Contributions from the Department of Meteorology and Wind Energy to the EWEC’94 conference in Thessaloniki, Greece

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Edited by Gunner C. Larsen

Risø National Laboratory, Roskilde, Denmark
January 1995
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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
Abstract  The 5th European Wind Energy Association Conference and Exhibition – EWEC’94 – was held in Thessaloniki, Greece during the period 10-14 October 1994. 461 delegates, mainly from Europe but also from other parts of the world, attended the conference. The conference contributions included 235 oral presentations and 143 posters.

The Department of Meteorology and Wind Energy contributed with 18 oral presentations and 3 posters with members of the department as authors or co-authors. The present report contains the full set of these papers, covering a wide spectrum of subjects including wind resources, reliability and load assessment, grid connection, wind-diesel systems, and marked aspects.
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Abstract  This paper will describe the state of the development of the new Irish Wind Atlas. The new atlas is made up of three parts: Observations from 14 Irish Meteorological Service stations, measurements from a CEC-funded measuring campaign from 12 stations and finally output from the KAMM meso-scale model.

1 Introduction

More than 10 years have now passed since the last of the data used in the Irish part of the CEC-funded European Wind Atlas (Troen and Petersen, 1989) were measured. This means that another 10 years from these stations can be added to improve the climatic stability and the accuracy of the old Irish Wind Atlas. On top of this a measuring campaign funded by the CEC JOULE programme has added 12 stations with approximately 2 years of data from each of the stations. This has given us a very solid basis for making an updated Irish Wind Resource Atlas.

It is well known that even with very intensive measurement networks - as the one in Ireland - some areas have very sparse coverage. To meet this problem, and to enhance the general resolution of the Atlas the KAMM meso-scale model of University of Karlsruhe has been run for the entire Irish island. The model is initialised with geostrophic wind statistics.

Ireland is a very interesting area for doing this sort of analysis, because its landscape ranges from the most gently sloping meadows to the very rugged west of Ireland. General statements about the abilities of the method can therefore be derived from this study.

This paper will describe the current status of this ongoing effort.

2 The Irish Meteorological Service data

Data from 13 synoptic stations covering most of the Republic of Ireland have been used. For the location of the stations see Figure 1. The data analysed have all been provided by the Irish Meteorological Service. The measurements have been taken every hour at all of the stations. In the present study data from 20 years have been used. This is to make the estimate as climatologically stable as possible. A drawback of using such a large time span is that the surroundings of the station might have changed during the period, resulting in corrections not optimal for the entire period. However, studying the climatological fingerprints of the stations, no trends are found, indicating eg that the area around the site is getting more and more build up.

In case of instrument failure the observers have estimated the wind speed and direction, meaning that virtually all observations for all of the period are present. The anemometers used are the Dines pressure tubes which consists of a tube with a wind vane attached. The readings are plotted on a drum mounted with a paper chart and at each observation time the observer reads the chart averaging over the last 10 min and reports the reading. The instruments are calibrated yearly by the Irish Meteorological Service. If an objective analysis of the climates constructed from these measurements were carried out the wind resource atlas shown in Figure 2 would result.

Comparing this picture to the old Irish Wind Atlas (Troen and Petersen, [2], p 40) the results are more or less the same except for the climate for Shannon Airport which in the present study has been calculated as being much lower than in the European Wind Atlas, see
Section 2.1. Comparing the northern part of the island, some discrepancies are also found. These are due to the fact that the only wind climate there is Malin Head, which compared to the European Wind Atlas has had a higher mean wind speed in the period studied. When the rest of the measuring stations have been analysed, it is expected to get a better coverage of this area. cf Figure 1.

2.1 Comparison with European Wind Atlas

If the present analysis of the synoptic stations is compared to the analysis carried out when making the European Wind Atlas the results in Table 1 are found. It can be seen that most of the stations give the same result, there are, however, a few exceptions:

- Belmullet: since the mean of the two raw time series is more or less the same, the difference between the two atlases must be found in the differences in the roughness description. In this new analysis a larger area has been taken into account, leading to the fact that more water is now present for WAP to see, leading again to a lower climatic mean.

- Claremorris: despite the fact that the two means are different (by 9 %) the two climates are equal, the reason for this can be found in the differences in the roughness analysis, where a lower roughness has been assigned in the present study.

- Cork Airport: since the new raw data time series has a higher mean, the climate found using this series also has a higher mean.

- Shannon Airport: if the two roughness descriptions are compared the explanation of the differences is found. Since the area now is quite full of trees and has been for some time, the roughness in the present study has been set to a higher value around the site, but more water has been included further away from it, resulting in a lower wind climate.

- Roches Point: has not been properly analysed, yet.

- Casement Aerodrome: has not been properly analysed, yet.

3 The measuring campaign

One of the reasons why a new version of the Irish wind atlas has to be made is that for more than two years now a number of masts have been erected in the expected high wind areas of Ireland, see Figure 1 for the location. The masts have been operated by the University College Dublin and the Electricity Supply Board and are typically equipped with wind speed and direction sensors at 10 and/or 30 metres. The masts collect...
Table 1: Comparison of the New Irish Wind Atlas with the stations in the European Wind Atlas. Column 1 is the name of the station, columns 2, 3, 5 and 6 are the result of using the .LIB-files to predict the mean wind speed (m/s) and energy density (W/m²) over a flat uniform field (roughness 0.03 m) at 10 m agl using the new Irish Wind Atlas and the European Wind Atlas, respectively. If the surroundings and the overall wind climate have not changed the two numbers should be the same (ie comparing horizontally). Also, if two stations are within the same wind climate the prediction should be equal (ie comparing vertically). Columns 4 and 7 are the mean (in m/s) of the raw data used in the two studies. Stations in parenthesis are stations for which the analysis have not been completed yet.

<table>
<thead>
<tr>
<th>Name</th>
<th>New IWA</th>
<th>EWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belmullet</td>
<td>5.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Birr</td>
<td>4.0</td>
<td>–</td>
</tr>
<tr>
<td>(Casement)</td>
<td>6.7</td>
<td>–</td>
</tr>
<tr>
<td>Claremorris</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Clones</td>
<td>5.0</td>
<td>197</td>
</tr>
<tr>
<td>Cork</td>
<td>5.8</td>
<td>5.4</td>
</tr>
<tr>
<td>Dublin</td>
<td>5.4</td>
<td>5.5</td>
</tr>
<tr>
<td>Kilkenny</td>
<td>3.9</td>
<td>5.0</td>
</tr>
<tr>
<td>Malin Head</td>
<td>6.5</td>
<td>6.2</td>
</tr>
<tr>
<td>Mullingar</td>
<td>5.0</td>
<td>5.2</td>
</tr>
<tr>
<td>(Roches Point)</td>
<td>6.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Shannon</td>
<td>4.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Valentia</td>
<td>6.1</td>
<td>6.2</td>
</tr>
</tbody>
</table>

10 min averages every hour. A more detailed description of the masts can be found in Watson [3].

4 The KAMM/WAsP-method

To create a uniform mesh of site independent climatologies (.LIB-files in WAsP) for the entire island KAMM (Karlsruhe Atmospheric Mesoscale Model) has been used. This model has been proven to work in fairly complicated terrain (Adrian and Fiedler, [1]), so it is likely that it will work under the conditions found in the island of Ireland, too. It is necessary to use a meso-scale model (as opposed to a large-scale one) to correctly simulate the different flows generated by the change from water to land and orography. Note, that the way the model is used here, is novel, since normally KAMM is used to predict the flow at a specific time. In this study, the model is used to calculate typical climatological flow patterns, forced by a geostrophic wind.

5 KAMM

The KAMM model is a nonhydrostatic mesoscale model based on the primitive equations for hydrodynamic flow, with a simplified equation for the flow in the vertical. The model has a terrain following coordinate system, and the anelastic approximation of shallow convection is used for filtering sound waves. For a more detailed description see Adrian and Fiedler [1].

6 The Method

To generate a site-independent climatology, basically two ingredients are needed:

1. a geostrophic wind climatology for the area in question.

2. a model that can calculate the effect on the flow at the surface of a particular geostrophic wind.

With these two items it is possible to link each geostrophic wind to a probability and thereby link each wind at the surface to a probability. To construct a WAsP.LIB-file is then the mere question of transforming the surface wind and its probability to different heights and roughnesses, and then calculate the Weibull $A$ and $k$ parameters.

