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Implementation of a new Foundations Concept for Offshore Wind Farms

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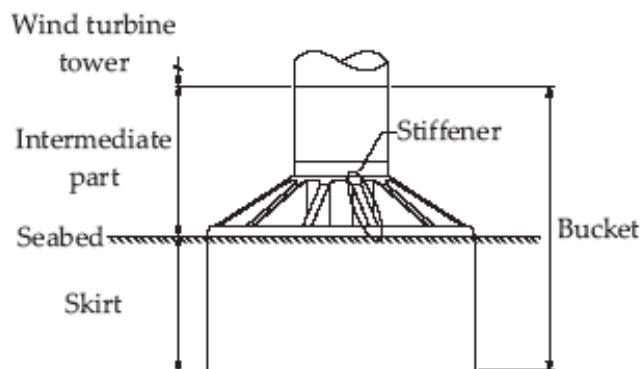
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ABSTRACT: The foundation principles for the recent major offshore wind farm projects in Europe have been dominated by two types of foundation solutions, the gravitational foundation and the monopile. A fully operational 3.0 MW offshore wind turbine was installed on a prototype of the bucket foundation at the test field in Frederikshavn in December 2002. 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. 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. In this paper the full-scale field installation of the prototype is described. A design procedure has been developed in cooperation with the certifying party in order to maintain an approval procedure in future projects. In order to develop these design procedure relevant studies involving techniques as diverse as laboratory model testing, field trials at reduced scale, and a full-scale field installation, has been performed. The nature of these tests is outlined. The main problems which has been studied, in order to reduce the uncertainties in the new design of the bucket foundation, is the in service performance. The in service performance is evaluated and compared with the design criteria's for the prototype.



Figure 1. The suction bucket location and the Vestas V90- 3.0 MW wind turbine on the premises in Frederikshavn.



(a) Definitions of the different parts



(b) The prototype in the embanked area

Figure 2 Definitions and illustration of the prototype of the bucket foundation in Frederikshavn.

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 over the past five 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 October 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, as shown in 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 project reported in this paper is related to the development of the bucket foundation.

In this paper the full-scale field installation of the prototype and its in service performance is described. The in service performance has been measured during a period of nearly three years.

2. THE PROTOTYPE IN FREDERIKSHAVN.

The bucket foundation is a welded steel structure consisting of a tubular centre column connected to a steel bucket through flange-reinforced stiffeners (intermediate part, see Figure 2). The stiffeners distribute the loads from the tubular centre column to the edge of the bucket. The wind turbine tower is connected to the tubular centre column with a flange connection. The lower part of this flange connection is welded on the tubular centre column during the production of the bucket. No transition piece is therefore needed. The wind turbine tower is connected to the flange above mean sea level.

The steel bucket consists of a vertical steel skirt extending down from a horizontal base resting on the soil surface. The prototype of the bucket foundation in Frederikshavn is shown in Figure 2.

The bucket is installed by means of suction. Lowering the pressure in the cavity between the

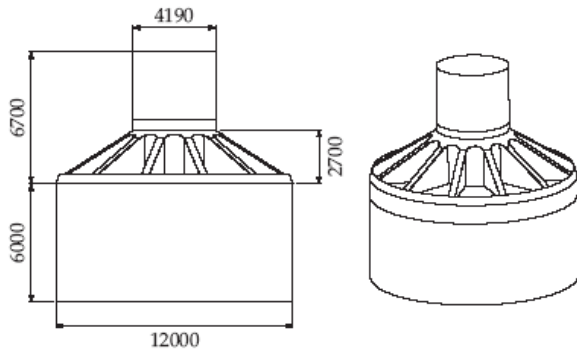


Figure 3. Dimensions of the prototype. Dimensions in mm.

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.

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.

It is important to realise that the loading regimes on offshore turbines differ in important respects from those on structures usually encountered in the offshore oil and gas industry. Firstly the structures are likely to be founded in much shallower water: 10m to 20m. Typically the structures are relatively light, with a mass of say 600t (vertical dead load 6MN), but in proportion to the vertical load the horizontal loads and overturning moments are large. For instance the horizontal load under extreme conditions may be about 60% of the vertical load, as discussed by Houlsby, Ibsen and Byrne (2005).

Table 1. Overall dimensions of steel plates used in the structure.

Part	Thickness [mm]
Skirt	25-30
Stiffeners	15-30
Tower	40-50

The dimensions of the prototype are illustrated in Figure 3. The skirt is 12m in diameter and the

height is 6m. Therefore, the bucket has been sucked 6m into the seabed. The dimension of the steel plates in the structure is shown in Table 1. The total weight of the prototype is 135 tons. It is 100 tons less than the monopile design at the same location.

3. THE TEST FIELD

The offshore research field is located next to the harbour of Frederikshavn in the northern part of Denmark, as shown by Figure 1. The test field consists of four 2-3 MW wind turbines. The three southerly turbines are located at sea, while the northerly turbine is located in a basin, see Figure 4. The basin is a test field in which a series of model tests with different foundation solutions are going to be carried out. 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 at location no.1, as shown by Figure 4. The basin has been constructed by laying an outer breakwater and divides the dike

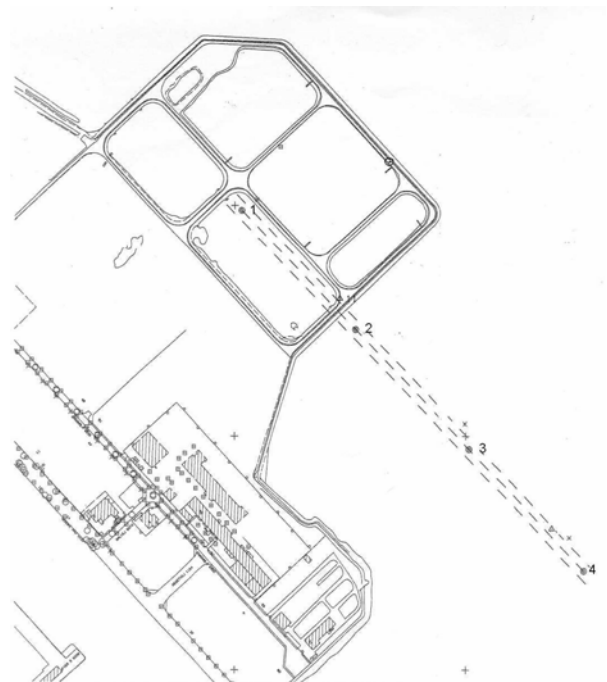


Figure 4. The offshore research field and the location of the four wind turbines.

area into five basins, as shown by Figure 4. These basins are dredged and then filled with harbour mud. Today the outer three basins are in use while the basin where the wind turbine no. 1 has been ejected consists of the natural seabed.

