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Design of a new foundation for Offshore Wind Turbines

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ABSTRACT. The gravitation platform and the monopile have in the previous major offshore wind turbine projects been dominating. A four-year research and development project has proven the bucket foundation to be feasible in suitable soil condition in water depth from near shore to app. 40 meters. A prototype was installed at the test field in Frederikshavn in late 2003, with a 3 MW wind turbine in normal operation. The R&D work is continued the complete the bucket concept and having the design standards for the construction and installation methodologies recognised. The design saves about half of the steel weight as compared to a traditional pile foundation, it is much easier to install and it can easily be removed when the wind turbine is taken down. However, the new design is suffering from uncertainties in the accumulated fatigue in the both the steel structure and the surrounding earth material. Therefore an on-line monitoring system has been utilized on the 80 m high operating test 3 MW wind turbine. It is explained how the system is being used to obtain mode shapes and modal parameters during different operating conditions, and how the response measurements are being used to improve the estimation of fatigue.

INTRODUCTION

In recent major offshore wind turbine projects, Middelgrunden, Blyth, Horns Rev, Samsø and Nysted, two foundation principles have be dominating, the gravitation platform and the monopile. In future project with bigger wind turbines and/or greater foundation depth tripod foundations or even jackets may be feasible. This paper describes the development of a prototype foundation of a novel principle, the bucket foundation. The bucket foundation is a new type of foundation, which has been developed over the past 3 years and today it is used for a Vestas V90-3.0 MW offshore wind turbines as a prototype. This offshore wind turbine was erected in November 2002, next to the harbour of Frederikshavn, Denmark, as shown in Figure 1. The turbine is a part of a test field concerning offshore wind turbine research consisting of four 2-3 MW offshore prototype wind turbines. In the test field a series of model tests with different foundation solutions are going to be carried out. The test field for offshore wind turbine research has been built in connection with a joint research and development program between Centre for Wind Energy Systems, Aalborg University and MBD Offshore Power. This program deals with the foundation of wind turbine in general. The test field has been constructed by laying an outer pier in the sea. The basin where the wind turbine has been erected consists of a natural

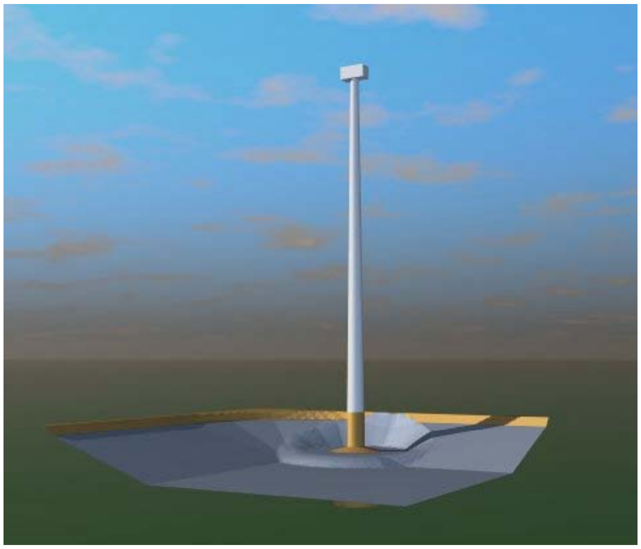


Figure 1. Vestas V90-3.0 MW offshore wind turbine on the bucket foundation in the test field in Frederikshavn Denmark.

seabed. The first project in the research program is the development of the bucket foundation. It is an innovative foundation solution with great potential and an economically/environmental sound construction for offshore wind turbines considering a life cycle analysis. The bucket foundation differs in its 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 caissons penetrate 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. 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 of them 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.