The output from KAMM used here is a grid of winds, friction velocities and stability parameters at the two lowest model levels for a number (120) of geostrophic wind clusters. In each grid point the following is then done: The probability corresponding to the forcing geostrophic wind is assigned to the quantities at the surface. For each of the geostrophic wind cases this gives then a (sparse) distribution of the wind at the the surface. This distribution is the basis for the distributions generated in the following.
7 The input

The KAMM/WVP-method needs 3 kinds of input:

1. A geostrophic wind climatology, used to force the flow over the model domain

2. The orographic information

3. Information about the roughness

Each of these kinds of input will be dealt with in the following sections.

7.1 The geostrophic wind

The geostrophic wind statistics are obtained from a database of geostrophic winds obtained from the analysis of the initial fields for a numerical model. The resolution is 1.5° resulting in a 9 x 13 grid over the island of Ireland. The resulting geostrophic wind roses are shown in Figure 3. It can be seen from this figure that the wind roses are very homogeneous, making it possible to use only one rose in the cluster analysis. In this first study we have used wind data from 1992 to 1993, i.e. two years.

7.2 Cluster analysis

To economise on the number of runs with the model a cluster analysis has been carried out. A cluster analysis takes the geostrophic data and identifies clusters of data, i.e. areas (in the u-v space) with a high occurrence of geostrophic wind vectors. The result of the cluster analysis is shown in Figure 4. A more sophisticated cluster analysis would also include atmospheric stability, since this could be a very important parameter in some parts of the world.

7.3 The orography

The orography is generated from a 1:625,000 scale map (Ordnance Survey, 1972) with height contours with a 300 ft (91 m) resolution. The map has been digitised and a grid (5 x 5 km²) has then been calculated from this map using the "Inverse Distance" method. It was necessary to edit some of the points in the grid to avoid obvious errors such as negative heights over the water and so on. The map is shown in Figure 5.

One of the parameters to be estimated in this study is the proper resolution of the orography. It is clear that using too high a resolution (i.e. grid points close to each other) will make the scale of what KAMM models overlap the scale of the orographic effects that WAP models. If, on the other hand, the resolution is too low (i.e. grid points further away from each other) all the phenomenon on the meso-scale will not be seen, and the reason for using a meso-scale model will be lost.

Figure 3: The wind rose of the geostrophic winds (actually the 700 hPa wind) used in the KAMM/WVP-method.

Figure 4: The 120 clusters identified by the cluster analysis of the geostrophic wind data.
7.4 The roughness

The roughness has been generated using the coastline of Ireland, a mesh of $5 \times 5 \text{ km}^2$ has been overlayed on this; a point inside the coastline is set to have a roughness of 10 cm, which is an estimate of the overall roughness of Ireland and a point outside is set to $10^{-4} \text{ m (water)}$. When data from the CORINE land-use database will become available (later this year) it is planned to use this as the basis of the roughness evaluation.

7.5 A first map

A first preliminary run of the KAMM model has been carried out. The input is as described in the previous sections. The result is shown in Figure 6. From this figure it can be seen that KAMM is indeed able to model the flow around the Irish island. Some features can be seen from the figure:

1. Because of the homogeneous roughness the island stands out as one entity. By including a more correct roughness description the minimum in the middle of the island is expected to appear.

2. Lee from the larger groups of mountains can also be seen (most of the dark areas on the island). This results because of the prevailing westerly wind.

3. The expected high winds over the water as compared to the land are also found.

8 A second map

The map shown in Figure 7 has been generated by running KAMM with a slightly different set-up. Instead of using a $5 \times 5 \text{ km}^2$ grid a $20 \times 20 \text{ km}^2$ grid has been generated. The way this is done is by taking a square of 16 ($4 \times 4$) heights from the 5 km grid, finding the maximum and using this value as the new value for the height in the central point. This procedure generates a "envelope" of the orography, making the model less sensitive to small height variations not significant to the mesoscale. This method has also been used in models for the general circulation. The roughness is just a thinned version of the 5 km roughness. Some new features appear in the map: instead of showing a reduction on the leeward side of the mountains, the wind is this time slowed down on the windward side.

9 The new Irish Wind Atlas

The new Irish wind atlas will be published at the end of the year in connection with the report to the European Commission. The atlas will consist of pages describing the stations similar to the ones in the original European Wind Atlas. There will, however, be some added information: firstly, a map of the surrounding area of

Figure 5: The orography used as input to KAMM. Resolution 5 km. Initial resolution of contours 300 ft (91 m).

Figure 6: The first results of running the KAMM model in a climatological mode. Resolution between gridpoints $5 \times 5 \text{ km}^2$ in calculations and $5 \times 25 \text{ km}^2$ in the plot.

Risø-R-797
the station will be included, this will enable the user to
evaluate more easily whether the wind climate from the
station in question will resemble the climate searched
for. Secondly, a table with the monthly means will be
included, this is to make it possible to make a first very
simple correlation with any on-site data. Note, that if
a full measure-correlate-predict analysis is to be carried
out, the original data from the station in question must
of course be used.

The stations in the atlas will be all the synoptic sta-
tions (13) plus the new measuring stations (12). Fur-
thermore, a number of the KAMM generated .LIB-files
will also be included, in such a way that no point on
the island will be further away than a certain maximum
distance (eg 5-20 km).

Since the analysis of all the stations has not been com-
pleted yet, and furthermore, since the KAMM model
has not be run with the full orographic and roughness
descriptions, it does not make sense, yet, to draw a new
wind atlas for the island of Ireland. This map will be
included in the final version of the Irish wind atlas.

10 Further Work

The work presented in this paper is of a very prelimi-
nary nature, so before the final version of the new Irish
wind atlas is ready a number of things must be done.
Firstly, we must continue the search for the best resol-
uition of the orography, so as to avoid overlappong of scales
between KAMM and WAP. Secondly, the information
from the CORINE land use data base must be har-
nessed, to get a better and more objective description
of the roughness. Thirdly, the cluster analysis should be
rerun with the 10 years of geostrophic winds. Finally,
the possibility of including stations from Northern Ire-
l and will be looked into.

11 Summary

In this paper we have presented the present state of the
development of the Irish Wind Atlas. The Atlas is made
up of three components:

1. Measurements from synoptic stations, 13 in all.

2. Measurements from masts specifically aiming at
measuring the wind resource, 12 in all.

3. Model output from a meso-scale model, KAMM.

The final results in the form of a publication are ex-
pected at the end of the year.

Acknowledgements

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programme (contract JOUR-0067).

References

[1] Adrian G. and F. Fiedler. 1991: Simulation of
Unstationary Wind and Temperature Fields over
Complex Terrain and Comparison with Observa-


elling in the Republic of Ireland. Proceedings from
the European Wind Energy Association Conference
and Exhibition. Thessaloniki, Greece.

We would like to thank Dr Gerhard Adrian, who has
performed the cluster analysis of the geostrophic wind
data and run the KAMM model on the University of
Karlsruhe vector computer. Also, we would like to thank
the Irish Meteorological Service, especially Mr Dennis
Fitzgerald, for making the observations available to us.
Helpful discussions with Mr Liam Burke and Mr Peter
Barry from the Irish Meteorological Service are also ac-
knowledged. Finally, we would like to thank the Istituto
di Fisica dell' Atmospfera in Italy for providing us with
the geostrophic wind data.
Figure 7: A second result of running the KAMM model in a climatological mode. Resolution between gridpoints $20 \times 20$ km$^2$ in calculations and in the plot. The orography is the envelope of the 5 km one.
1. INTRODUCTION

We have seen increasing planning and environmental problems with the siting of wind turbines on land, and consequently it may be necessary to place wind turbines offshore in the future. The cost of offshore windfarm installations is higher than for their land-based counterparts, but the wind resource is also higher at sea. Reliable tools are available for the estimation of the wind resource for open sea conditions, but the most likely sites for offshore windfarms are in near-coastal areas, where the wind resource is diminished by the influence of the nearby rougher land surface. More knowledge of the wind climate of the coastal region is needed such that we can identify optimum sites and establish a reliable basis for economical evaluations of the feasibility of proposed offshore windfarms.

The general characteristics of the offshore wind climate is somewhat different from the onshore situation. The rather small values for surface roughnesses encountered at sea are responsible for higher windspeeds and reduced turbulence intensities. There are a number of interesting problems associated with this environment:

- The surface roughness of the sea is quite well known for open ocean conditions, but in the near-shore situation we would expect somewhat different (higher) values because of changed wave structure with breaking and refracting waves near the coast.

