OUTPUT-ONLY MODAL ANALYSIS USED ON NEW FOUNDATION CONCEPT FOR OFFSHORE WIND TURBINE

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Abstract

The foundation principles for the recent major offshore wind farm projects in Europe have been dominated by two types of foundation solutions, the gravitational foundation and the monopile. A five-year research and development project has proven the bucket foundation to be feasible in suitable soil conditions in water depth from near shore to approximately 40 meters. A fully operational 3.0 MW offshore wind turbine was installed on a prototype of the bucket foundation at the test field in Frederikshavn in late 2002. The bucket foundation design reduces the steel weight by half compared with a traditional monopile solution and the installation of the bucket foundation is much easier and does not require heavy installation equipment. The prototype at Frederikshavn has been equipped with an online monitoring system that measures the modal space of the foundation and the wind turbine. Output-only Modal analysis has been used to analyze the structural behaviour of the wind turbine in various operational conditions. The Modal analysis has shown highly damped mode shapes of the foundation/wind turbine system, which the present aero-elastic codes for wind turbine design are insufficient to model. Further studies are to be carried out with respect to soil-structure interaction.

1 Introduction

The recent major offshore wind farm projects in Europe have been dominated by two types of foundation solutions, the gravitational foundation and the monopile. The monopile solution has been used at Horns Rev, Samsø, North Hoyle and Kentish Flats, whereas the offshore projects at Nysted and Middelgrunden are based on gravitational foundations. In future projects at increasing water depths and/or with greater wind turbines tripod foundations or jackets may become practicable. A five-year research and development project has proven the novel principle of the bucket foundation to be feasible in suitable soil conditions in water depth from near shore to approximately 40 meters. The bucket foundation is an innovative solution that has been developed

Figure 1 Offshore research test field in Frederikshavn.

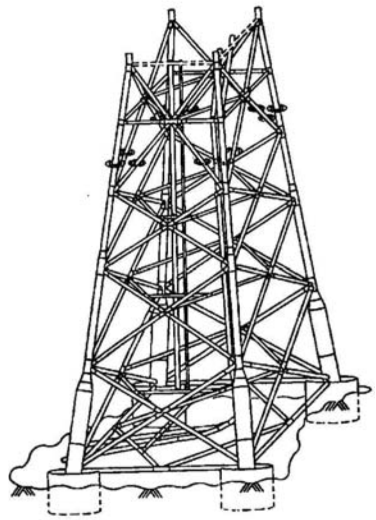

Figure 2 Suction bucket below the Norwegian jacket Draupner E

over the past 4 years and the foundation concept has been utilized for a Vestas V90-3.0 MW offshore wind turbine.

The fully operational 3.0 MW offshore wind turbine was installed on a prototype of the bucket foundation in Frederikshavn in late 2002. The wind turbine is a part of an offshore research test field consisting of four 2-3 MW wind turbines next to the harbour of Frederikshavn in the northern part of Denmark (Figure 1). The test field for offshore wind turbine research has been created as a joint research and development program between the Centre for Wind Energy Systems at Aalborg University and MBD Offshore Power. The research program deals with foundation of offshore wind turbines in general, but the on-going projects are related to the development of bucket foundations. The present activities concerns large scale model tests of bucket foundations and experimental modal analysis of the 3.0 MW offshore wind turbine. The latter is described in further detail in this paper.

The bucket foundation differs in the mode of operation from the well-known “Suction bucket” or ”Suction caisson”. The suction caisson has been used as foundation for a number of different offshore constructions, for instance the Norwegian jacket Draupner E. This platform was installed with 4 suction caissons, as shown in Figure 2. During the installation process the caisson penetrates into the seabed due to the weight of the structure and also due to the fact that suction is applied to the 4 caissons. The static system ensures that the caissons are loaded only with vertical forces from the wave loading. The stability is ensured because there is not enough time for the caissons to be pulled from the bottom during a wave period. The stability of the foundation relies on that negative pore pressure is generated inside the caisson.

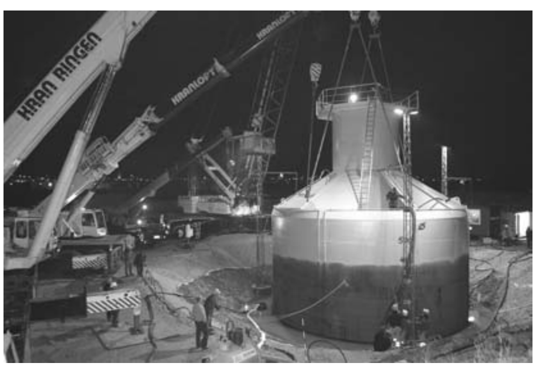

Figure 3 Installation of the prototype foundation at the test site in Frederikshavn, a) during installation and b) after installation.