Figure 5 shows a sketch of the installed bucket foundation. The foundation level is N.N -4.1m. The construction state consists of the following steps.

- Excavation and preparation of the seabed to -4.4m. Preparation of the seabed by filter layer. Foundation level N.N -4.1m.
- Installation of the bucket. The bucket penetrates into the ground due to the weight of the structure and due to the fact that suction is applied to the bucket.
- Establishing of scour protection. (50cm screened gravel)
- Erection of the wind turbine.

Geotechnical investigations, in the basin, shows postglacial marine deposits to level app. -15m. Down to level -11.4m well graded to graded fine sand has been found, below this un-graded deposits of sand and silt with varying small organic content have been found. Below level app. -15m sand without organic content has been found, probably a

late glacial marine deposit. Below level -18.8 (to the bottom of the drilling) firm and very firm silt has been found, which has been estimated to be a late glacial marine deposit, but it might be older due to its firmness.

In order to be able to determine strength and deformation parameters for the postglacial marine deposits two CPT (Core Penetration Test) and a Geotechnical drilling have been carried out at the position of the wind turbine. A good agreement appears, when the results of the CPT tests are compared to the drilling profiles and the classification tests. The CPT test, see Figure 6, shows that an almost homogeneous sand deposit is found down to level -11.0. The sand has a mean grain size of $d_{50} = 0.15\text{mm}$ and a unit weight $\gamma = 19.5 \text{ kN/m}^3$ i.e. a well graded fine sand, with a uniformity coefficient $C_U=1.8$. The sand is almost pure quartz sand $d_s = 2.65$, containing shell remnants and it has no organic material, since the reducing loss on ignition $\text{rgl.} < 1\%$. The relative density has been measured to $I_D = 90 \%$ according to the A-tubes samples. In a natural deposit the sand is assumed to be very firmly deposit, i.e. $I_D = 100 \%$. Such a firm deposit will dilate during sampling and be determined looser in the laboratory than in-situ.

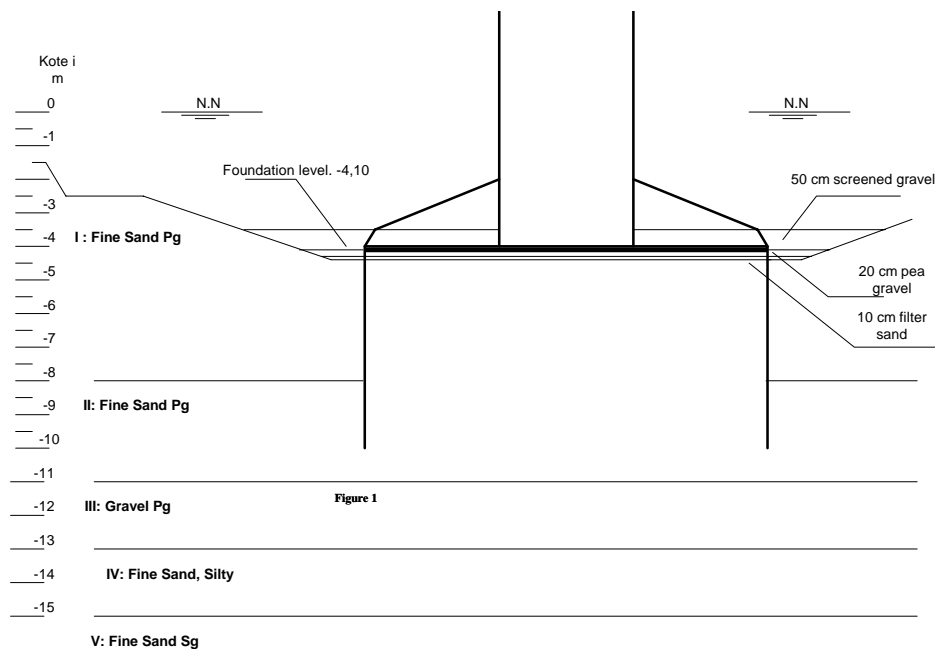


Figure 5. Sketch of the installed bucket foundation.