- The lower turbulence levels should consume less of the fatigue life of the turbines, but the wakes from upstream turbines will disperse more slowly and maintain larger velocity gradients than for the corresponding situation in a conventional windfarm. Are these effects significant?

- How far away from the coast should the windfarm be placed such that wind from land has accelerated to a value sufficiently close to its equilibrium open sea value.

- Atmospheric stability effects on the windprofiles are different from the land situation, how does this affect the windresource?

In the following we will concentrate on the first two problems, surface roughness and turbulence, and touch briefly on third problem. The last question has been dealt with in detail recently by Barthelmie et al (1994).

2. SURFACE ROUGHNESS

Over land, the surface roughness can usually be assumed to have a constant value (as long as the vegetation does not change) with values varying from 0.01m to 0.1m for the types of terrain of interest for wind energy purposes.

At sea the situation is much more complicated. The roughness is very small at low windspeeds but increases then rapidly with increasing windspeed. A very simple description of this behavior was derived by Charnock (1954) and is still in widespread use:

\[ z_0 = A \frac{u^2}{g} \]  

where \( z_0 \) is the surface roughness, \( u_\ast \) the surface friction velocity, \( g \) acceleration of gravity and \( A \) a constant.

\[ U = \frac{u_\ast \ln \frac{z}{z_0}}{k} \]  

where \( z \) is the height over ground and \( k \) the von Karmann constant.
Using the logarithmic wind profile (eq. 2) to eliminate \( u_0 \), we obtain

\[
\frac{z_0}{\ln \frac{z}{z_0}} = \frac{A k^2 u^2}{\ln \frac{z}{z_0}}
\]

From this implicit equation for \( z_0 \) it is obvious that the roughness varies more rapidly than windspeed squared.

Normally accepted values for the "constant" \( A \) are 0.011 for open ocean and a somewhat higher value 0.018 for near coastal conditions. These values then result in a variation of roughness length over three orders of magnitude for a normal range of windspeed variations: Roughness lengths \( 10^{-5} \) - 0.01 m (4-25 m/s).

3. TURBULENCE INTENSITIES

The turbulent intensity, defined as the ratio of standard deviations of windspeed fluctuations to the average windspeed, typically for averaging times of 10-30 minutes, can be written as a function of the surface roughness only, for neutral conditions assuming that windspeed standard deviations vary proportionally to \( u_0 \) (the constant of proportionality happens be about 2.5 cancelling out the von Karmann constant which is 0.4):

\[
I = \frac{\sigma_u}{U} = \frac{\sigma_u}{u_0} \frac{k}{\ln \left( \frac{z}{z_0} \right)} = \frac{1}{\ln \left( \frac{z}{z_0} \right)}
\]

4. MEASUREMENTS

We have looked at measurements from three sites:

1) Nibe, a north-south running coastline with shallow fjord to the west with 5-20 km fetch over water. Data were selected from the 56m tower in a 90° West sector, and a 90° East sector with a slight offset from straight east to get free of boom distortion. 12 years of 10 minute average values (four each hour) were used.

2) Vindeby, the offshore wind turbine site, with two 48m offshore towers at varying distances from the shoreline, and one 48m tower just on the shoreline. Neutral data were selected from a 90° sector to the west of the tower situated west of the windfarm. The site and instrumentation was described in Barthelmie et al (1994). Upstream fetch was 10-20km over water depths of 5-20m. We had about one year of 30 minute averages.

3) For comparison, the Nørrekær Enge II, a coastal windfarm site with two masts inside the farm, one close to the shore and the other one on the far side of the windfarm. The measurements were reported in Højstrup et al (1993).

4.1. Turbulence intensities

Figs. 1 and 2 show the average turbulence intensities for neutral conditions as a function of windspeed, and we see large constant values over land (except for low windspeeds) and values increasing significantly with windspeed for over water fetch, increasing to almost over land values for very high windspeeds. A quite similar situation is seen from the Vindeby SeaMastWest, with increasing turbulence intensities with increasing windspeeds.

Fig. 4 shows the overall picture where a simple linear expression was fitted to all data from the different sites, it is quite obvious that Vindeby and Nibe are very similar with very low intensities, Nibe data fell between the Vindeby land mast and the two offshore masts. At the Nørrekær Enge windfarm we see much higher values caused by a mixture of terrain and windfarm effects. A roughness of a few centimeters would create turbulence similar to that found at Nørrekær Enge, roughness lengths of one millimeter would create turbulence like that found at Nibe and Vindeby (as an average over all data).

4.2. Roughness lengths

Roughness lengths can now be calculated using either the definition given in equation 2 or by using the assumptions resulting in eq. 4. The results are shown in figs. 5 and 6.

We can see that the results for over water fetch are very similar for Nibe and Vindeby with values larger than those resulting from eq. 1 at high windspeeds (both methods) and values lower than Charnock at low speeds for the profile method and larger than Charnock for the turbulence method.
There are less assumptions involved in the profile method, and this method is probably most accurate, but poses also grave requirements for accurately calibrated velocity sensors at several levels, undisturbed by local terrain features. The turbulence method seems to give reasonable results at high windspeeds where the roughness attains larger values. Also in fig. 5 is shown results for over land fetch where both methods agree nicely. The lower turbulence levels over water seem to be much more sensitive to the more frequent occurrence of instationary situations at low windspeeds causing large velocity standard deviations.

4.3. Flow acceleration

In fig. 7 is shown a set of plots taken from Højstrup et al (1994) where the flow direction is offshore for the Vindeby site, such that the two offshore masts see different fetches, about 1.5km and 2km. The measurements are averages over eight 30 minute runs. We see the flow accelerating, and the turbulence levels decreasing as it moves out over the water surface.

REFERENCES


Figure 4 Linear fits to all data from: the three Vindeby masts (38m), the two Nørrekær Enge masts (31m) and the Nibe mast (45m). Also shown are turb.int. for $z_0 = 0.03$ m and 0.0001 m.

Figure 5 Nibe Roughness lengths derived from profiles and turb.int. compared with Harnock model.

Figure 6 Roughness lengths from the Vindeby West mast derived from profiles and turb. int. compared with the Charnock model.
Figure 7 Profiles of averages and standard deviations of windspeeds. Plots on the left were measured (average of eight 30 min. runs), model results on the right.
EXPERIMENTAL STUDY OF FLOW MODIFICATION IN A COASTAL MEDITERRANEAN AREA: APPLICATION OF A MESOSCALE MODEL.

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- Osservatorio Astronomico di Cagliari, Italy.

INTRODUCTION

Under the EEC project "Wind Atlas for Europe" (1981-1988) a model to simulate regional and local surface wind statistics based on conventional weather observations, orography and topography information has been developed, Troen et al. (1). The Wind Atlas method and model have been shown to yield reliable results in the North and North-Western regions of Europe. In those regions, due to the presence of moderate or strong winds, the quasi-neutral conditions and the same surface geostrophic wind over all the considered area, assumed by the model, appear to be reasonably fulfilled. For coastal regions, such as in the Mediterranean area, the local weather is strongly influenced by local circulations due to diurnal heating cycle and modification of synoptic flow by blocking and channelling. For this reason, a previous climatological study has been carried out by using eight years of upper air wind data from the multivariate analysis of the European Centre for Medium-range Weather Forecasts (ECMWF) of Reading (UK), Lavagnini and Sempreviva (2). The analysis has shown:
- a strong decoupling between surface and upper level wind over the Po valley and the regions at the foot of high mountain ranges;
- a minor but well enhanced difference between surface and upper-air data at the coastal regions where, close to the surface, sea breeze phenomena take place.

The results of the mentioned analysis could be used in first approximation as a tool for selecting areas where the conditions assumed by the EEC model are better satisfied.

In this paper we study the climatology of flow regimes in a typical Mediterranean coastal area to give a contribution for the design of a model more suitable to such regions. Furthermore the mesoscale model of the Department of Meteorology of the University of Uppsala has been applied to investigate the possibility of using prognostic models in wind climatology as an alternative tool for selecting suitable areas for the application of WAsP. Results of the simulations for episodic cases which can be used to provide the information required for wind resource assessment are shown and discussed.