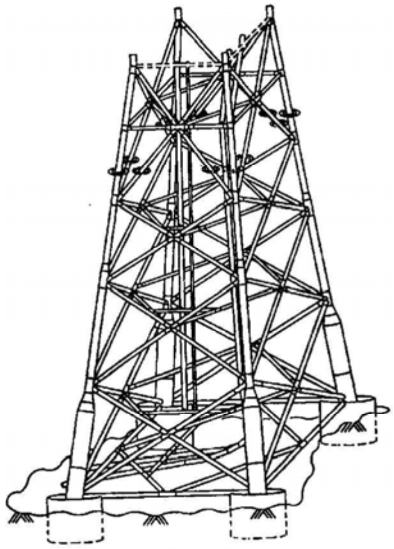


Figure 2: Suction bucket below the Norwegian jacket Draupner E

THE PROTOTYPE 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 MW turbine was erected on the foundation in December 2002.

Figure 3: Installation of the prototype in Frederikshavn by suction. a) before installation, b) after installation .

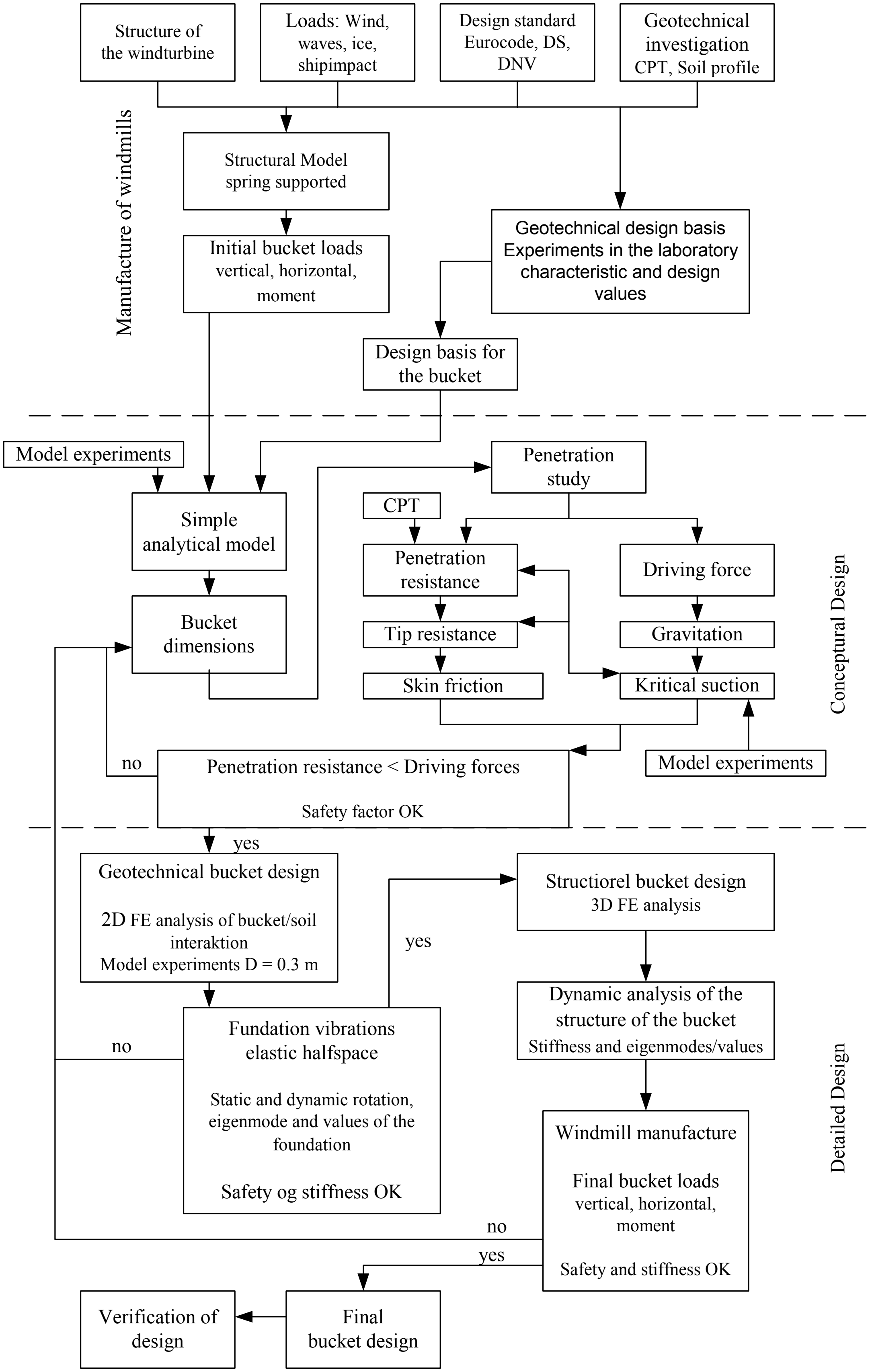


Figure 4. Design chart for bucket foundations.

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 4. the design procedure is illustrated schematically. As seen the design process are divided into tree 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). 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 4. 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 shirt 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 shirt. 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 (Core Penetration Test).

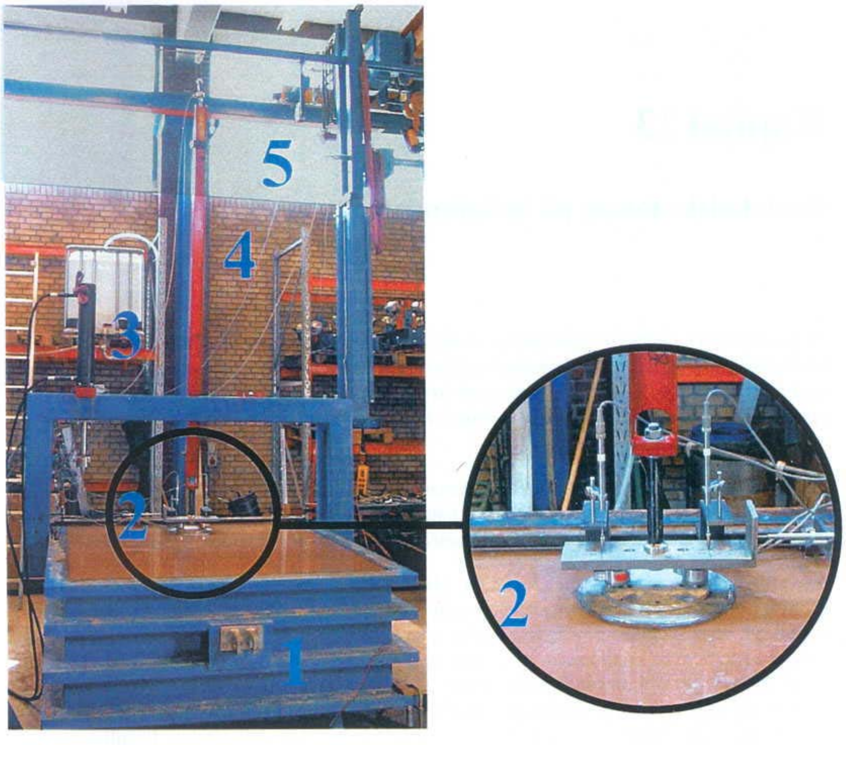


Figure 5. Experimental set-up at the soil mechanics laboratories at Aalborg University.

Figure 6. The 4x4 meter test bucket successfully installed.

The principle has been verified during a long series of model test in the laboratories of Aalborg University starting in 1999. The tests are carries on bucket from 50 mm to 400 mm with skirt length varying from 0 to the same as the diameter of the bucket. The experimental test set-up are shown in Figure 5.

Further test regarding the installation method, control of the inclination and control of the penetration rate are carried out in the test field in Frederikshavn with a 4-meter bucket, as shown by Figure 6.

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 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 interactions 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 verified the used FE – analysis the model test's has been back calculated. Figure 7 shows a FE – analyse of the soil structure interaction.