Comparing the bucket foundation to the suction caisson, the only thing they have in common is that they are installed in the same fashion. Both types use suction as the driving force during installation. Lowering the pressure in the cavity between the bucket and the soil surface causes a water flow to be generated, which again causes the effective stresses to be reduced around the tip of the skirt and the penetration resistance is reduced. Assuming the wind turbine is to be founded on one large bucket, the static mode of operation is very different from that of the suction caisson. When the bucket foundation has been installed, the loads from the wind on the wind turbine will cause the foundation to be influenced by a large moment. The stability of the foundation is ensured by a combination of earth pressures on the skirt and the vertical bearing capacity of the bucket.

2 The Prototype foundation in Frederikshavn

The prototype in Frederikshavn is designed with a diameter of 12 meters and a skirt length of 6 meters. The water depth is 4 meters, and as the sitting is in a basin, no wave and ice loads are applied. The steel construction weight app. 140 tons, and was placed late October 2002. The actual installation period lasted app. 12 hours, where the soil penetration period lasted 6 hours, using a computer system to perform the inclination guidance and control of the suction pressure and penetration rate, see Figure. 3. Det Norske Veritas (DNV) has certified the design of the prototype in Frederikshavn to B level. The Vestas V90 3.0 MW turbine was erected on the foundation in December 2002. The structure is illustrated in Figure 4. The development of the design procedure for the bucket foundation is described in ref [1].

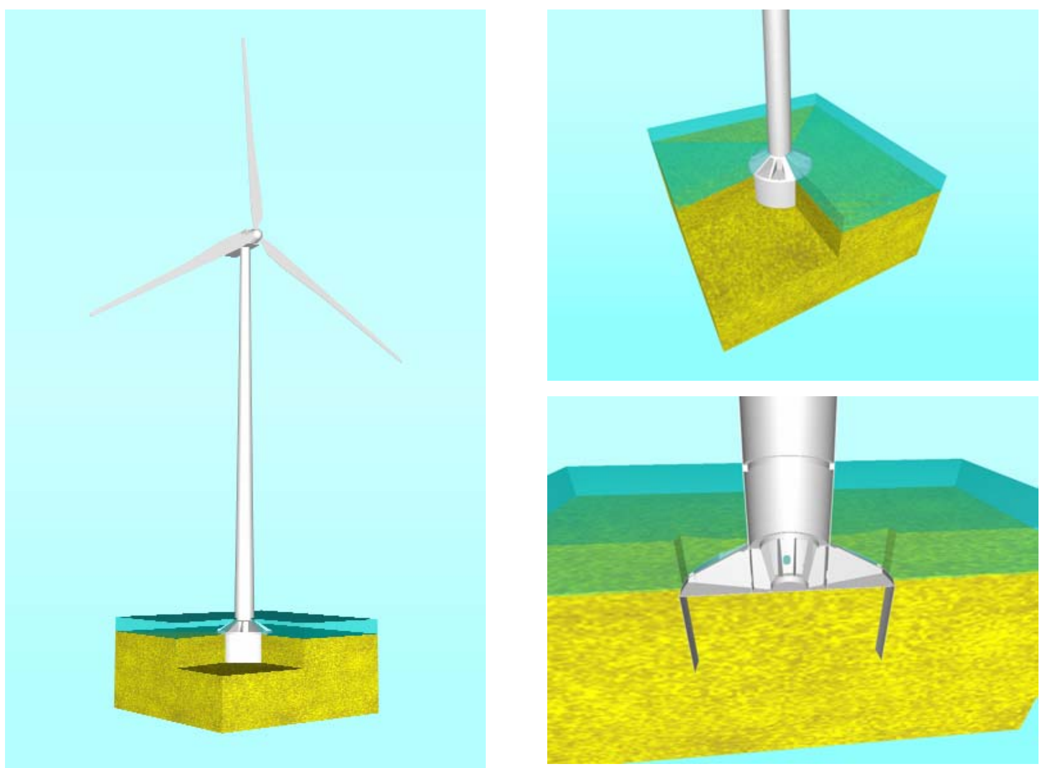

Figure 4 Illustration of the 3.0 MW offshore wind turbine prototype on bucket foundation