EXPERIMENTAL SET-UP

Part of a data set (December 89 - July 91) from the SARDEX (Sardinia Experiment) in Italy has been analysed. Two areas of different topographical complexity were selected in western Sardinia (Figure 1) from the Astronomic Observatory of Cagliari. The first area with two stations included the island of S. Antioco (Figure 2a) between the mountainous island of S. Pietro and the Sardinian coast. Due to the orographic situation this stations are subject to a channelling effect. The second area was around the Oristano gulf (Figure 2b). A fairly flat area extends down to 15 km from the coast then the terrain rise rapidly up to a height of 700-800 m. The three stations of Tabentis, Pira Inferta and Monte Arci were located here orthogonally to the coast at respectively 1.5, 11 and 25 kilometres from the coast line. The first two on the plain and the last one on a plateau at 700 m. In Table 1 geographical characteristics of the stations are given.

The data-set for each station consists of one minute averages of wind speed and direction at 15 m (sampling every second), ten minutes averages of air temperature and global radiation (sampling every minute). The measurements have been controlled and organized into a database consisting of Julian day, time, wind speed and direction every 10' (6 pairs of values), hourly values of temperature, radiation and standard deviation of wind speed. About 75% of the data were considered to be valid.

Radiosoundings from the synoptic station of Cagliari belonging to the Italian Meteorological Service and located at the South coast were used to initialize the mesoscale model.

THE EEC WAsP MODEL

The EEC model for estimating ground-level wind climatology, contains a hierarchy of sub-models to correct the effects due to orography, surface roughness, obstacles and stability conditions around a considered station. The utility package is called WAsP. For details see Troen et al. (3). The model is able to calculate the wind climatology of a site by using the regional geostrophic wind climatology. WAsP is used to calculate a regional geostrophic wind distribution by correcting a known wind distribution within the region from local effects and extrapolates it to geostrophic height. The geostrophic wind distribution can then be used to estimate the wind climatology of a site of interest by extrapolating down at the ground and introducing the local effects around the location. The model output provides the scale (k), form (k) Weibull distribution function parameters for each of the twelve sectors of 30 degrees. The Weibull function being defined as

\[ f(u) = (k/A)_u \exp(-(u/A)^k) \]  

(1)
ANALYSIS OF STABILITY

Since one of the basic constraints of the EEC WASP model is that a region should have the same atmospheric stability, we have tried to characterize each site. The correct method to calculate the stability parameters is based on the use of the variances and co-variances of the of velocity components, temperature and humidity (4). Other methods have been devised based on the profiles of wind speed and temperature (4), (5). However, alternative empirical methods have been developed for other purposes - e.g. to initialize Gaussian models of atmospheric dispersion. These methods are based on the concept of stability class, (6) and use more readily available parameters such as solar radiation, wind speed and cloudiness, standard deviations of the lateral (v) and vertical (w) components of the wind speed. In our case, due to the lack of turbulence profiles data, two different methods were chosen, one for daytime and one for night-time.

For daytime, Smith’s method (7) which uses solar radiation and wind speed has been used. For nighttime, we used lowered Irving’s method (8). Sammetti (9) adopted by the EPA (10), which uses average wind speed and lateral intensity of turbulence, Details can be found in Sempreviva et al. (11). In Figure 1, the results from the stability analysis the frequency of each stability class are shown for each station. As expected high frequencies of neutrality (class D), induced by strong winds, are observed at M. Arci (46%) and at the two stations on the island of S. Antioco subjected to orographic channelling effects. The lowest frequency of neutrality is found at Pira Inferta, which is also the station with the most frequent conditions of stability (F) and strong instability (A), we guess due to the foot-hill position.

If we focus on the stations located in the second area, we notice that Pira Inferta and Monte Arci show opposite stability conditions while Tabentis is in between the two.

STATISTICAL ANALYSIS AND APPLICATION OF THE WASP MODEL

By using the WASP utilities package the experimental parameters A and k of the Weibull function were calculated for each sector as well as the respective frequencies for all the stations in Tab. 1. Comparison with the model has been restricted to the three stations facing the Gulf of Oristano, whose topography represents a typical situation of an coast sites.

Figures 4 a and b compare respectively the mean wind and frequency for each sector for the stations number 1 and 2, located in the first area. Figure 4a shows generally higher mean wind values for Spiaggia Grande respect to Masona, except at 10° where the latter lies over Calasetta and at 30° where Masona face part of the island of S. Pietro. The greatest difference between the two sites is for winds from 180°. In this sector the wind arrive at Masona after crossing the whole of the island of S. Antioco and at Spiaggia Grande after only a few kilometres of coast. Figure 4b shows a clear different frequency distribution for the two stations despite the short distance between them. This difference is clearly due to the different path that the wind flow follows before arriving to the two stations, coinciding only when the wind blows from the open sea (240° and 270°).

Figure 5 a and b show the same analysis for the stations within the second area. While there is no orographic forcing when the wind comes from the sea, Figure 5a) wind coming from the land is very strong in the mountains and weak over the plain facing the sea. Figure 4b shows the same frequencies for winds from the sea sectors but very different frequencies for the other sectors, with a rotation of the frequency peak at 30° for Tabentis, 90° for Pira Inferta and 150° for M. Arci. If we focus on this area, we shall now see how the model is able to reproduce the statistics of one site on the basis of another one.

Figures 6a and b compares respectively the experimental scale factors of Inferta and M. Arci with those simulated by using the experimental wind distribution from Tabentis. The simulation for Pira Inferta, (Figure 6a), gives satisfactory results whereas simulation for M. Arci (Figure 6b) shows that the model is not giving reliable results in predicting the orographic forcing when the wind comes from the land and overestimates such forcing for wind from the sea.

Figures 7 a and b compares respectively the experimental frequencies of Inferta and M. Arci with those simulated by using the experimental wind distribution from Tabentis. It is evident that the model cannot simulate the real wind distribution. Let us now focus on the ability of the model in reproducing the mean wind speed averaged over all the sectors: in Tab.2 the intercomparison between the three stations is shown. The number in the diagonal indicates the station predicting itself, the vertical is the station to be predicted and on the horizontal is the predictor station. Tabentis and Monte Arci predict each other quite well, the same Tabentis and Pira Inferta. The model instead does not give reliable results when using Pira Inferta to simulate Monte Arci and viceversa. By considering the stability analysis performed in the previous section, we could explained this with the opposite stability conditions that can be found in the two locations.

Since the area in which the simulations were carried out is affected by sea breezes for long periods of the year, it was considered worthwhile to investigate peculiarities of the wind flow in the area.

FLOW FIELD CHARACTERISTICS

We now focus on the raw data trying to understand the feature of the air flow when the wind comes from the sea sector. We have calculated the percentage variation of direction (Dir), wind speed (V) and temperature (T) between Tabentis and Pira Inferta, considering the former as reference station by using the following formula:

$$
dx(\theta) = \frac{(X_{-TBN} - X_{-INF})100}{X_{-TBN}} \frac{250}{\text{DIR}_{-TBN}} 290^\circ$$

where $X = T, V, \text{Dir}$

for $250^\circ < \text{DIR}_{-TBN} < 290^\circ$
In Figure 8 a, b, c and d we have plotted the daily evolution of the percentage variation of the wind direction respectively for Winter, Autumn, Summer and Spring. In Figures 9 a, b, c and d and 10 a, b, c, d the daily evolution of temperature and wind speed percentage variations are shown as well. In all the figures we notice a daily trend according to the length of the daytime. This can be observed by comparing the period for Winter and Summer (Figures 8a, 9a, 10a).

Before sunset and after sunrise the two stations present different values while during the daytime the two stations agree better. The agreement during daytime could be explained by the fully developed sea breeze regime while in the early morning and in the late afternoon the site of Pira Inferta, at the mountains foot undergoes local effects (i.e. mountain-valley breeze). Further evidence of different wind regimes is obtained by plotting the values of the directions at Pira Inferta versus the ones at Tabentis. Figure 11 a shows the plot for all the data, while Figure 10 b shows as the previous figure but with the filter of wind speed higher than 4 m/s. Comparing figures 11 a and 11 b we notice that the two stations show the same wind direction only in cases of strong winds while there are two preference directions for winds coming from sea sectors. If we compare the figures relatives to wind direction and temperature we notice that the trend is similar. This means clearly that, in such a region, besides the sea-land temperature difference, large horizontal surface temperature difference is the reason of the different flow regimes between the two stations.

