LOAD RESPONSE MEASUREMENTS AT THE HORN REV WIND FARM

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ABSTRACT

Building offshore wind farms in areas with severe wave climate constitutes at major engineering challenge. Being the first to design such an offshore wind farm in the North Sea, Elsam Engineering and Vestas have, as part of the design process, faced numerous uncertainties regarding design parameters, load assumptions and validity of existing models for this type of offshore structures.
To gain more knowledge regarding these uncertainties, Elsam and Vestas have started a load response measuring campaign on one of the turbines in the Horns Rev wind farm. This campaign is described in this paper.
The load response measuring campaign is fully financed by Elsam and Vestas and is intended to support internal R&D projects in the two companies. However, processed data will be used in public research projects in Denmark and the European Union and can upon request be made available for specific analysis work of other non-commercial research projects, provided that it does not compromise the interests of Vestas or Elsam.

KEY WORDS

Full scale measurements, load response, wave loads, wind loads, model calibration

I. INTRODUCTION

Horns Rev offshore wind farm is the first wind farm built as part of the Danish Government's offshore wind energy programme. It was built by the Danish utility group Elsam in 2002 and consists of 80 Vestas V80/2MW wind turbines. The wind farm is situated on a natural reef called Horns Rev in the North Sea, 14 to 20 km from the shore at the westernmost point of Denmark.

Figure 1. The Horns Rev Wind Farm seen from the air. The wind farm covers more than 20 km^2

Building offshore wind farms in areas with severe wave climate constitutes at major engineering challenge, especially when selecting steel monopile foundations, which will cause significant and design driving interaction between turbine, tower and foundation.
Being the first to design such an offshore wind farm in the North Sea, Elsam Engineering and Vestas have, as part of the design process, faced numerous uncertainties regarding design parameters, load assumptions and validity of existing models for this type of offshore structures, and at the same time the companies have been forced to find a practical solution in order not to stall the design process.

To gain more knowledge regarding these uncertainties, Elsam and Vestas have started a load response measuring campaign on one of the turbines in the Horns Rev wind farm. The turbine is equipped with measuring devices in blades, nacelle, tower and foundation, and the

data acquisition system will collect data on structural response in blades, main shaft, tower and foundation as well as simultaneous data on wave height, current, wind direction and wind speed.

II. Horns Rev Offshore Wind Farm

From a scientific point of view, the Horns Rev wind farm is very interesting for the following reasons:

- It is an offshore wind farm being exposed to low turbulence flow that has an absolute minimum disturbance from the underlying surface
- It has a very regular shape and layout that is perfectly suited for general studies
- It is fairly large, enabling studies of impacts in large wind farms
- It will be exposed to wind from all possible wind directions

The wind farm layout is a 10 times 8 matrix forming a slightly oblique rectangle. The distance between the turbines is 560 metres in both directions, corresponding to 7 rotor diameters.

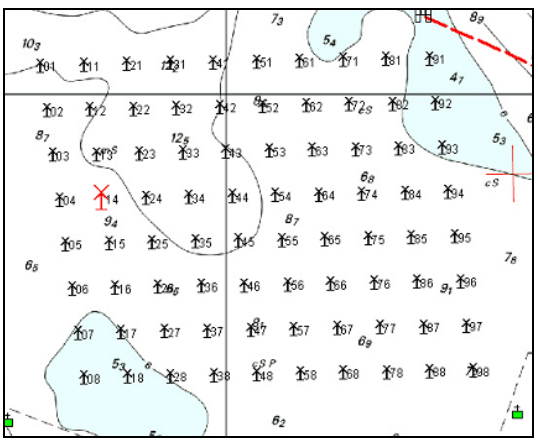

Figure 2. Wind farm layout. Instrumented turbine (14) shown in red

The turbines are numbered so that the westernmost column is numbered from 01 to 08 with 01 being the turbine in the northwest corner, and the easternmost column being numbered 91 through 98.

Referring to UTM zone ED32, the co-ordinates of the corner turbines in the rhombus are:

01: 423974, 6151447	**91: 429014, 6151447**
08: 424386, 6147543	**98: 429431, 6147543**

Table 1. Corner turbine coordinates

The wind farm is located in the North Sea, approximately 30 km west of Esbjerg. The distance to the nearest point on shore (Blåvands Huk) is approximately 13 km.

