in frequency implies an increase in risk of excitation.

5 Time Domain Load Cases

5.1 Approach

The time domain load analysis has been performed with the nonlinear aero-elastic code ADCoS-Offshore. ADCoS-Offshore has been developed by Aero Dynamik Consult Ingenieursgesellschaft (ADC) and Fraunhofer Institure for Wind Energy and Energy System Technology (IWES). ADCoS-Offshrore is an enhancement of ADCoS which has been developed by ADC. A detailed description of ADCoS has been given by Kleinhansl et al. (2004), more details on ADCoS-Offshore have been presented by Vorpahl et al. (2009). The wave loads are calculated using ASAS, finite element tool widely used in the offshore oil and gas industry, and introduced into ADCoS as nodal load time series.

Several load cases derived from the design load cases as described in the Guidelines by Germanischer Llyod (c.f. GL (2005)) have been investigated. Selected load time series, especially from elements which are subject to strong local oscillations and which are located below MSL, have been investigated after transformation to the frequency domain (FFT). The elements of the two lower jacket bays meet the previously defined criteria and have therefore been investigated. One of these elements is element 158 as depicted in figure 5.

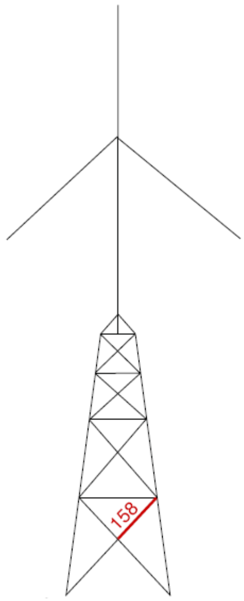

Figure 5: *Position of element 158 in the jacket.*

Two examplary load cases are presented in this paper.

1. This loadcase features a constant wind of 30 m/s and regular Airy waves. The waves have a height of 1.25 m and a wave period of 5.75 s. The cut-out wind speed of the wind turbine is 30 m/s, therefore it is idling and the aerodynamic damping is reduced.
2. This loadcase features a turbulent wind based on the Kaimal spectrum with a wind speed of 11.5 m/s, which is slightly above rated wind speed causing the wind turbine to operate normally. The standard deviation in longitudinal wind direction is 4.2 m/s. The waves in this load case are Airy waves based on the JONSWAP spectrum. The significant wave height of this loadcase is 3.75 m and the peak period is 8.5. The loadcase features a commonly used peak enhancement factor of 3.3.

5.2 Results

In the following section examplary results for element 158, the position is illustrated in figure 5, of the substructure are presented. The bending moments investigated are the resulting bending moments.

In the first loadcase, FFT transformed results are illustrated in figure 6, two main peaks can be found in

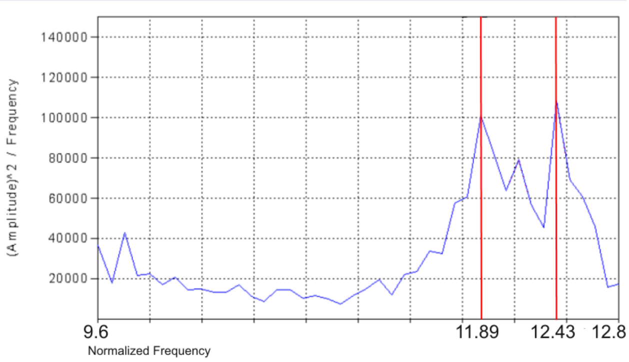

Figure 6: *Resulting bending moment spectrum of element 158.*

the normalized frequency range from 9.6 to 12.8 at the normalized frequencies of 11.89 and 12.43. These two frequencies correspond with the modes J and L when considering water added mass.

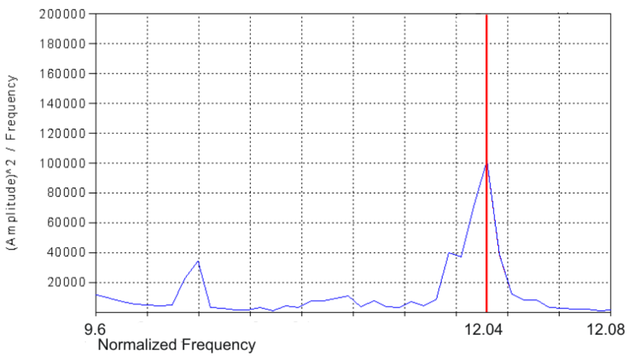

Figure 7: *Resulting bending moment spectrum of element 158.*

The second loadcase with FFT transformed results as visible in figure 7 shows a significant peak in the normalized frequency band from 9.6 to 12.8 at the normalized frequency of 12.04. This frequency corresponds with mode K.

Neglecting water added mass these peaks would not be generated correctly. The mode shapes associated with these peaks have a significantly higher frequency when neglecting water added mass.

6 Conclusion

The water added mass has a significant influence on the natural freuencies and mode shapes of the jacket substructure investigated in this study. For some mode shapes the natural frequency drops by almost 50 %. These mode shapes lead to peak loads on the elements subject to local oscillations which are not generated when neglecting the water added mass. However the natural frequencies of the mode shapes that are subject to change in frequency when considering water added mass are in a band which is not likely to experience excitations by the rotor frequency and blade passing frequency.

Nevertheless neglecting water added mass possible excitations might be overlooked in a worst case and thereafter resulting loads might not be considered in the design of the substructre. These facts would lead to a non-conservative design of the substructure which has to be avoided.

References

DeVries, W. (2008). Soft-stiff bottom mounted support-structures - analysis of monopile and multi-member support structures for offshore wind turbines.

GL (2005). Guidelines for the certification of offshore wind turbines. Technical report.

Hartnett, M., Mullarkey, T., and Keane, G. (1997). Modal analysis of an existing offshore platform. *Engineering Structures*, 19:487–498.

Jonkman, J., Butterfield, S., Musial, W., and Scott, G. (2009). Definition of a 5-mw reference wind turbine for offshore system developement. Technical Report NREL/TP-500-38060, NREL, Golden, Colorado.

Kleinhansl, S., Mayer, M., and Mangold, A. (2004). Adcos - a nonlinear aeroelastic code for the complete dynamic simulation of offshore-structures and lattice towers. In *Deutsche Wind Energie Konferenz (DEWEK)*. Aero Dynamik Consult Ingenieursgesellschaft mbH.

Kooijman, H.-J., Lindenburg, C., Winkelaar, D., and van der Hooft, E. (2003). Dowec 6 mw pre-design: Aero-elastic modelling of the dowec 6 mw pre-design in phatas. Technical report, Energy Research Center of the Netherlands.

Korotkin, A. I. (2009). *Added Masses of Ship Structures*. Springer Science and Business Media B:V.

Seidel, M. (2007). Jacket substructures for the repower 5m wind turbine. In *Conference Proceedings European Offshore Wind 2007*.

Vorpahl, F., van Wingerde, A., Blunk, M., Busmann, H.-G., Kleinhansl, S., Kossel, T., Kohlmeier, M., Bker, C., Kaufer, D., Azcona, J., Martinez, A., and Munduate, X. (2009). Validation of a finite element based simulation approach for offshore wind turbines within iea wind annex xxiii - simulation challenges and results for a 5-mw turbine on a tripod substructure. In *Proceedings of the Nineteenth International Offshore and Polar Engineering Conference*.