By looking at the percentage difference in wind speed (Figure 10 a, b, c and d) we notice a minor daily variation respect to direction and temperature. Wind speed is generally higher in Tabentis than in Pira Inferta, due to the inland position of the latter.

WIND MODELLING

The model

We have applied the model of the Department of Atmospheric Physics of the University of Uppsala in Sweden (MIUU).

The main characteristics of the model are:

- Primitive equations of motion with hydrostatic approximation,
- Diagnostic equation for potential temperature,
- Diagnostic equation of pressure by Exner function,
- Terrain following coordinate system and
- Level 2.5 model for turbulence closure.

Further details can be found in Enger (18). The purpose was not to validate the model against data but to apply the model to some real situations and see whether the model can give reliable picture of some experimental evidences.

In Figures 12 and 13 results of simulation are shown for 10 am when the sea breeze starts to develop and at 1.00 p.m. where the sea breeze system is totally developed. The simulation is compared with the experimental results presented in the previous section showing that wind directions between Tabentis and Pira Inferta, located at five kilometres from each other, are different before sunrise and been the same during the daytime. Comparing Figure 12 with Figure 13 we can notice that the sea breeze front moves inland and the horizontal depth depends on the direction and strength of the geostrophic wind.

CONCLUSIONS

In this paper we have considered data series of wind and temperature from five stations located at the West coast of Sardinia. We have estimated stability conditions frequency and wind distributions and found that sites located within an area of few kilometres of radius can have different characteristics. Furthermore we have noticed that on the contrary of north European regions, in such a typical Mediterranean area horizontal variation of temperature can be very strong and become the most important parameter to explain the mentioned differences. We have focused on one of the areas and applied the DEC model WASP to simulate the wind distributions within it. The model does not give reliable results. From the experimental results, we guess that this is mainly due to the two constraints on which WASP is based namely same surface geostrophic climatology and same stability within the considered region of application.

Starting from this argument we could try to identify areas that can fulfill WASP conditions and apply the model within the area. This could be achieved by using prognostic mesoscale models and good surface and upper-air databases.

REFERENCES

3. Troen I., E.L. Petersen, N.G. Mortensen, 1988: WASP - Wind data analysis and application programs. RISOE National Laboratory-DK.


12 Enger L., 1986: A higher order closure model applied to dispersion in a convective PBL. Atmos. Environ. 20, 879-894.

<table>
<thead>
<tr>
<th>Station</th>
<th>Alt. Dist. fr. sea (m)</th>
<th>Latit.</th>
<th>Long.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Spiaggia grande (SPG)</td>
<td>10</td>
<td>39°05'20&quot;N</td>
<td>8°23'37&quot;E</td>
</tr>
<tr>
<td>2 Massone (MNSW)</td>
<td>50</td>
<td>39°05'10&quot;N</td>
<td>8°23'37&quot;E</td>
</tr>
<tr>
<td>3 Tabentis (TNB)</td>
<td>5</td>
<td>39°50'30&quot;N</td>
<td>8°34'43&quot;E</td>
</tr>
<tr>
<td>4 Pira Inferta (INF)</td>
<td>10</td>
<td>39°49'30&quot;N</td>
<td>8°41'08&quot;E</td>
</tr>
<tr>
<td>5 Monte Azzai (ARC)</td>
<td>700</td>
<td>39°47'30&quot;N</td>
<td>8°44'38&quot;E</td>
</tr>
</tbody>
</table>

Table 1: Geographical characteristics of the stations.

<table>
<thead>
<tr>
<th>TBN</th>
<th>INF</th>
<th>ARC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBN</td>
<td>3.9</td>
<td>3.8</td>
</tr>
<tr>
<td>INF</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>ARC</td>
<td>4.9</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 2: Comparison between experimental and simulated mean wind speed over all the sectors.

Figure 1. Sardinia.

Figure 1. Frequency of the stability classes for each station.
Comparison among experimental and modelled wind distribution

Figure 6. (a) Comparison between the experimental scale factors of Inferta with those simulated by using the experimental wind distribution from Tabentis (A_Infera_Tabentis). (b) Comparison between the experimental scale factors of Monte Arci with those simulated by using the experimental wind distribution from Tabentis (A_Arci_Tabentis).

Comparison of the mean wind for each sector

Figure 7. (a) Comparison between the experimental frequencies of Inferta with those simulated by using the experimental wind distribution from Tabentis (f_Infera_Tabentis). (b) Comparison between the experimental frequencies of Monte Arci with those simulated by using the experimental wind distribution from Tabentis (f_Arci_Tabentis).

Comparison of the A factor for each sector

Figure 4. (a) Comparison of the mean wind for each sector for the stations number 1 and 2, located in the first area. (b) The same as 4a but for the frequency.

Comparison between the experimental frequencies for each sector

Figure 5. (a) and (b) show the same analysis as in Figure 4a, b but for the stations 3, 4, and 5 located within the second area.
Figure 8. Seasonal analysis of the daily evolution of the percentage difference between the wind direction at Tabentis and Pira Inferta calculated by Eq. 2. Winds at Tabentis should come from the sea. Winter (a), Spring (b), Summer (c) and Fall (d).

Figure 9. As in Fig. 8 but for the Temperature.
Comparison of wind direction at TBN and SMM

Comparison of wind direction at TBN and SMM

Comparison of wind direction at TBN and SMM

Comparison of wind direction at TBN and SMM

Figure 11. (a) Wind directions measured at Tabencis (TBN) versus the wind directions at Fira Inferta (SMM). (b) The same as in Fig. 11 but with v > 4 m/s.

Figure 10. As in Fig. 8 and 9 but for the wind speed.
Figure 12. Horizontal wind field simulated by the model at 10.00 am.

Figure 13. Horizontal wind field simulated by the model at 1.00 pm the same day as Fig.13.
IMPLEMENTING WIND FORECASTING AT A UTILITY

L. Landberg
Riso National Laboratory, DENMARK

SYNOPSIS This paper will describe a project that has as its main task to implement prediction of the power produced by wind farms in the daily planning at a utility. The predictions are generated from forecasts from HIRLAM (High Resolution Limited Area Model) of the Danish Meteorological Institute. These predictions are then made valid at individual sites (wind farms) by applying a matrix generated by the submodels of WPP (Wind Atlas Application and Analysis Program). In the project 17 wind farms have been selected for study. The farms are located on the Zealand (13) and Bornholm (4) islands and all belong to the Danish utility ELKRAFT/Sjællandske Kraftværker.

1 INTRODUCTION

To fully benefit from large amounts of wind energy in a grid, it is necessary to know the part of the electricity production generated by the wind. The time frame is up to two days in advance. This will enable the utility to control the conventionally fueled plants in such a way that fossil fuels will in fact be saved. With the abilities of present day numerical weather prediction models, it is now possible to accomplish the aforementioned task; this has been shown in a now finished CEC-funded JOULE-project (Landberg et al [1]).

This paper will describe a model based on predictions from HIRLAM (High Resolution Limited Area Model) run by the Danish Meteorological Institute, (Machenhauer [3]). The WPP (Wind Atlas Analysis and Application Program) model of Riso National Laboratory (Mortensen et al [4]) has been used to take local phenomena into account. Local phenomena are e.g. the sheltering of wind breaks, the effect of different roughnesses and the changes in these and the speed-up/down by the orography.

The model will be implemented at the Danish utility ELKRAFT and will include 17 wind farms with a total capacity of 35.7 MW, see Figure 1 and Table 1. These 17 farms are then linked to the rest of the installed wind power (totalling approximately 100 MW) by a factor varying from hour to hour.

The project has three partners: ELKRAFT, The Danish Meteorological Institute, and Riso National Laboratory. It is funded by the Danish Ministry of Energy under the EFP-programme.

2 THE METHOD

The idea behind the physical model is that the predicted wind from HIRLAM, which is a wind specific to a gridcell of 26 x 26 km², is transformed to the surface using the geostrophic drag law.

\[ G = \frac{H_0}{K} \left( \ln \left( \frac{H_0}{f z_0} \right) - A \right)^2 + B^2 \]  \hspace{1cm} (1)

where \( G \) is the geostrophic wind, \( u_* \) the friction velocity, \( \alpha \) the Von Kármán constant (≈0.4), \( f \) the Coriolis parameter.

Table 1: The selected wind farms and their configuration.