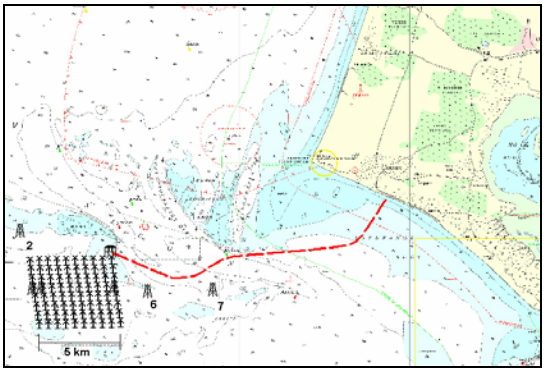

Figure 3. Wind farm, met masts and land closer than 20 km

Around the wind farm three met masts are installed.

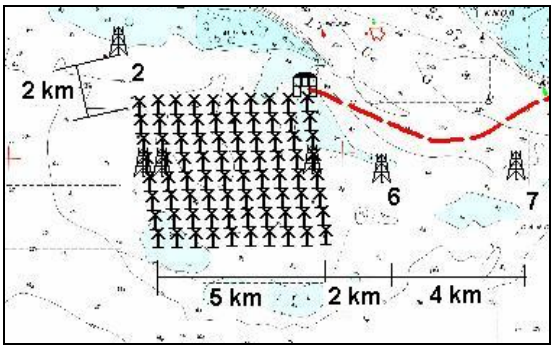

Figure 4. Wind farm distance to met masts

The oldest mast is called M2. This mast was installed before construction of the wind farm and is the one that was used to determine the wind resource at the site. Several other papers have described and analysed measurements from that mast.

In the summer of 2003 two more masts (called M6 and M7) were installed. The purpose of these masts is to study the recovery of the wake flow behind the wind farm for westerly winds, and support the development of new scientific and engineering models for calculation of external wake effects from large offshore wind farms.
Referring to UTM zone ED32, the co-ordinates of the three masts are:

Mast	X co-ordinate	Y co-ordinate
M2	423412	6153342
M6	431253	6149502
M7	435253	6149502

Table 2. Met mast coordinates

Plotting of these co-ordinates will show that M2 is located 2 km north-northwest of the northwest corner turbine (01). M6 and M7 are located 2 and 6 km east of the wind farm, respectively, on a line that passes right through the middle of the fourth and fifth rows.

The turbine selected for instrumentation is carefully selected as the one expected to give the broadest picture of the loads experienced by turbines in a large offshore wind farm. Being in the middle of the second row of turbines from the west this turbine will experience almost any wake situation one can imagine. There is a sufficiently wide opening in the front row to ensure that free inflow undisturbed by any turbine can be found. Direct wake from a single turbine at distances of 7, 10 and 16 rotor diameters is expected to be identified, and situations with wake from 3, 4 and 8 turbines directly upwind of the instrumented turbine will be seen.

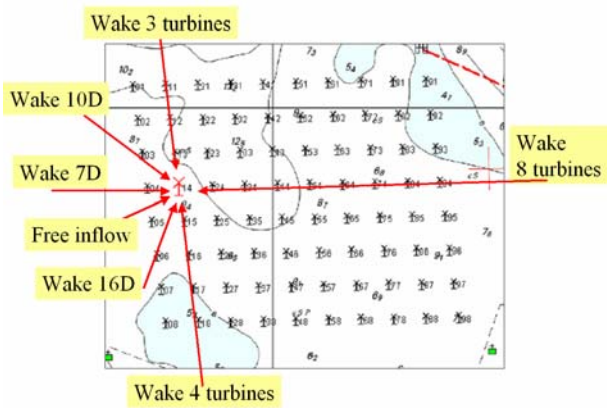

Figure 5. Possible wake situations for instrumented turbines

III. The turbines at Horns Rev

The wind turbines are all of the Vestas V80 type shown in the picture below. The picture was taken just after the construction, and at that time the turbines were not allowed to go into normal operation yet, which explains the different orientations of the nacelles.

Figure 6. Vestas V80 2 MW offshore turbines at Horns Rev

The dimensions of the turbines are shown in the sketch below.