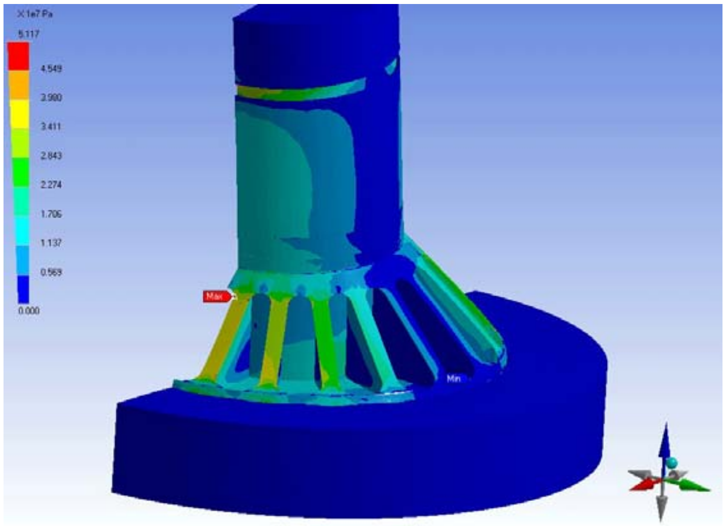


Figure 7: FE-model for detail design

Hot spot's for fatigue in the steal and in the soil have to be investigated to verified the Fatigue Limit State (FLS). The fatigue in the soil has up to now only been verified on the basis of model tests. However, the new design is suffering from uncertainties in the accumulated fatigue in the both the steel structure and the surrounding earth material. Therefore an on-line monitoring system has been utilized on the 80 m high operating test 3 MW wind turbine. Below, it is explained how the system is being used to obtain mode shapes and modal parameters during different operating conditions, and how the response measurements are being used to improve the estimation of fatigue.

FATIGUE ANALYSIS

In the present fatigue analysis problem, one of the largest problems is to estimate the stress history $\sigma(\mathbf{x},t)$ in a certain point $\mathbf{x}$ of the structure. If we know this history, then for the considered point, we can estimate the stress cycle distribution, and then for the steel part of the structure we can use the SN curve together with Miners rule to calculate the accumulated fatigue damage for a certain time span $T = t2 - t1$. For the surrounding earth material, the accumulated fatigue damage can be calculated in similar way.

In fact, what we need to do to monitor the fatigue damage of the considered structure, is to be able to keep track of the fatigue damage in N number of points $\mathbf{x}_n, n = 1,2..N$ on the steel structure and in the surrounding earth material. Also we need to have a flexible approach that allows us with no restrictions to enlarge the number of points without any restrictions to magnitude and place. This requirement totally excludes traditional measurement techniques like strain gauge and even more sophisticated measurement techniques like fibre optic gauges since they can normally only be applied on solid materials in pre-defined points. To effectively overcome this problem, an approach was followed where the measured accelerations is integrated twice to obtain displacements, and then the displacements are transferred to modal space by performing a modal decoupling based on experimentally obtained modal characteristics. When this is done, mode shapes estimated by a calibrated Finite Element Analysis can by used in stead of the experimentally obtained mode shapes, and thus, both displacements and stresses are known anywhere in the structure and in the surrounding material. The so developed procedure is described in detail in the following.

Let us assume that M acceleration degrees of freedom are measured on the structure $a_1, a_2 ... a_M$. Thus, each of these signals are measured as a function of time $a_m = a_m(t)$. The corresponding displacements $y_1, y_2 ... y_M$ can be obtained by Integrating the acceleration signals twice and removing the drift by application of a high-pass filter with a cut-off frequency typically around 1 % of the Nyquist frequency.