<table>
<thead>
<tr>
<th>Name</th>
<th>Turbines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avedøre 1000</td>
<td>1 x 1000 kW</td>
</tr>
<tr>
<td>Kyndby</td>
<td>21 x 180 kW</td>
</tr>
<tr>
<td>Köllerød</td>
<td>1 x 500 kW</td>
</tr>
<tr>
<td>Avedøre</td>
<td>12 x 300 kW</td>
</tr>
<tr>
<td>Østermarie</td>
<td>7 x 225 kW</td>
</tr>
<tr>
<td>Sose</td>
<td>2 x 225 kW</td>
</tr>
<tr>
<td>Rosendal</td>
<td>3 x 225 kW</td>
</tr>
<tr>
<td>MAVJ2</td>
<td>2 x 750 kW</td>
</tr>
<tr>
<td>Vindesby</td>
<td>11 x 450 kW</td>
</tr>
<tr>
<td>Kappel</td>
<td>4 x 400 kW</td>
</tr>
<tr>
<td>Flåkøbinge</td>
<td>1 x 225 kW</td>
</tr>
<tr>
<td>Mejsumhedsodde</td>
<td>23 x 225 kW</td>
</tr>
<tr>
<td>Thysofte</td>
<td>3 x 450 kW</td>
</tr>
<tr>
<td>Sprove</td>
<td>2 x 150 kW</td>
</tr>
<tr>
<td>Skovlønge</td>
<td>2 x 150 kW</td>
</tr>
<tr>
<td>Prejelega</td>
<td>1 x 500 kW</td>
</tr>
<tr>
<td>Nybålle Hede</td>
<td>2 x 500 kW</td>
</tr>
</tbody>
</table>

Figure 1: 13 of the 17 selected wind farms in the ELKRAFT/Sjællandske Kraftværker area. The last four farms are located on the island of Bornholm (not shown). The farms have a total capacity of 35.7 MW.
ter, and \( z_0 \) the aerodynamic roughness length. \( A \) and \( B \) are constants here set equal to 1.8 and 4.5, respectively, in accordance with Troen and Petersen [6].

To get a velocity in the surface boundary layer the logarithmic wind profile

\[
u(z) = u_* \frac{\ln \left( \frac{z}{z_0} \right)}{ \kappa}
\]

is used. Here \( u(z) \) is the velocity at height \( z \). These equations are in their neutral form. For further details, see Landberg and Watson [2], The wind calculated so far is still valid for quite a big area and it must now be corrected to take local effects into account. This is done using WA\( ^\circ \)P. WA\( ^\circ \)P is taking the following local effects into account:

- Shelter from obstacles (houses, wind breaks etc).
- Effects of roughness and changes in roughness.
- Effects of the orography, speed-up/down.

Note, that this list does not include thermally-driven effects as e.g. sea-breezes and katabatic winds. In most of Northern Europe (including Denmark) these latter effects will not be of any importance, and can thus be left out without losing any accuracy.

From the previous study (Landberg and Watson [2] and Landberg et al [11]) an estimate of the error of the method is of the order of 0.1 m/s and the RMS error around 1.5 m/s for a typical station in Northern Europe. The study also showed that implementing MOS (Model Output Statistics) greatly improved the predictions for some of the stations, and as a consequence this method will also be used in this study to explain the effects not explained by the physical models. The parameters in the MOS model will be estimated using detailed measurements of the 17 wind farms and model output from HIRLAM. The measurements consist of data from the individual turbines plus a number of meteorological parameters at each farm. The look-ahead time will be 36 hours and HIRLAM will be run twice a day.

A further refinement of the method will be to include time dependent roughness descriptions, this is due to the fact that roughness is actually a time-varying quantity (e.g. trees have leaves in the summer and none during winter), the only one in the list above. The time-variance of roughness is not taken into account in WA\( ^\circ \)P because WA\( ^\circ \)P is estimating climatological quantities (e.g. the yearly production), and therefore it would be wrong to let the roughness vary, in this approach, on the other hand, we look at individual times, making it necessary to include this time dependence. The time variability of the roughness will be included by making four different roughness descriptions: one for each season.

To take into account the influence of wakes hitting other turbines in the same park the PARK program (Sanderhoff [5]) has been used to create a park efficiency rose (i.e. a sector-wise list of the actual production seen relatively to the rated production). The forecasting system from the output from HIRLAM to the final forecast at the utility is sketched in Figure 2.

### 3.1 WA\( ^\circ \)P-analysis

Before the predictions can be made it is necessary to carry out a complete WA\( ^\circ \)P and PARK analysis. The results of the former are shown in Table 2, where for each sector the influence on the undisturbed wind by orography, roughness and obstacles is shown. This is called the WA\( ^\circ \)P-matrix.

![Figure 2: Flow chart.](image)

#### 3 AN EXAMPLE

To give an example of the analysis of a wind park the Nøjsomhedsodde wind farm has been chosen. The farm consists of 23 225 kW VESTAS machines (see Figure 3) and is located near the Vindeby off-shore farm (see Figure 4).
Figure 4: The position of Nøjsombedsodde wind farm. The position of the off-shore wind farm Vindeby is also shown. Furthermore, the height contours of the surrounding area, used in the W passionate-study, are displayed.

Table 2: The W passionate-matrix for Nøjsombedsodde wind farm valid at 30 m agl. The first column is the orientation of the sector (degrees from north). The second and third columns are the influence on the speed and direction, respectively, of the free wind from roughness (the roughness is the summer roughness). Columns four and five are the influence on the speed and direction, respectively, of the undisturbed wind from orography. The last column is the "meso-scale" roughness. There are no obstacles or other effects influencing the flow.

<table>
<thead>
<tr>
<th>DIR</th>
<th>ROU</th>
<th>ORO</th>
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<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.57</td>
</tr>
<tr>
<td>30</td>
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<tr>
<td>60</td>
<td>-0.33</td>
<td>0.00</td>
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<tr>
<td>90</td>
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<td>0.00</td>
<td>0.12</td>
</tr>
<tr>
<td>120</td>
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<tr>
<td>330</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.59</td>
</tr>
</tbody>
</table>

3.2 PARK-analysis

The sector-wise efficiency of each turbine is calculated, so that it is possible to calculate the actual production of this turbine given the power curve and the predicted wind at the site. The result of the efficiency calculations for the entire farm is shown in Figure 5. As can be seen from this figure all of the turbines are sited quite well.

4 OUTPUT

The output that the person in charge of the dispatching at the utility will receive twice a day will look something like the following (please note that the example is constructed, the standard deviation is set equal to 0.6 times the prediction, and the prediction itself has been artificially generated):

<table>
<thead>
<tr>
<th>Hour (UTC)</th>
<th>Forecast (MW)</th>
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</thead>
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<td>6</td>
</tr>
<tr>
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<td>5</td>
<td>13.8</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>15.7</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>15.1</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>16.3</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>18.5</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>4.4</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>3.8</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>31.3</td>
<td>19</td>
</tr>
<tr>
<td>13</td>
<td>22.8</td>
<td>14</td>
</tr>
<tr>
<td>14</td>
<td>15.2</td>
<td>9</td>
</tr>
<tr>
<td>15</td>
<td>17.7</td>
<td>11</td>
</tr>
<tr>
<td>16</td>
<td>3.7</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>15.6</td>
<td>9</td>
</tr>
<tr>
<td>18</td>
<td>8.3</td>
<td>5</td>
</tr>
<tr>
<td>19</td>
<td>14.2</td>
<td>9</td>
</tr>
<tr>
<td>20</td>
<td>0.0</td>
<td>2</td>
</tr>
</tbody>
</table>

Next available forecast: 1200 UTC OCT 10 1994

This output is created by applying the calculated local wind to each turbine in turn. The power is calculated using the power curve for the individual turbine (different turbines...
in the same park can have different power curves) and the effect of the other turbines is then taken into account. All the productions are then added for each turbine in each farm, leaving the total production of all the wind farms as the final result. If a turbine is stopped for some reason or another, this will be put in the description file of the wind farm, and its production will not be taken into account.

5 TIME SCHEDULE

The project started in February of this year and will run for two and a half years. In the first year (now) the models will be developed and applied and the different wind farms will be analysed. The development of the models involves running the MOS part of the models using measurements from all the wind farms: wind speed and direction measured at the on-site masts, the production and status (operating/not operating) of each turbine in the wind farm. In the second year the model will be run - by the Danish Meteorological along with a Kalman-filtering model of their own - and the results will be used in the planning at ELKRAFT. In the last half year the use of the models will be evaluated and a report written detailing the findings.