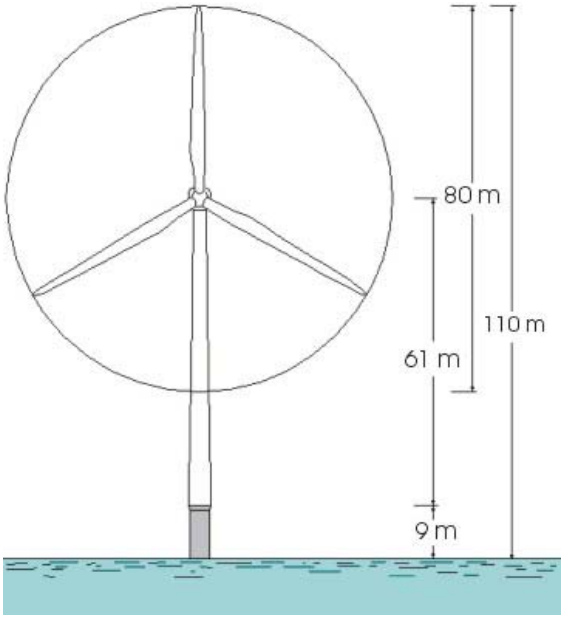

Figure 7. Turbine dimensions

At the position of the instrumented turbine, the average water depth is 8 metres, measured from mean sea level to the top of the scour protection layer around the turbine.

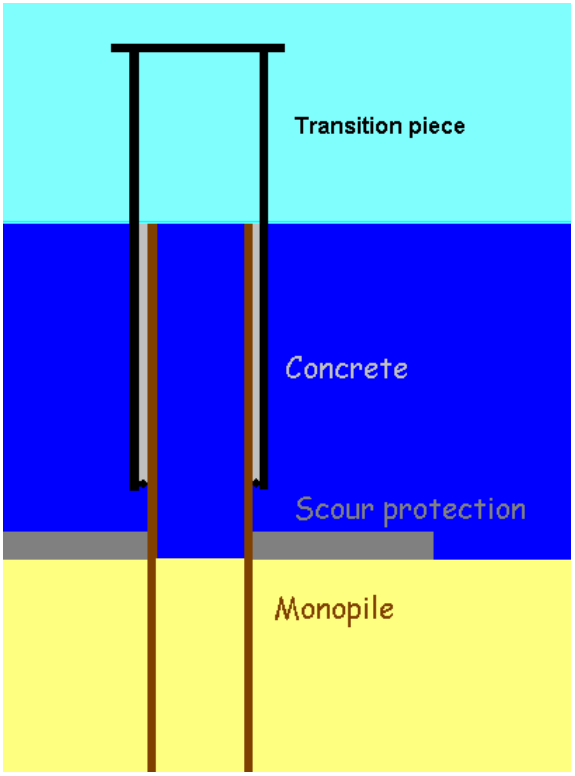

Figure 8. Sketch of monopile foundation design

The monopile structure consists of a simple pile with a diameter of 4 metres. The pile is driven into the ground.

On top of that, a transition piece is mounted. The transition piece has a slightly larger diameter than the monopile and they are grouted together using a special concrete.

The monopile extends 24 metres below the seabed.

Around the monopile a scour protection layer is installed to protect the seabed from erosion. The scour protection has a thickness of 2 metres and consists of a filter layer and an armour layer with 40 cm diameter stones.

The seabed at the site is mainly sand that tends to be hard in the upper layer but becomes gradually softer further down. At a certain depth (typically 15 metres down) the sand contains some organic material, which tends to reduce the strength of the sand significantly.

IV. Instrumentation

The instrumented turbine is equipped with strain gauges at the following positions:

- Blade root, flap and edgewise, all three blades
- Main shaft, torque and bending in two directions
- High speed shaft, torque
- Tower, bending in two directions at five different levels
- Foundation, bending in two directions at five different levels