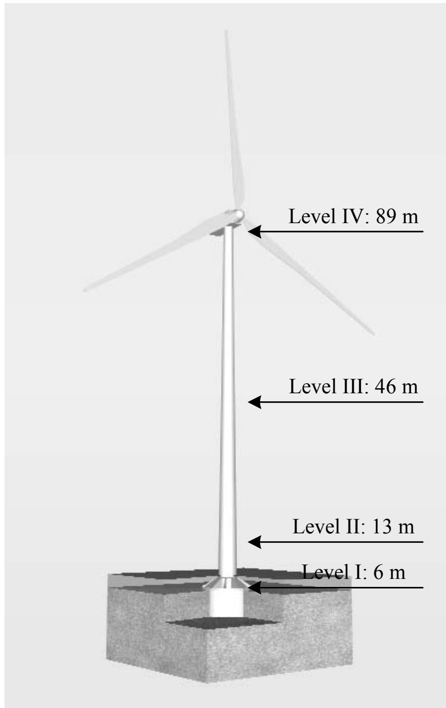

Figure 5 Sensor positions in tower and foundation.

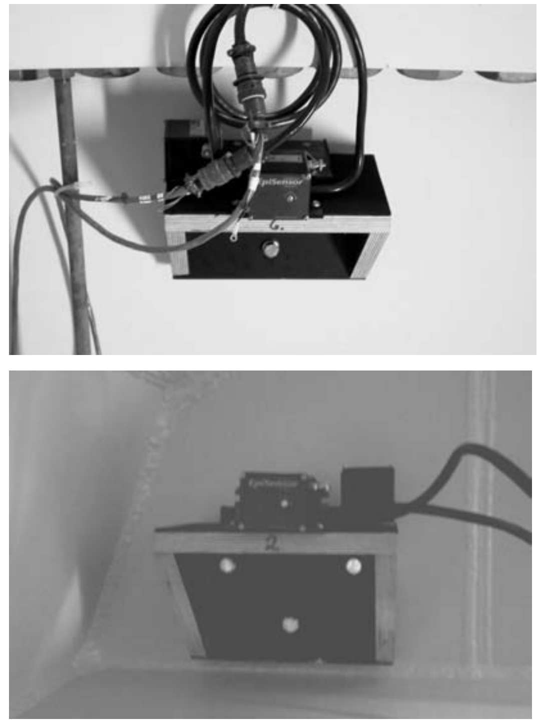

Figure 6 Sensor mounting. Top: mounting in tower. Bottom: mounting in foundation.

3 Monitoring System and Analysis Software

3.1 Monitoring System

The Vestas 3.0 MW prototype wind turbine is instrumented with 15 accelerometers and a real-time data-acquisition system. The sensors are Kinemetrics force balance accelerometers, model FBA ES-U. The accelerometers are placed at three different levels in the wind turbine tower and at one level in compartments inside the bucket foundation. The positions are shown in Figure 5. The accelerometers are mounted on the steel structure by magnets, as shown in Figure 6. The online monitoring system consists of a DigiTexx PDAQ-8 portable data acquisition system with 16 channels and 16 bit resolution. The remote portable data acquisition system is placed inside the wind turbine and the DigiTexx RTMS-2001R Remote Client Software is used for real time data acquisition and monitoring at Aalborg University (Figure 7). The performance of the wind turbine is also monitored online by live web imaging, see Figure 8.

3.2 Analysis Software

The modal analysis of the wind turbine makes use of "Output-only modal identification" which is utilized when the modal properties are identified from measured responses only. "Output-only modal identification" is also known by the terms "ambient identification" or "ambient response analysis" within the field of civil engineering. The geometry of the structure and the sensor settings and locations are defined in the test planning toolbox "ARTeMIS Testor", see Figure 9.

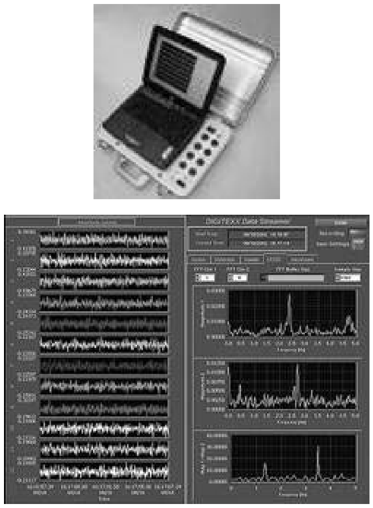

Figure 7 Top: portable DAQ system. Bottom: Real time client software.

Figure 8 Online image of the Vestas V90 3.0 MW in operation.

The “ARTeMIS Extractor” is the key application of the software package. The software allows accurate modal identification under operational conditions and in situations where the structure is impossible or difficult to excite by externally applied forces. The typical outputs of the analyses are modal information about the natural frequencies, mode shapes and damping ratios.