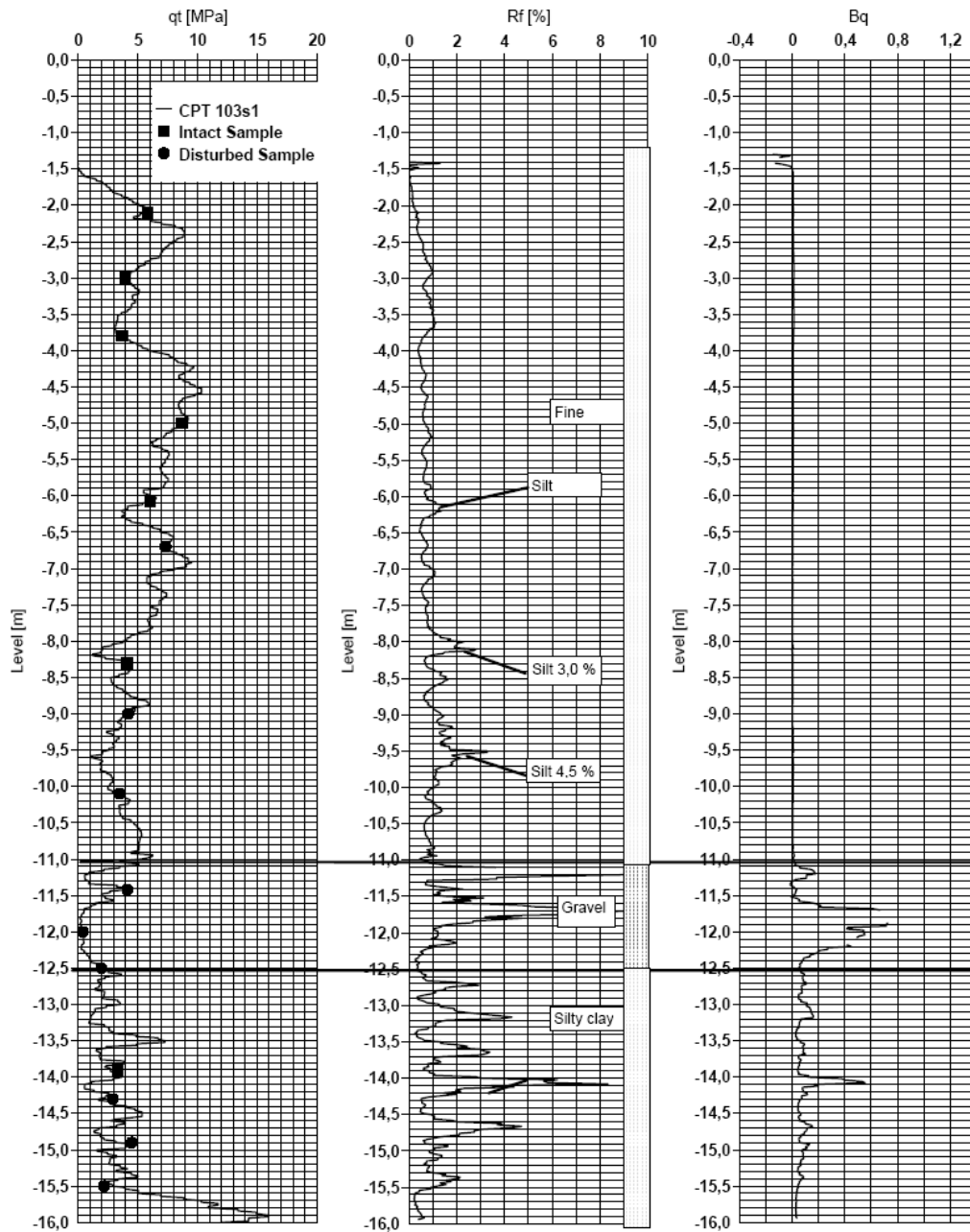


Figure 6. Geotechnical investigation and CPT test performed at the position of the bucket foundation.

The sand layer appears to be homogeneous with a tendency of being siltier below level -8 m. The silty layers are clearly seen in the CPT measurements, see Figure 6. A shell rich deposit has been found in level -2.8 m to -3.8 m, which is also clear in the CPT measurements. The CPT measurements also

show that the permeability of the sand deposit is so large that no pore pressure build up appears, pore pressure parameter $B_q = 0$, during the penetration of fine sand layer, as shown by Figure 6. This as well as the firm deposit renders, that a fatigue of strength due to variable loads is very unlikely.

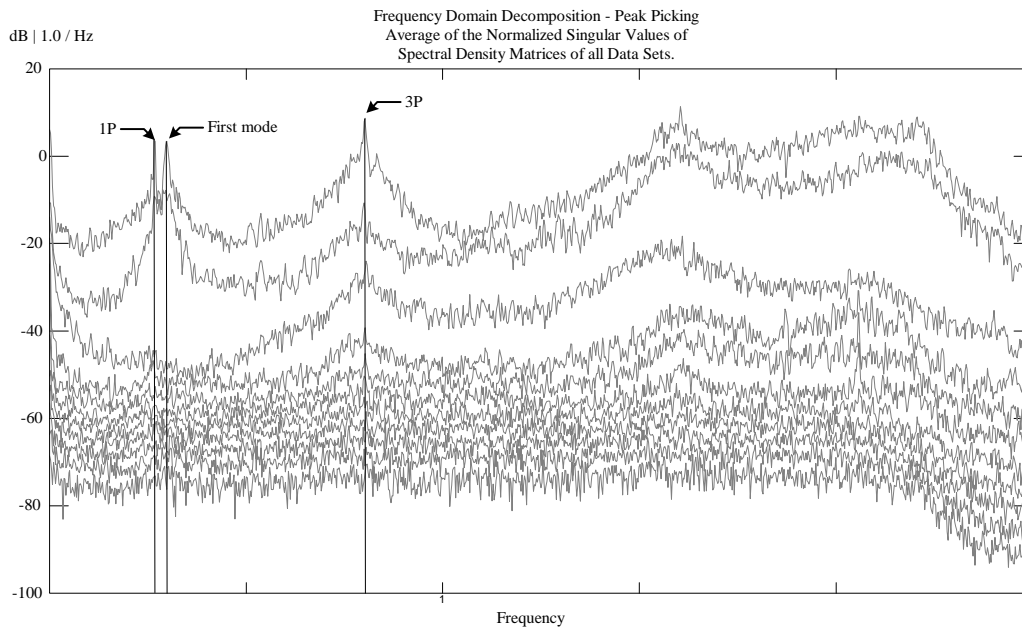


Figure 7. Frequency plot for measurement performed on a wind turbine in operational mode.

In the boring as well as in the CPT tests an un-graded deposit of gravel, sand and silt with varying small organic content (reduced loss on ignition rgl <2%) has been found at level -11.0m to -12.5m.

Below un-graded deposit of sand and silt with varying small organic content (reduced loss on ignition rgl <2%) have been found. The deposit may be characterized as silt with layers of clay. According to the A-tubes the relative density has been measured to $I_D = 90\%$.

3. DESIGN PROCESS

Realistic combinations of loads need to be considered. For instance the maximum thrust on the turbine occurs when it is generating at the maximum allowable wind speed for generation (say 25m/s). At higher wind speeds the blades will be feathered and provide much less wind resistance. It is thus unlikely that the maximum storm wave loading would occur at the same time as maximum thrust. In this project the prototype is located in an embanked area filled with water preventing wave forces to act on the structure. So no wave loads are used in the design. But the design must consider important load cases such as emergency braking. It is important to recognise that the design of a turbine foundation is not usually governed by

considerations of ultimate capacity, as discussed by Houlsby, Ibsen and Byrne (2005).