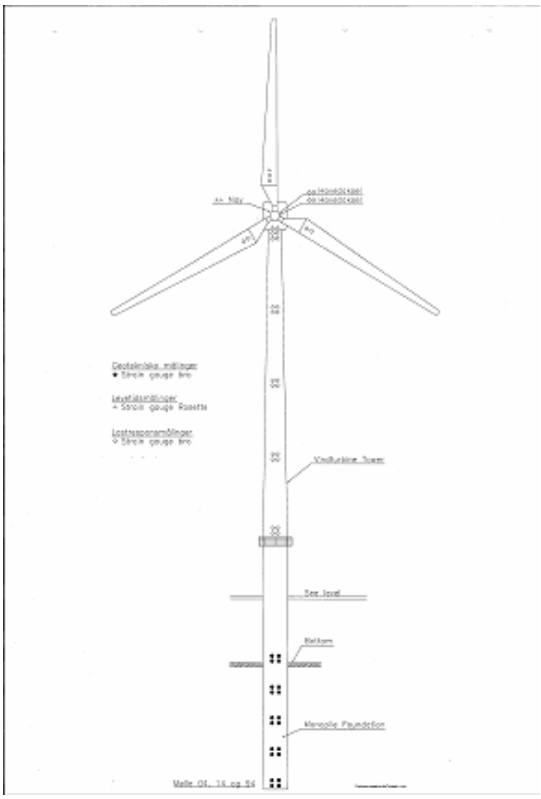

Figure 9. Sketch of sensor positions

The strain gauges in the foundation are all mounted on the monopile below the area covered by the transition piece. The highest level is located at the top of the scour protection layer, which at turbine 14 is located 8 metres below mean sea level. The four other levels are all below the seabed and are mainly installed for the purpose of investigating how the load from the turbine is transferred to the sand.

To further protect the waterproof strain gauges below seabed, a special steel cover is made, and waterproof filler is added around the gauges. Wires are hinged in springs at every measurement section to dampen accelerations during ramming of the monopile. Strain gauges are duplicated at every measurement point, as access to these is not practically possible after installation.

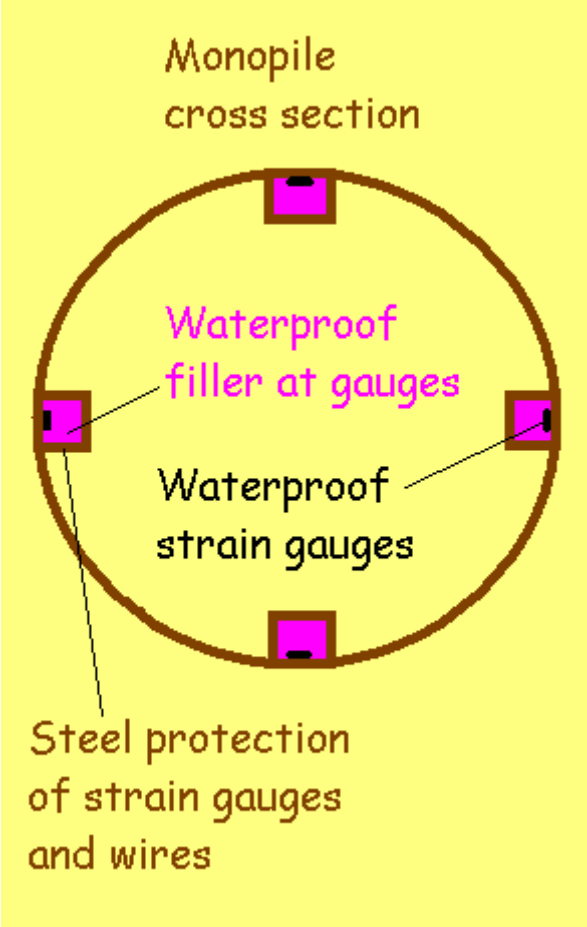

Figure 10. Sketch of strain gauge protection

This has proven to be a very efficient way of installing strain gauges. Now, three years after installation, only one of the sensors seems to be out of order.

Besides the strain gauge signals, data are collected at high frequency from the turbine controller on

- power production
- rotor speed
- blade pitch angles
- nacelle wind speed
- nacelle wind direction
- power reference

The power reference signal indicates whether the wind farm main controller is in use. This gives different loads on the turbine and needs to be sorted out for certain kinds of analyses.

V. EXTERNAL DATA COLLECTION SYSTEMS

Met masts

From the three metrological masts around the wind farm wind speed, wind direction and temperature are collected in several heights as ten-minute average statistics. This enables investigation of effects of ambient turbulence, wind gradients and stability of the boundary layer.

Wave data

Wave data are collected at two different points using two different instruments.

At a point 25 metres west-southwest of the turbine an Acoustic Doppler Current Profiler (ADCP) is positioned. This instrument provides information about instantaneous water level (wave height) at the point as well as instantaneous current speed and direction recorded every 0.5 metres from 1 metre above seabed and up. Scanning frequency of the ADCP measurements is 2 Hz.

In the middle of the wind farm a wave rider buoy is recording wave height. The wave rider provides a 20-minute time series every 30 minutes, and it is logging at a frequency of 2.56 Hz. As the wave rider data are recorded around 2 km from the turbine, they are mainly intended as a reference or backup signal for the ADCP.