6 SUMMARY

This paper has described a model that predicts the wind power produced energy up to 36 hours ahead. The model is based upon forecasts from the Danish Meteorological Institute's HIRLAM model. These forecasts are made valid locally by using the WASP program. The model will be implemented at the Danish utility ELKRAFT early next year (ie in 1995).

References


FLY-WHEEL CALIBRATION OF CUP-ANEMOMETERS

Ole Fabian

Risø National Laboratory, Denmark

INTRODUCTION

Within the business of wind turbine energy the accurate measurement of wind speed is an important but difficult exercise. To estimate the energy with sufficient confidence anemometers used to measure the wind speed must usually be calibrated in a wind tunnel, where the anemometer signal can be related to the wind speed via a pitot-static tube (and other instruments). Furthermore, the accuracy must be maintained through periodic calibration since most anemometers are subjected to wear and tear, which may change the properties.

Anemometer calibration in a wind tunnel, however, is quite expensive because a relatively large tunnel must be used. This is due to the requirement that the flow field around the anemometer must not be influenced by the presence of the tunnel walls; otherwise the calibration will not apply to the real situation, where the anemometer is mounted in the free wind at the top of a meteorological mast. Furthermore, large wind tunnels are normally used for research projects with huge budgets, which may occupy the tunnel for many weeks. In other words, calibration of anemometers is usually given low priority.

In the present method the anemometers are tested purely mechanical rather than using the wind tunnel. Only a sample of 2-3 anemometers shall be calibrated in the wind tunnel. Then the measured calibration characteristic can be generalized with sufficient accuracy by subjecting all anemometers to appropriate quality assurance (QA). All anemometers must be checked periodically, whereas the wind tunnel calibration of the test sample need only be carried out once.

The QA-system under development at The Test Station for Wind Turbines at Risø National Laboratory is based on measuring the mechanical friction and inspecting the anemometer cups by means, which can be established in any workshop.

TESTING THE RISØ CUP-ANEMOMETER

Figure 1 shows the anemometer type used at Risø. The anemometer body is characterized by a relatively long and thin stem, in which the rotor shaft is supported by two ball-bearings, one at each end of the stem. The shaft carries a rotor with 3 cups made from a synthetic material. At the other end of the shaft a non-touch sensing device generates pulses in proportion with the rotation - usually 2 pulses per revolution.

The figure shows a recent model P2244 developed at Risø. Older models and clones made outside Risø National Laboratory are slightly different from P2244 but belong in principle to the same family and exhibit very close calibration characteristics.

![Fig. 1 The Risø anemometer P2244](image)

Since the sensing device is frictionless the driving moment acting upon the shaft consists of the aerodynamic torque from the rotor and the friction from the bearings. Without any bearing friction the anemometer would start spinning at 0 m/s, i.e. the anemometer characteristic would have zero offset. With finite bearing friction a certain offset applies. Figure 2 illustrates the two cases.

The individual bearing friction is measured in a test setup, where a fly-wheel (disk) is mounted on the anemometer shaft instead of the normal rotor. Then the bearing friction can be determined by pushing the fly-wheel and analyzing the deceleration history.
In order to represent the right bearing friction the flywheel must have the same mass as the rotor. The flywheel used for the Risø-anemometers is given in Table 1.

<table>
<thead>
<tr>
<th>radius</th>
<th>mass</th>
<th>inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 cm</td>
<td>50 g</td>
<td>200 g cm²</td>
</tr>
</tbody>
</table>

### Table 1: Fly-wheel properties

Furthermore the anemometer is tilted a small angle during the test, so that a lateral shaft load corresponding to the thrust acting upon the cups is introduced. In relation to estimating the annual energy output from a wind turbine the accuracy of an anemometer should be considered at a reference wind speed around 8 m/s. From theoretical considerations the thrust at 8 m/s is roughly estimated to 10 N. Accordingly, the shaft is tilted 12°, but experience shows that the angle is not essential.

### EQUATION OF MOTION

The deceleration of the fly-wheel is given by Newton's second law:

\[ I \alpha = \tau_{\text{aero}} + \tau_{\text{mech}} \]  

(1)

where \( I \) and \( \alpha \) denote the moment of inertia and the angular acceleration of the fly-wheel, respectively.

The torque \( \tau_{\text{aero}} \) denotes the aerodynamic friction due to the viscosity \( \nu \) of the air surrounding the fly-wheel. Rotating disks in viscous fluid is a classical problem in literature. Schlichting (1) gives the following solution:

\[
\tau_{\text{aero}} = -0.616 \pi \rho R^4 (\nu \omega^3)^{3/2}
\]

\[ = -f_{\text{aero}} \omega^{3/2} \]  

(2)

where \( \rho \) and \( \nu \) denote the density and the kinematic viscosity of air, respectively, and \( \omega \) is the angular speed of the fly-wheel. In units of g, cm and s the following values apply:

\[ \rho = 0.00123 \text{ g/cm}^3 \]

\[ \nu = 0.144 \text{ cm}^2/\text{s} \text{ (laminar flow)} \]

The term \( \tau_{\text{mech}} \) in eq. 1 is the unknown bearing friction.

### NUMERICAL PROCEDURE

The deceleration is measured by recording the time periods between sequential pulses. For each two pulses the rotor has turned an angle of 2π radians. Thus the basic result of a friction test can be recorded as a series of non-equidistant time points \( t_i, t_2, t_3, ... \) where the \( i \)'th point corresponds to the accumulated rotation angle \( \theta_i = 2\pi i \) as shown in Fig. 3.

In the next step of the numerical procedure the recorded time history \( (t_i, \theta_i) \) is differentiated with respect to time using the 3-point difference scheme:

\[
\omega_i = \frac{(t_i - t_{i+1})}{(t_{i-1} - t_i)(t_{i-1} - t_{i+1})} \theta_i + \frac{2(t_i - t_{i-1})}{(t_{i-1} - t_i)(t_i - t_{i+1})} \omega_{i-1} + \frac{t_{i+1} - t_{i-1}}{(t_{i+1} - t_i)(t_{i+1} - t_{i-1})} \omega_{i+1}
\]

(3)

The angular speeds \( \omega_i \) derived this way have been included in Fig. 3. Knowing \( \omega_i \) the difference scheme can be used another time to calculate the angular acceleration \( \alpha_i \).

Once the acceleration \( \alpha_i \) and the angular speed \( \omega_i \) have been calculated eqs. 1-2 can be rearranged as follows:
\[ \tau_{\text{mech}}(\omega_i) = I_\alpha + f_{\text{mech}} \omega_i^{3/2} \]  

(4)

Figure 4 shows the calculated bearing friction \( \tau_{\text{mech}} \) as a function of \( \omega \).

As can be seen from the figure the experimental data fits quite well a friction law of the form

\[ \tau_{\text{mech}} = -(f_0 + f_1 \omega) \]  

(5)

where \( f_0 (>0) \) is the static friction and \( f_1 (>0) \) is the coefficient of the dynamic friction. In the QA-system at Risø the two quantities \( f_0 \) and \( f_1 \) have been combined into a single friction parameter \( f_{\text{ref}} \) defined as follows:

\[ f_{\text{ref}} = \frac{f_0 + f_1 \omega_{\text{ref}}}{\omega_{\text{ref}}} \]  

(6)

\[ \omega_{\text{ref}} = 40.8 \text{ rad/s} \]

The selected value of \( \omega_{\text{ref}} \) corresponds to a wind speed of 8 m/s for a Risø-anemometer, approximately.

**FRICTION VS. TEMPERATURE**

An interesting aspect of measuring the bearing friction by the present method is the possibility of investigating the anemometer sensitivity to temperature variations. Low temperatures may lead to excessive bearing friction and thereby to unexpected bias-error of the anemometer characteristic.

The results in Fig. 5 were obtained by placing the test setup in a cooling cabinet a couple of hours before the measurements. The connected points in the figure apply to two anemometers, which were carefully treated with a new lubricant. The scattered points apply to anemometers lubricated less carefully.

**WIND TUNNEL EXPERIMENTS**

The wind tunnel

The intended QA-system has been investigated in the so-called boundary-layer wind tunnel (BLWT) at the Danish Maritime Institute (DMI).