A modern offshore wind turbine, as the Vestas V90 3.0 MW, is installed with a variable speed system. The rotational speed of the rotor varies from 10-20 RPM. This means that the excitation frequency of the rotor system varies. The first excitation frequency interval then becomes 0.17 - 0.33 HZ (for 10-20 RPM) and is referred to as the 1Ω frequency interval. The second excitation frequency interval corresponds to the rotor blade frequency that depends on the number of blades. For a three-bladed wind turbine the 3Ω frequency interval is equal to 0.5 – 1.0 HZ (for 10 - 20 RPM). Since the first resonance frequency ω_1 of the modern offshore wind turbines is placed between 1Ω and 3Ω , it is of utmost importance to be able to predict the resonance frequencies of the wind turbine structure (nacelle, blades, tower, foundation and soil structure interaction) accurately.

Figure 7 shows a representative frequency plot of a selection of measured displacements for the Vestas V90 3.0 MW wind turbine and the bucket foundation, in operational mode. The measured data, monitoring system and Output-Only Modal Analysis used to establish the frequency plot are

described in Ibsen and Liingaard (2005). The first mode of the structure is 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. In order to avoid resonances in the structure at certain key excitation frequencies the structural designer needs to know the stiffness of the foundation with some confidence, this means that problems of deformation and stiffness are as important as capacity. Furthermore, much of the structural design is dictated by considerations of high cycle fatigue (up to about 10^8 cycles), and the foundation too must be designed for these conditions.

The design criteria's for the prototype bucket foundation have been:

- The first resonance frequency ω_1 for the wind turbine structure and foundation > 0.295 HZ.
- The flange (interaction point between bucket and the tower) maximum must be $\pm 0,25^\circ$ out of level after installation of the bucket.
- The permissible out of level deformations due to plastic deformations caused by dead weight, static and fatigue loads must not result in that the maximum tilt exceed $\theta = \pm 0,5^\circ$.

4. DEVELOPMENT OF THE DESIGN PROCEDURE

In order to handle the design process, a design procedure has been developed in cooperation with the certifying party in order to maintain a standard approval procedure in future projects. The design procedure for the bucket foundation can be divided into a number of parts. In Figure 9 the design procedure is illustrated schematically. As seen the design process are divided into three main bodies. Design basis, Conceptual design and Detail design.

DESIGN BASIS: As in any other design the basis for the design must be established. The design basis consists of a description of the wind turbine and the site conditions. The wind turbine manufacturer delivers the foundation loads in the form of vertical, horizontal and moments due to the wind turbine.

CONCEPTUAL DESIGN: In this phase, a “first guess” of the dimensions is made, based on simple analytical models. The dimensions of the bucket, i.e. the diameter D and the skirt length d are determined. The calculation is based on the ultimate limit state. The load acting on the bucket are typically given from a structural model, where the bucket and surrounding soil is modelled as springs reflecting torsion, rotation and displacements. The springs are initially uncoupled, based on assumption on vertical, horizontal and rocking movements. Later in the design the springs are coupled reflecting the interaction between the different responses (stiffness matrix is changed).

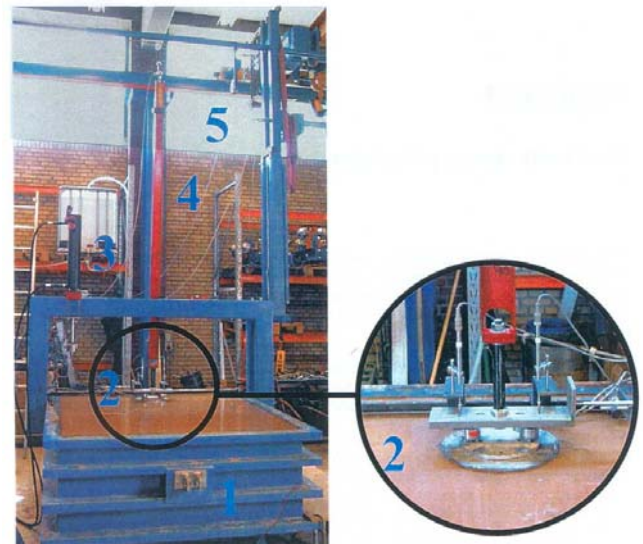


Figure 8. Experimental set-up at the soil mechanics laboratories at Aalborg University.