A natural input modal analysis can now be performed either on the directly measured accelerations or on the obtained displacements by using one of the modern powerful modal analysis tools like the Frequency Domain Decomposition (FDD) technique, Brincker et al. [1] or the Stochastic Subspace Identification technique Overschee and De Moor [2]. Both estimation techniques are available in ARTeMIS Extractor software that is used for the analysis in the present case. By doing so, the P experimentally obtained mode shapes $\boldsymbol{\varphi}_{e1}, \boldsymbol{\varphi}_{e2}, ... \boldsymbol{\varphi}_{eP}$ can be used to model the displacement response

$$(1) \qquad \mathbf{y}(t) = \boldsymbol{\varphi}_{e1} q_1(t) + \boldsymbol{\varphi}_{e2} q_2(t) + ... = \boldsymbol{\Phi}_e \mathbf{q}(t)$$

where $\mathbf{y}(t)$ a column vector containing the displacements, $q_1(t), q_2(t) ... q_P(t)$ are the modal coordinates, and $\boldsymbol{\Phi}_e$ is the experimentally obtained mode shape matrix $\boldsymbol{\Phi}_e = [\boldsymbol{\varphi}_{e1}, \boldsymbol{\varphi}_{e2}, ... \boldsymbol{\varphi}_{eP}]$. If the number of modes P is the same as the number of observation points M, i.e. if $P = M$, then the mode shape matrix is quadratic and can be inverted without any problems (it is well known that a well estimated mode shape matrix always has full rank). On the other hand, if there are more observation points than active modes, i.e. if $P < M$, then equation (1) must be solved by linear regression in which case we will get an improved estimate of the modal coordinates and a measure for the quality of the regression (for instance the variance of the prediction error). Thus as long as $P \le M$, then in a generalized sense, the modal coordinates can be obtained as

$$(2) \qquad \mathbf{q}(t) = \boldsymbol{\Phi}_e^{-1} \mathbf{y}_N(t)$$

Now let us assume that a FEM solution has given us the corresponding detailed mode shapes $\boldsymbol{\Phi}_{fem}$ such that with reasonable approximation

$$(3) \qquad \boldsymbol{\Phi}_e = \mathbf{A} \boldsymbol{\Phi}_{fem}$$

where $\mathbf{A}$ is a an observation matrix containing only ones and zeros, then the response can be calculated in any point of the structure by replacing the experimental mode shapes with the FEM mode shapes in equation (1)

$$(4) \qquad \mathbf{y}_{fem}(t) = \boldsymbol{\Phi}_{fem} \mathbf{q}(t)$$

Thus, by measuring the response in only a relatively small number of points, then after an output-only modal ID, the corresponding response in any point of the structure can be calculated. A similar relation holds for stresses, because in a linear model, if the displacements are known, so are the stresses. Thus in all the points defined by the FE model – or in the subset of points defined in the beginning

$$\boldsymbol{\sigma}(t) = \left[\sigma_1, \sigma_2 \ldots \sigma_N\right] \tag{5}$$

$$\boldsymbol{\sigma}(t) = \mathbf{C}\mathbf{q}(t) \tag{6}$$

The elements of the matrix $\mathbf{C}$ can be associated with the stress concentration factors. In this formulation they relate the amplitude of the mode shape to the hot spot stress contribution from each of the modes. The matrix $\mathbf{C}$ is estimated as a part of the Finite Element analysis.

Doing an analysis like described in this section, the engineer can perform an improved fatigue analysis by-passing all the uncertainty from loading modelling and from relating the loading with the stress history. Since a large uncertainty is removed a more accurate fatigue analysis can be performed and a better prognoses for the future damage accumulations can be performed.

MONITORING SYSTEM

The performance of the Vestas 3 MW wind turbine is monitored online by a surveillance camera. The image is shown in Figure 8. To measure the modal space the foundation and the turbine tower are equipped with a monitoring system complying of 15 Kinematrics force balance accelerometers, model FBA ES-U. The position of the accelerometers in the tower and bucket are shown in Figure 9, 10 and 11. The on-line monitoring system is seen in Figure 12.

Live web imaging unleashed.

Figure 8: Online image of the Vestas 3MW - V90 in operation.