The experimental modal analysis of the wind turbine prototype is performed by means of the software package ARTeMIS (Ambient Response Testing and Modal Identification Software, see ref [2]). The software is fully compatible with the hardware of the monitoring system described above.

The modal analysis within this software is based on the assumptions that the underlying physical system of the structure is linear and time-invariant. The linearity imply that the physical system comply with the rules of linear superposition. The time-invariance implies that the underlying mechanical or structural system does not change in time. Within this frame the program is based on two different estimation techniques, one in time domain and one in frequency domain. The analyses described in this paper are based on the frequency domain technique.

The frequency domain estimation is a non-parametric model based on a Frequency Domain Decomposition (FDD) method. The basic principle of the Frequency Domain Decomposition (FDD) technique is to perform an approximate decomposition of the system response into a set of independent single degree of freedom (SDOF) systems;

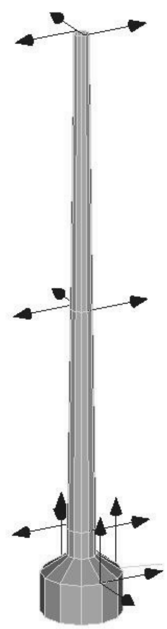

Figure 9 Location and orientation of sensors (green arrows)

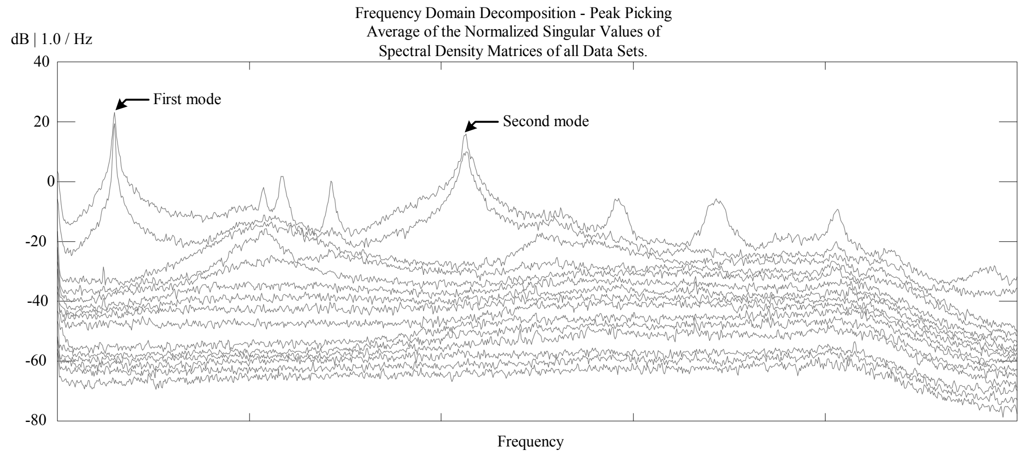

Figure 10 Frequency plot for measurement "15feb05" (idle mode).

each corresponding to an individual mode. In the FDD the Spectral Density matrix is decomposed by means of the Singular Value Decomposition (SVD) into a set of auto spectral density functions, each corresponding to a single degree of freedom system. The key feature is that the singular values are estimates of the Auto Spectral density of the SDOF systems, and the singular vectors are estimates of the mode shapes. The basic theory concerning identification by FDD is given in ref [3] and [4].

4 Natural Frequency Estimation

The natural frequency of the wind turbine structure has been estimated by means of the Frequency Domain Decomposition (FDD) method. The estimation technique is used for two situations; idle conditions and operational conditions.

4.1 Idle conditions

Figure 10 shows a representative frequency plot for the wind turbine in idle mode. The measured data used in the analysis was recorded the February 15 2005. The data set consists of a 1 hour measurement in 15 channels. The sampling frequency was 200 Hz and the data was decimated by an order of 20. The FDD technique was used for peak picking. In Figure 10 the peaks for the first and second mode of the structure are shown. Note that there are closely spaced modes at the selected frequencies, which suggests that there are two perpendicular modes at each natural frequency. The first and the second natural frequency are shown in Figure 10. The mode shapes are illustrated in Figure 11.

Figure 11 mode shape for first (left) and second (right) natural frequency.

4.2 Operational conditions

For an operational wind turbine there is a harmonic excitation that comes from the rotor. The rotor's rotational frequency is the first excitation frequency and is commonly referred to as 1P. The second excitation frequency to consider is the blade passing frequency, often called 3P (for a three-bladed wind turbine).