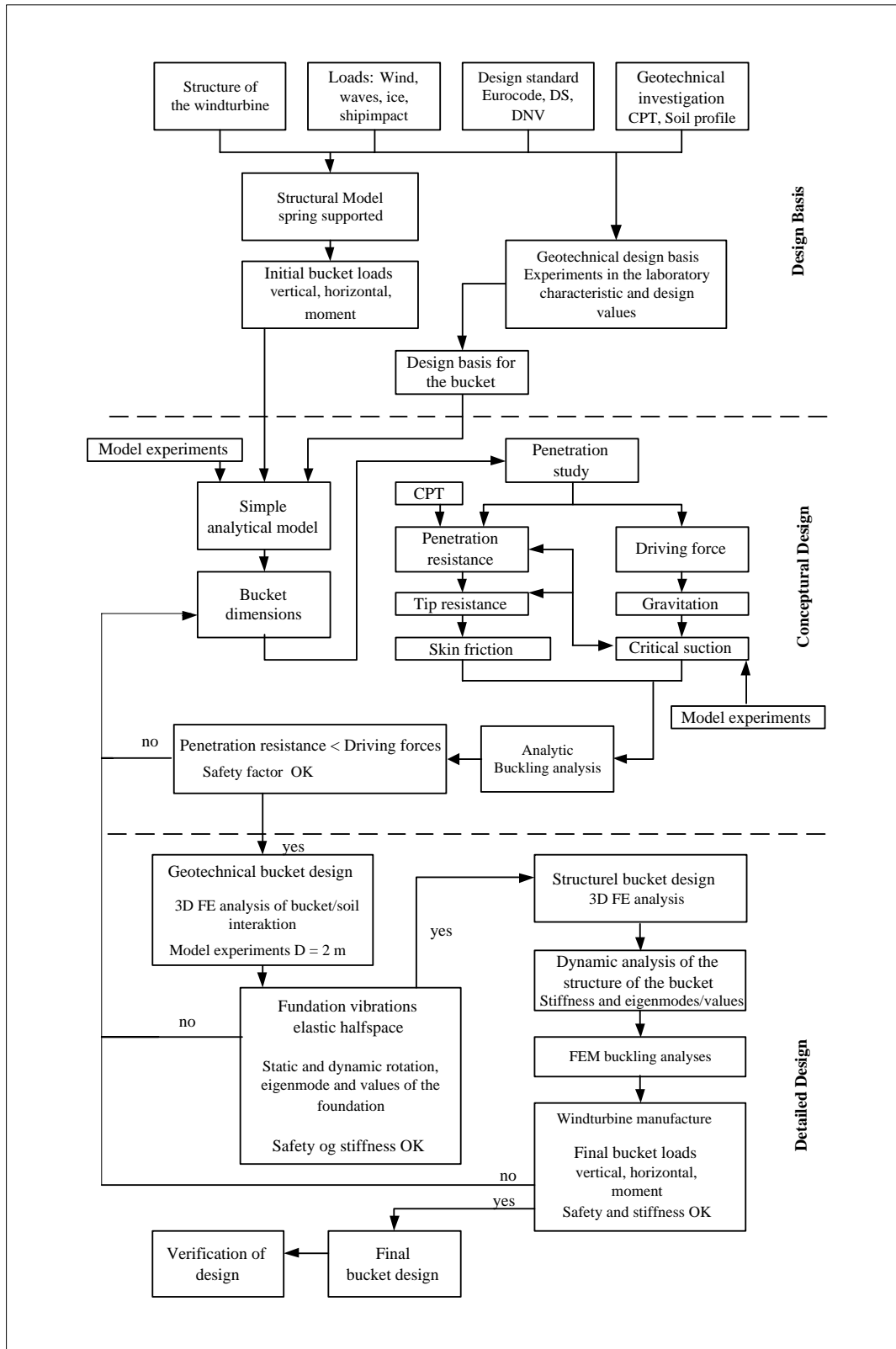


Figure 9. Design Chart for bucket foundations.

The bucket dimensions are determined based on the load combination and Limit State (ULS, SLS, ALS or FLS), which results in the largest dimensions. In case of an offshore wind turbine the design load case is normally emergency stop of the wind turbine, ice load or fatigue.

It is necessary to perform a penetrability study of the bucket to ensure that the driving force is larger than the resistance from the soil, see Figure 9. Furthermore the driving force consists of the load acting on the bucket and the applied suction; hence it is necessary to check that the critical suction is not exceeded. An analytical bearing capacity model has been developed to investigate the ultimate limit state. The calculation follows the procedure of design of a traditional embedded gravity foundation. The gravity weight of the foundation is primarily obtained from the soil volume enclosed by the bucket, yielding also an effective foundation depth at skirt tip level. The moment capacity of the foundation is obtained by traditional eccentric bearing pressure in combination with the development of resisting earth pressures over the height of the bucket skirt. Hence, the design may be carried out using a design model that combines the well-known bearing capacity formula with equally well-known earth pressure theories. The foundation is designed so that the point of rotation lies above the foundation level, i.e. in the bucket, and the bearing capacity rupture happens as a line failure, which develops below the foundation. The present design is additionally documented by numerous laboratory tests, which allows for optimisations within the framework of the above mentioned design model. The penetration investigations are done on the basis of the performed CPT.

DETAIL DESIGN: During this phase a Finite element analysis of the bucket and surrounding soil is established. The design load cases are resolved to ensure that the bearing capacity is sufficient and the

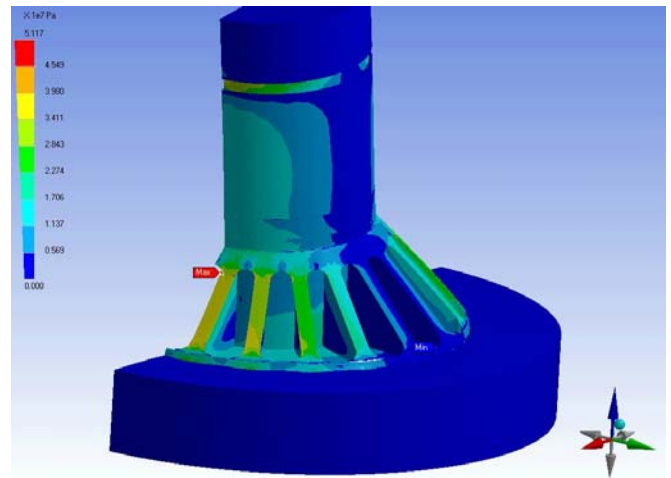


Figure 10. Finite Element model for detail design.

load-deformation performance acceptable. The Finite element analysis shall include constitutive soil models and pore pressure development (consolidation routine). In this way the serviceability limit state, (SLS) can be verified.

The interaction between the bucket and the soil has to be investigated in details and the stiffness matrix is established. During this phase changes to the design may occur. To verify the used FE – analysis model test's has been back calculated. Figure 10 shows a FE – analyse of the soil structure interaction.

Hot spot's for fatigue in the steal and in the soil have to be investigated to verify the Fatigue Limit State (FLS). The fatigue in the soil has up to now only been verified on the basis of model tests.

5. CASES FOR STUDY

In order to develop these design procedure relevant studies involving techniques as diverse as laboratory model testing, field trials at reduced scale, and a full-scale field installation, has been performed. The main problems witch has been studied in order to reduce the uncertainties in the new design of the bucket foundation are:



Figure 11. The critical suction has been achieved and soil failure by piping has occurred.

- Installation.
- Performance at static loads.
- In service performance.

Complementing these experiments are numerical studies using finite element techniques, and the development of plasticity-base models to represent the foundation behaviour.