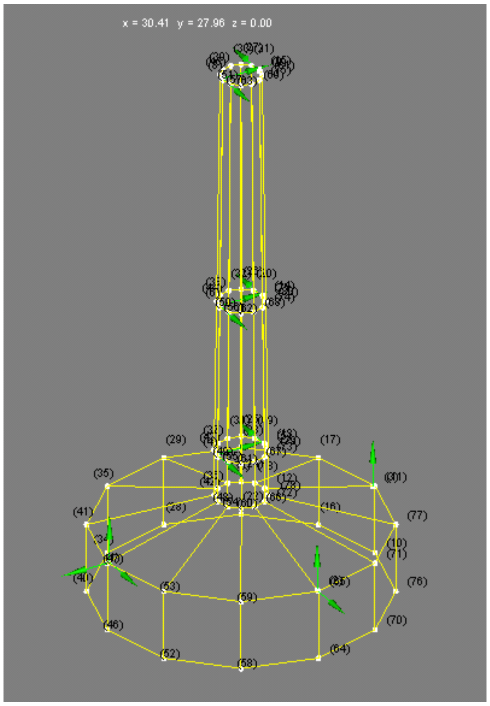
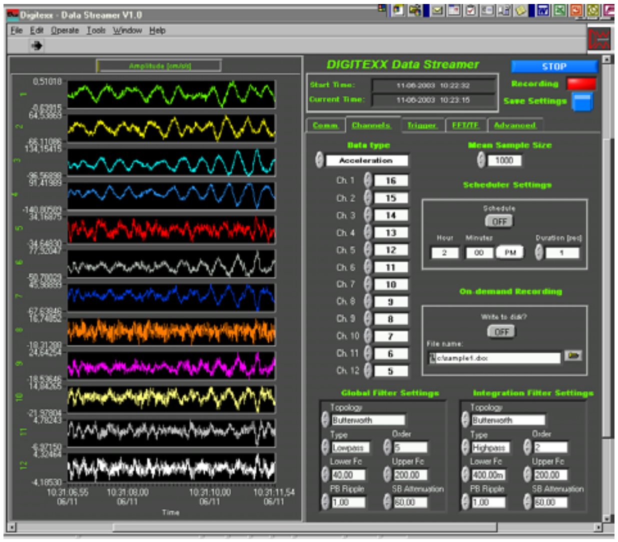


Figure 9. The position of the accelerometers in the tower and bucket foundation.

Figure 10. Accelerometer mount at the connection between the tower and the foundation.

Figure 11. Accelerometer mount in the bucket near the skirt.



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Mean Sample Size: 1000

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Ch. 2: 15
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Ch. 5: 12
Ch. 6: 11
Ch. 7: 10
Ch. 8: 9
Ch. 9: 8
Ch. 10: 7
Ch. 11: 6
Ch. 12: 5

Schedule: OFF
Hour: 2
Minutes: 00 PM
Duration [sec]: 1

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PB Ripple: 1,00
SB Attenuation: 60,00

Integration Filter Settings
Topology: Butterworth
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Upper Fc: 200,00
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SB Attenuation: 60,00

Figure 12: Online monitoring of foundation/tower structure

CONCLUTION

The research work and the development of the bucket foundation will continue during 2004 to determine the most feasible methodologies to design and install the bucket foundation of the future. The work will be carried out in the test field in Frederikshavn with a 2x2 meter bucket for load test, the 4x4 meter bucket for penetration test in various soil conditions e.g. clay and analyses on the prototype in normal operation.

The gravitation platform and the monopile have in the previous major offshore wind turbine projects been dominating. A four-year research and development project has proven the bucket foundation to be feasible in suitable soil condition in water depth from near shore to 40 meters. A prototype was installed at the test field in Frederikshavn in late 2003, with a 3 MW wind turbine in normal operation. The R&D work is continued the complete the bucket concept and having the design standards for the construction and installation methodologies recognised.

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