Figure 12 shows a representative frequency plot for the wind turbine in operational mode. The measured data used in the analysis was recorded the November 03 2004. The data set consists of a 1 hour measurement in 15 channels. The sampling frequency was 200 Hz and the data was decimated by an order of 40. The first mode of the structure is again estimated and corresponds to the frequency from the idle conditions. The peak to the left of the first natural frequency is the forced vibration of the rotor. To the right of the first natural frequency is the 3P frequency, equal to three times the 1P frequency. It should be noted that the 1P and 3P frequencies in general cover frequency bands instead of just two values due to the fact that the Vestas wind turbine is a variable speed turbine.

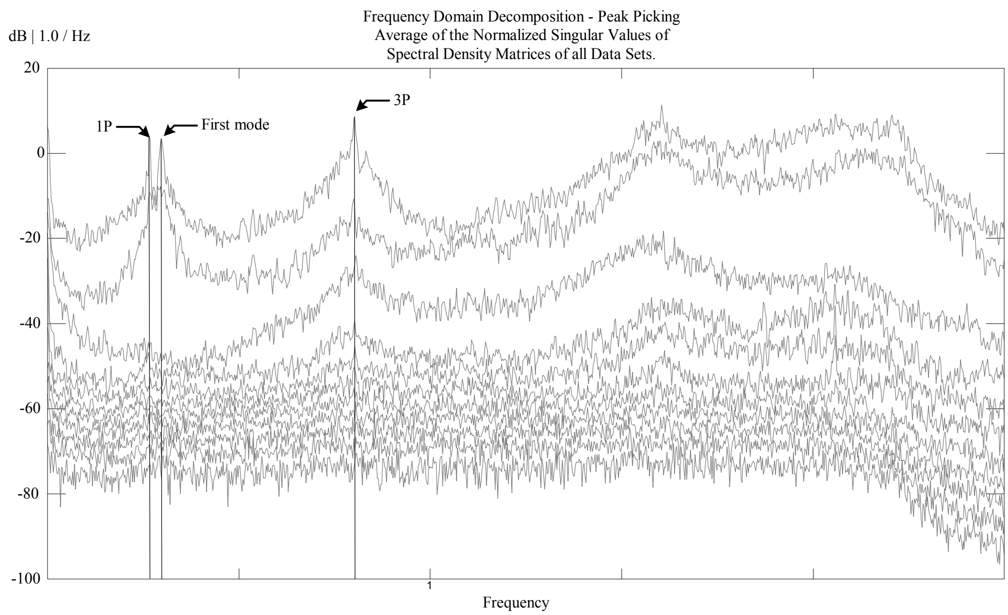

Figure 12 Frequency plot for measurement “03nov04” (operational mode).

5 Conclusion

The bucket foundation is an innovative solution that has been developed over the past 4 years and the foundation concept has been utilized for a Vestas V90-3.0 MW offshore wind turbine. The research project has proven that the novel principle of the bucket foundation is feasible in suitable soil conditions in water depth from near shore to approximately 40 meters.

The Output-only modal identification technique has been utilized for estimating the natural frequencies and mode shapes for a fully operational offshore wind turbine. The mode estimation for idle conditions is relatively simple; however there are several "sub-structural" modes of the wind turbine blades within the frequency range of the first and second natural frequency of the tower. Detailed information about the blade modes is necessary. The mode estimation for operational conditions is more complex. It is crucial to have information about all the possible "forced harmonic modes" from e.g. gears, generators, rotors and pitch systems. The analysis has shown that it is possible to locate the 1P and 3P frequency for the wind turbine in operation and compare it with the first natural frequency. Furthermore it should be noted that the structural system of an operational wind turbine is time-varying, so there are errors introduced in the system, since the framework of the modal estimation relies on the assumptions that the underlying physical system of the structure is linear and time-invariant.

The research and development work within the field of offshore foundations for wind turbines continues and present and future studies concerns the general performance of monopile-, gravitational- and bucket foundations for offshore wind turbines. The foundation concepts are to be analysed with respect to the static, dynamic (frequency dependent) and cyclic behaviour.

6 References

[1] Brincker, R. and Ibsen, L.B. "Design of New Foundation for Offshore Wind Turbines", Proceedings of The 22nd International Modal Analysis Conference (IMAC), Detroit, Michigan, 2004.

[2] ARTeMIS software, issued by Structural Vibration Solutions (SVS) ApS, Novi Science Park, Niels Jernes Vej 10, DK 9220 Aalborg East, Denmark, www.svibs.com

[3] Brincker R., Andersen P. and Zhang L. (2000), Modal Identification From Ambient Responses using Frequency Domain Decomposition, Proceedings of The 18th International Modal Analysis Conference (IMAC), San Antonio, Texas, pp.625-630,2000.

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