6. INSTALLATION

In order to be able to carry out the installation of the prototype in Frederikshavn numerous test regarding the installation method, control of the inclination and control of the penetration rate have been carried out in the test field. The critical suction causing piping has been studied by installation tests on 2x2m and 4x4m buckets. Figure 11 shows a 4x4m bucket where the limiting suction has been achieved, and soil failure by piping has occurred.



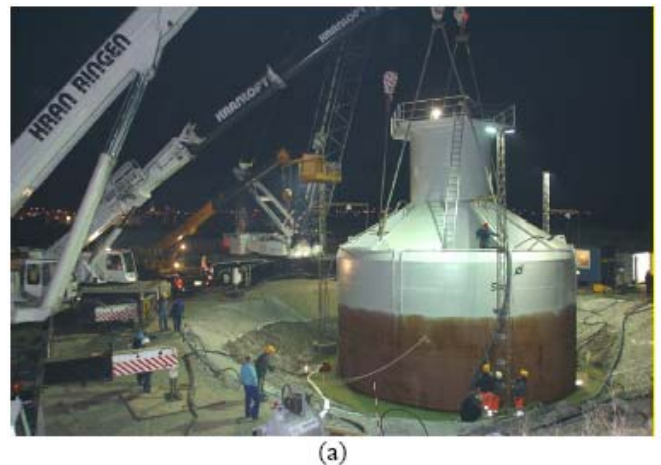
Figure 12. The 4x4m bucket successfully installed.

The soil outside the skirt is sucked into the caisson and the penetration of the bucket cannot proceed. Figure 12 shows a test where the controlled of the inclination have been perfect.

The installation of the prototype foundation at the test site in Frederikshavn is the largest completed installation in shallow water. The installation is shown by figure 13. As seen in the figure the bucket was installed in only 1m of water in the basin. The installation period was about 12 hours, with the soil penetration time being 6 hours. A computer system was used to control the inclination, suction pressure and penetration rate.

7. PERFORMANCE AT STATIC LOADS

A number of large scale tests have been devoted to studying the performance of the bucket under moment loading at relatively small vertical loads, as is relevant to the wind turbine design. The large



(a)



(b)

Figure 13. Installation of the prototype foundation at the test site in Frederikshavn: (a) during installation, (b) at the end of installation.



Figure 14. 2x2m buckle for field model test.

scale tests are complemented by laboratory studies. The laboratory and large scale tests are intended to model the prototype in Frederikshavn directly. In order to design a bucket foundation for offshore wind turbines several load combinations have to be investigated. Each load combination is represented by a height of load h above the foundation and a horizontal force H . The moment at the seabed is calculated as $M = hH$. Table 2 shows that the resulting loading height varies from 10m (for a wave force in shallow water) to 104.4m (force from normal production of a 3MW turbine in 20m of water).

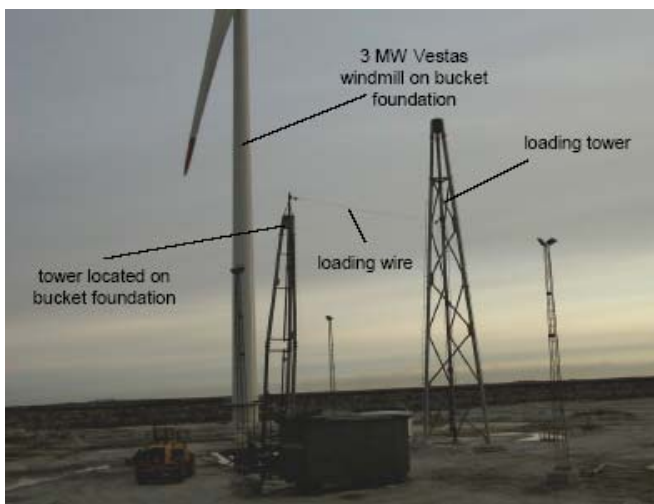


Figure 15. Setup for combined loading of 2x2m bucket at Frederikshavn. (Back: prototype 3MW Vestas wind turbine on the 12x6m caisson).

Scaling of the tests is achieved by:

$$h^m = h^p \frac{D^m}{D^p}$$

where D is the diameter of the bucket and index m and p are for model and prototype. The values of the loading height in the test program are shown in Table 2.

Table 2. Impact height in test program

Prototype	Laboratory Model			Field Model
$D^p = 12m$	$D^m = 0.2m$	$D^m = 0.3m$	$D^m = 0.4m$	$D^m = 2m$
h_{imp}^p [m]	h_{imp}^p [m]	h_{imp}^p [m]	h_{imp}^p [m]	h_{imp}^p [m]
104.4	1.74	2.61	3.48	17.40
69.6	1.16	1.74	2.32	11.60
38.0	0.63	0.95	1.27	6.33
20.0	0.33	0.50	0.67	3.33
10.0	0.17	0.25	0.33	1.67

The large scale tests at Frederikshavn employ loading by applying a horizontal load at a fixed height, under constant vertical load. A steel bucket with an outer diameter of 2m and a skirt length of 2m has been used. The skirt is made of 12mm thick steel plates. Figure 14 shows the bucket prior to installation, and Figure 15 the overall test setup. Currently 10 experiments have been conducted but the testing program is ongoing. Each test has three phases:

1. Installation phase: The caisson is installed by means of suction. CPT – tests are performed before and after installation of the caisson.
2. Loading phase: An old tower from a wind turbine is mounted on top of the caisson. The bucket is loaded by pulling the tower horizontally with a wire. The combined loading (H, M) is controlled by changing the height of loading.
3. Dismantling phase: The bucket is removed by applying overpressure inside the bucket.

The large scale tests are conducted as the laboratory model test. Figure 8 shows experimental set-up used to carry out the laboratory model test at the soil mechanics laboratories at Aalborg University.

8. IN SERVICE PERFORMANCE

The test program involving the prototype (turbine and bucket). The test program is focusing on long-time deformations, soil structure interaction, stiffness and fatigue. The prototype has been equipped with:

- an online monitoring system that measures the dynamic deformation modes of the foundation and the wind turbine,
- a monitoring system that measures the long-time deflection and rotation of the bucket,
- a monitoring system that measures the pore pressure along the inside of the skirt .