Neighbouring turbines

From the eight nearest turbines surrounding the turbine, 10-minute statistics on power production, pitch angle, rotor speed, nacelle wind speed and nacelle wind direction are recorded.

VI. DATA SYNCRONIZATION AND STORING

The data flow of the measurement programme is shown in the chart below.

First the strain gauge sensors are calibrated. Then data from the slower loggers are added and synchronized to the logging frequency and period of the strain gauge logger (20 Hz). The synchronisation is performed by making a simple linear interpolation of values from the slower loggers to the logging time stamps of the strain gauge logger.

After synchronisation, derived sensors are calculated. Derived sensors are e.g. rotor tilt and rotor yaw moments calculated from main shaft bending moments and rotor position, tower and foundation bending moments aligned with the nacelle yaw direction, etc.

All time series are stored both as raw files and as processed files. This ensures that all or parts of the raw data files can be reprocessed if errors are discovered or if calibration constants are improved.

Processed files are converted to and stored as FLEX5 compressed integer format files. This file format is chosen because it has excellent data access speed, and it enables Elsam and Vestas to use their existing data processing software from the load calculation tool in the analysis of the load response data. Standard tools exist to extract and convert these files to ASCII files for processing in other software packages (like Mathlab or Excel).

10-minute statistics are calculated for all sensors in the time series files and merged with statistics from the three met. masts, the special statistics calculated by the ADCP and statistics on the operation of the 8 neighbouring turbines to form complete data files that are easy to use for various scientific analyses.

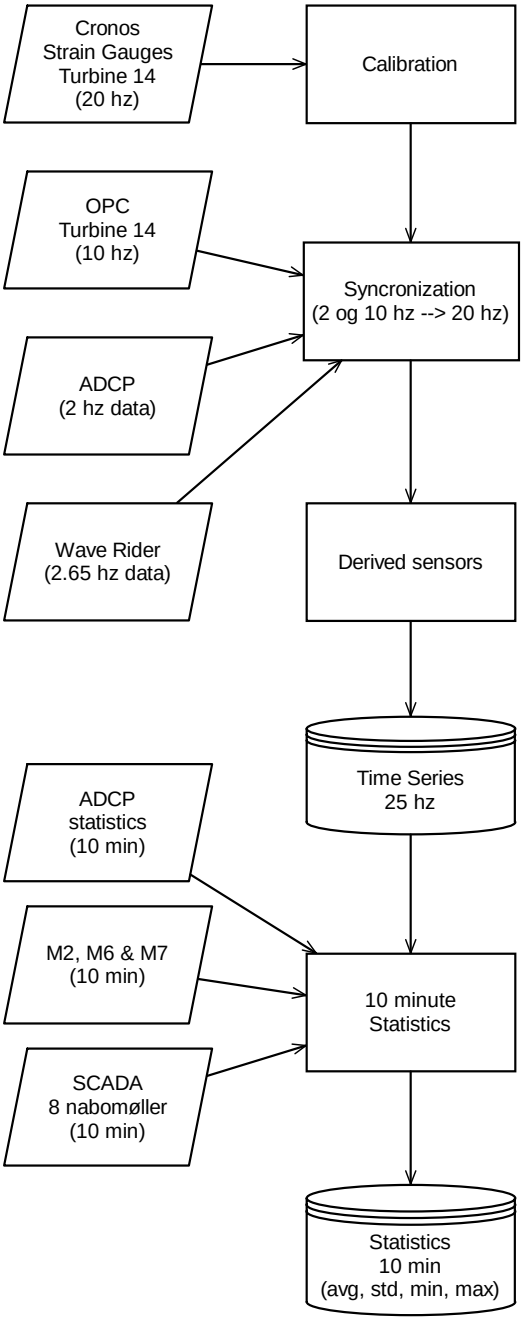

Figure 11. Measurement data flow chart

VII. Results

As the measurement program at present is just starting up, the results presented here will have to be of a very preliminary status.

Below an example of bending moment in tower and foundation is shown. As the signals are not yet calibrated, the raw measurement output has been scaled according to the local bending stiffness of the structure to produce something similar to a bending moment. The plot shows the standard deviation of this pseudo bending moment and is hence not affected by any missing zero-calibration.