The online monitoring system that measures the modes of deformation of the foundation and the

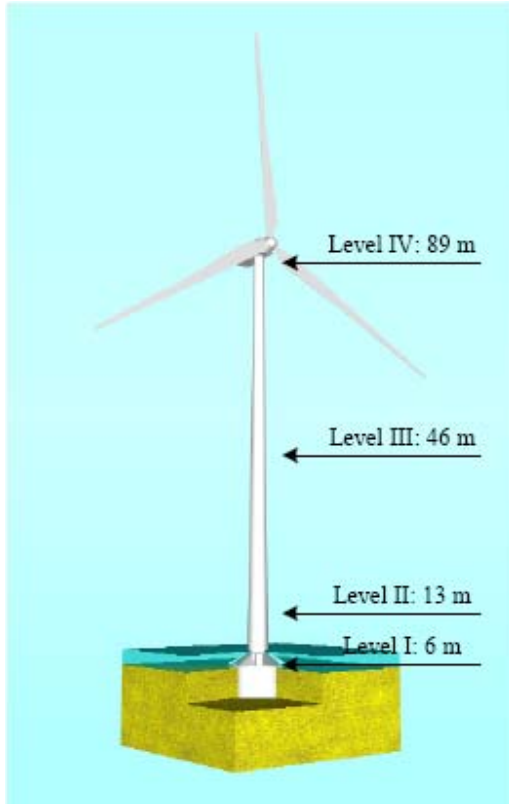


Figure 16. Sensor positions in tower and foundation.

wind turbine involves 15 accelerometers and a real-

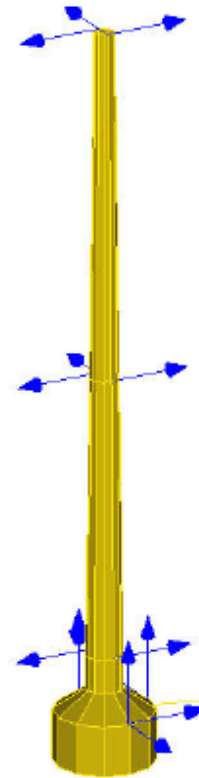


Figure 17. Location and measuring directions of the sensors mounted in the tower and foundation.

time data-acquisition system. 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 16, and the locations and measuring directions are defined by Figure 17.

A detailed description of the measuring system and the Output-only Modal analysis is given by Ibsen and Liingaard (2005).

NATURAL FREQUENCY ESTIMAT: The natural frequency of the wind turbine structure has been estimated by means of the Frequency Domain Decomposition (FDD) method. 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. In the following the estimation technique is used to

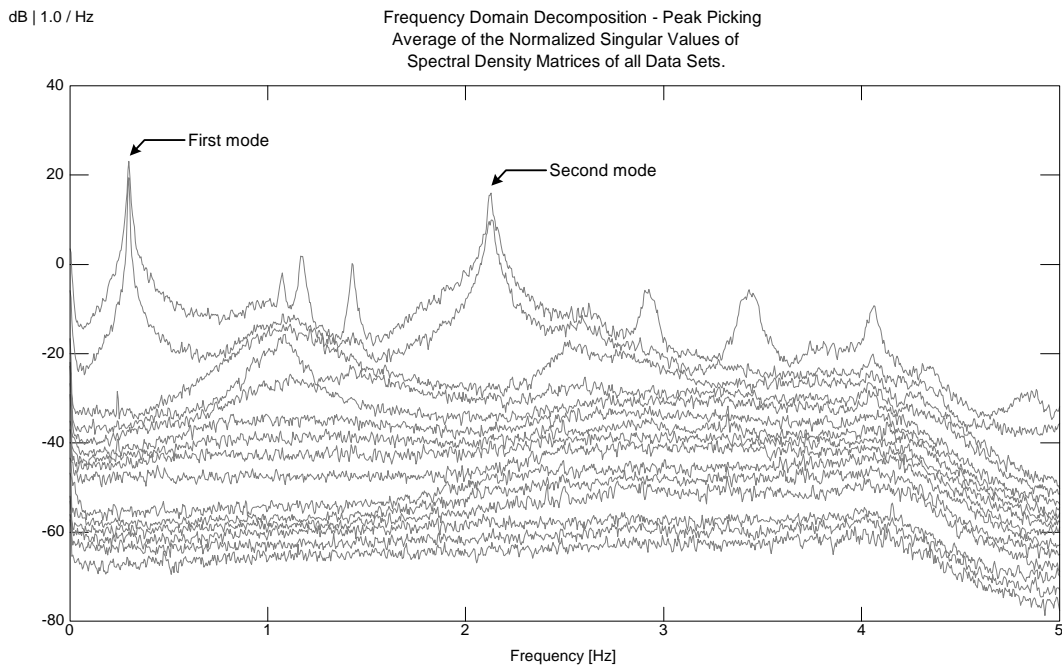


Figure 18 Frequency plot for measurement “15feb05” (idle mode).

examine the natural frequencies for three various situations. That is idle conditions, turbine without wings and turbine without wings and nacelle.

IDLE CONDITIONS: Figure 18 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 1818 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 resonance frequency is equal to 0.30 Hz and the second is 2.12 Hz.

The design criteria for the prototype was that the first resonance frequency $\omega_1 > 0.295$ HZ. The prototype is hereby shown to be designed in accordance with the specifications.

The local peaks between the first and second mode are most probably resonance frequencies for the wings.

WIND TURBINE WITHOUT WINGS: In the spring 2005 the nacelle of the wind turbine was replaced with a newer prototype version. In Figure 19 the wings have been removed prior to the replacement of the nacelle.



Figure 19. Replacement of nacelle in the spring 2005. The four wind turbine at the test field in Frederikshavn is shown. The Setup for combined loading of 2x2m bucket is also shown.