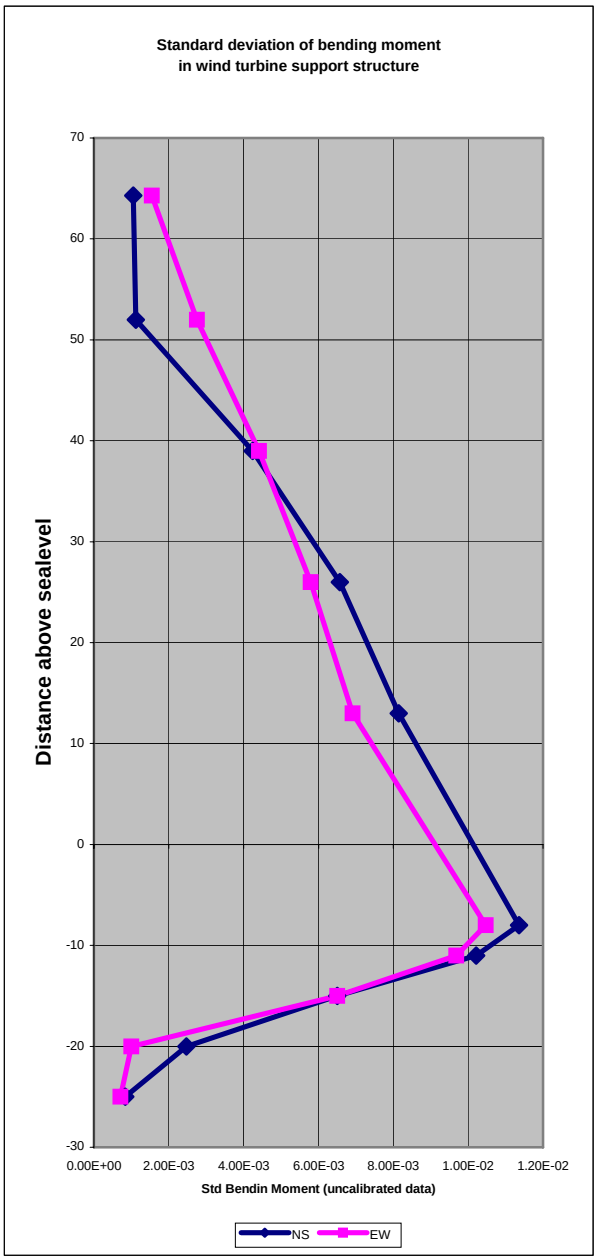

Figure 12. Distribution of bending moment in support structure

As expected, the signal shows a fairly linear increase in bending moment from tower top to sea surface with a slight increase at the seabed due to the contribution of the waves.

Below seabed the load drops due to the absorption of the load by the soil. This single observation indicates that the soil absorbs the load very well even at the top layer just below the scour protection. If this picture turns out to be representative it indicates that the load absorption of the soil around the monopole is significantly better than assumed during design.

VIII. Related R&D Projects

The present load response-measuring programme is financed with 50% by Elsam and 50% by Vestas, and is mainly intended to support the internal R&D projects in these two companies.

Besides that, however, agreements have been made with a number of public research projects to supply data for specific scientific investigations.

The primary research projects expected to use the data are:

- Design of offshore wind turbines. Collecting experience from the Danish offshore pilot projects – evaluation and conclusions regarding measurements. Headed by Risø National Laboratory and funded by the Public Service Obligations of Eltra and Elkraft.
- Soil Structure Interaction of foundations for offshore wind turbines. Headed by Aalborg University and funded by the Danish Energy Research Programme.
- UPWIND. Headed by Risø and funded by the 6th framework programme of the European Union.

Data can be provided on request for specific analysis work of other non-commercial research projects, provided the work does not compromise commercial interests of Vestas or Elsam.

Author Biography

Leo Enrico Jensen earned his Master degree in mechanical engineering in 1989 from Aalborg University, Denmark. In the period 1989-1999 he worked with wind turbine technology at Elsam Engineering. From 2000 to 2002 he worked as project manager of a large software project at LM Glasfiber A/S in Denmark. In October 2002 he returned to Elsam Engineering as responsible for development and maintenance of design and calculation software in the wind energy department.

Michael Høgedal earned his MSc and PhD in offshore engineering from Aalborg University, Denmark in 1989 and 1993, respectively. From 1993 to 1996 he worked as post-doc researcher and project manager with offshore and coastal projects primarily at LIM/UPC, Barcelona, Spain. From 1996 to 2003 he worked as port engineer, project manager and head of department in RAMBØLL. Since 2003 he has been responsible for the offshore activities in Vestas Technology (R&D).