During the period where the wings were removed, several data acquisition sequences have been performed. Figure 20 shows a frequency plot for the wind turbine without wings. The measured data was recorded the March 21 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. In Figure 20 there are closely spaced modes at the selected frequencies, which again suggest two perpendicular modes at each natural frequency. The first resonance frequency is equal to 0.33 Hz and the second is 2.12 Hz. Note that the local peaks between the first and second mode have disappeared.

WIND TURBINE WITHOUT WINGS AND NACELLE: Figure 21 shows a frequency plot for the wind turbine without wings and nacelle. The measured data was recorded the May 11 2005. The data set consists of a 30 minutes measurement in 15 channels. The sampling frequency was 200 Hz and the data was decimated by an order of 20. The first and second natural frequency of the structure has changed significantly after the nacelle was removed. The first resonance frequency is equal to 0.72 Hz and the second is 2.88 Hz

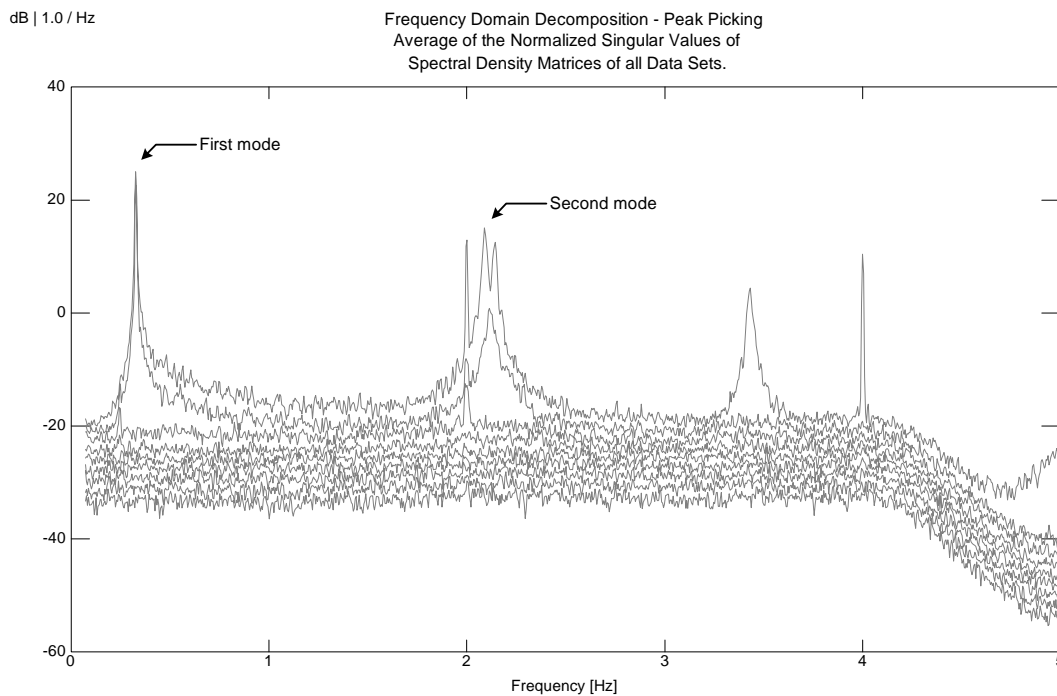


Figure 20 Frequency plot for measurement “21mar05” (without wings).

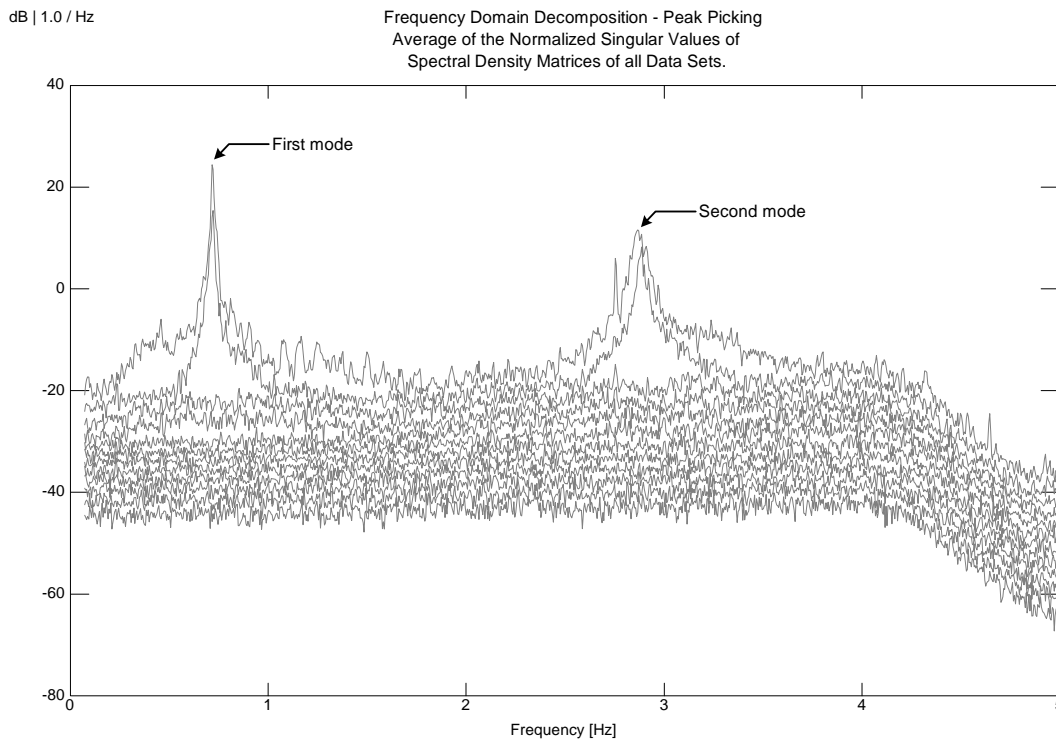


Figure 21 Frequency plot for measurement “11may05” (without wings and nacelle).

9. CONCLUSION

A fully operational 3.0 MW offshore wind turbine was installed on a prototype of the bucket foundation in Frederikshavn in October 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 this paper the full-scale field installation of the prototype and its in service performance is described. The in service performance has been measured during a period of nearly three years. And it is shown to be designed in accordance with the design specifications.

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.

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