The BLWT is a "linear" tunnel in the sense that the flow is re-circulated through the building which houses the tunnel. The area of the (closed) test section is 1.80*2.0 m. Anemometer calibration is carried out close to the tunnel contraction, where the flow profile is flat and the turbulence low.

In spring '94 all measurement instruments applied in the calibration of anemometers have been renewed. The new instruments are all calibrated with traceability to international standards. At the moment the estimated calibration uncertainty limit is 0.2 m/s at a wind speed of 8 m/s, but when the new instruments have been finally implemented the uncertainty limit can be expected not to exceed 0.05 m/s. In the present investigation, however, the calibration uncertainty is of minor importance. Our concern is about small differences between calibration results, so that highly repeatable measurements are required rather than absolute accuracy.

The recent instrument update is part of a general anemometer calibration project funded by the Danish Board of Energy, which also includes the derivation of a national recommendation on anemometer calibration in wind tunnels.

The experiments

In order to separate the effect of differences in the bearing friction and imperfections in the rotor geometry two series of experiments have been carried out.

In the first series one rotor was shifted between a number of anemometer bodies with different bearing friction.
The individual friction parameters were measured at 20°C, which was also the temperature in the BLWT.

In the other series one anemometer body was shifted between a random sample of rotors.

In both series the anemometers were calibrated in 6-8 points in the interval 6-10 m/s. In the results presented in Fig. 6 and 7, however, the measurement data have been condensed into a single parameter defined as follows:

\[ V_{13Hz} = AV_{ref} + B \]
\[ V_{ref} = 13 \text{ Hz} \]

where \( A \) and \( B \) denote the slope and the offset calculated by linear regression on all data points. With 2 pulses per revolution the signal frequency \( V_{ref} = 13 \text{ Hz} \) corresponds to the previously defined value of \( \omega_{ref} (V_{13Hz} = 8 \text{ m/s}) \).

Figure 6 shows the influence of the bearing friction for four selected anemometer bodies. As might be expected the indicated wind speed seems to be nearly a linear function of the friction, the sensitivity being about 0.1 m/s per 30 g cm²/s.

\[ \text{Fig. 6 Wind speed } V_{13Hz} \text{ vs. bearing friction } f_{ref}. \]

Figure 7 shows the scatter of the indicated wind speed due to deviations of the rotor geometry. It should be noticed that some of the rotors have been tested twice. For one of the rotors (#Elul148) the indicated wind speed deviate remarkably, although a close inspection didn't show any visible imperfections. Disregarding the obviously defect rotors the scatter of the wind speed is about 0.10 m/s.

\[ \text{Fig. 7 Wind speed } V_{13Hz} \text{ for various rotors.} \]

**QA-SYSTEM UNCERTAINTY BUDGET**

For field measurements in Denmark a temperature range from -10°C to +25°C has been assumed. With the recently improved lubrication the results in Fig. 5 show that the bearing friction \( f_{ref} \) then may vary within the interval 5-15 g cm²/s. In the QA-system under development at Risø the maximum acceptance limit has been set to 20 g cm²/s. Hence the difference between any two anemometers can never exceed 15 g cm²/s, which via the sensitivity factor given in Fig. 6 can be transferred to a variation of the wind speed of 0.05 m/s. The total uncertainty can be summarized as shown in Table 2.

\[ \text{Table 2 Uncertainty budget} \]

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>QA</th>
<th>Uncertainty limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind tunnel calibration</td>
<td>0.05 m/s</td>
<td></td>
</tr>
<tr>
<td>Bearing friction</td>
<td>(5 &lt; f_{ref} &lt; 15 \text{ g cm}^2/\text{s} )</td>
<td>0.05 m/s</td>
</tr>
<tr>
<td>Rotor imperfections</td>
<td>invisible by eye</td>
<td>0.10 m/s</td>
</tr>
<tr>
<td>Total (sum-root-square)</td>
<td></td>
<td>0.12 m/s</td>
</tr>
</tbody>
</table>

CONCLUDING REMARKS

The results show that wind tunnel calibration at laboratory temperatures - typically 20°C - does not ensure sufficiently low uncertainty in all cases. In contrast to for instance electronic instruments anemometers are traditionally not calibrated at the limits of the applied temperature range.
The QA-system under development at Risø seems to grant an anemometer uncertainty limit of 0.12 m/s (confidence level 95 % probability) at a wind speed level of 8 m/s or about 1.5 percent, relatively. This uncertainty includes the anemometer temperature sensitivity. The major source to the uncertainty, however, was found to be variations in the rotor geometry - at least for the sample of rotors considered.

As for the lubrication of the bearings also the rotor of the anemometer can be improved. The rotor used until now is assembled from a hub and three cups, which are bonded together. Very recently, the design of this rotor has been reconsidered with QA on the geometry in mind. As a result two redesigned rotors will be available from different suppliers in Denmark within the nearest future. When these new rotors are ready a second testing and calibration campaign will be carried out.

REFERENCES

1 INTRODUCTION

The purpose of this poster is to show the differences between the variability of the available wind at individual sites and the available wind taken over a European scale.

The idea behind this is that weather systems affecting Europe and particularly the fronts associated with these have a length scale so small (typically between 100 to 1000 km) that Europe proper will not be affected by the same system and consequently that the European variability will be smaller than the variability found at an individual site. This will make the prediction of wind energy less sensitive to the ability of numerical weather prediction models to predict low-pressure systems exactly. And this in turn will make wind energy produced electricity a more robust resource.

One of the underlying assumptions in this study is that wind energy can be used by utilities on a European scale, (almost) without any losses during the dissipation through the grid.

The method we have used is based on scaled winds from stations scattered all over Europe normalised with a factor determined from the European Wind Atlas (Troen and Petersen [2]). The reason why the winds are scaled is that this makes them (to a first approximation) independent of the location of the site: winds from a well-sited site will display the same variance as winds measured at a site not optimal for wind energy purposes. To get a realistic picture of the European variation the winds are all normalised with a factor determined by using the Wind Atlas so that each station is made representative of the area it is located in.

The expected outcome of this study is of course that the variability of the resource taken as a whole will be significantly smaller than that of individual stations, one of the further purposes of this study will therefore be to quantify this statement.

2 THE DATA

The data used have been provided by the Danish Meteorological Institute and cover one year (December 1992 to November 1993). The data have been taken from 58 meteorological stations scattered all over Europe (see Figure 1). Measurements are taken every three hours at all the stations. Most of the measurements are taken at 10 m agl a few at other heights. The accuracy is integer knots (approx. 0.5144 m/s) for the speed and 10 degrees for direction. The measurements have originally been used in a CEC-funded JOULE study of short-term predictability (Landberg et al [1]).

3 THE METHOD

To create a time-series with a variation specific to more than just the measuring site the following has been done: Each of

the 58 time-series has been normalised with its mean. This procedure removes dependence of location, e.g. a station situated on a hill will display a variation equal to a meter-by-meter station on a flat field. This new time-series is then multiplied with a factor characteristic to the area in which the station is located. The factor has been determined using the European Wind Atlas and is listed in Table 1.

After having applied this procedure to all the time-series it is possible to generate a time-series time-step by time-step by averaging all the readings at a certain time-step. The resulting time-series will in a first approximation resemble a "European wind", both with respect to the magnitude but also with respect to its variation.

Table 1: The factors assigned to each area, taken from the European Wind Atlas. The factors are the mean wind speeds found for that area for a well exposed site.

<table>
<thead>
<tr>
<th>Country</th>
<th>Belgium</th>
<th>Denmark</th>
<th>England</th>
<th>France (N)</th>
<th>France (S)</th>
<th>Germany</th>
<th>Greece</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.25</td>
<td>7.30</td>
<td>7.00</td>
<td>5.50</td>
<td>5.00</td>
<td>6.00</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.00</td>
<td>5.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It is clear that this is only a first approximation: Firstly, it is assumed that once the wind has generated the power at a specific site, this power is available at any location in Europe. This is clearly an approximation, and an improvement to the procedure would be to incorporate some sort of a distance measure. Secondly, it is assumed that all national grids are interconnected, this is clearly not true since eg the Irish electrical grid is completely independent. Thirdly, there is the assumption that by scaling the wind with its mean value the variation is also made independent of the mean, this is not the case, since winds with higher averages tend to have smaller relative variation than winds at low mean wind speed sites. And finally, the assumption that by using the scaling factors listed in Table 1 the winds can actually be compared with respect to their mean but also with respect to their variation. Having all these reservations in mind, we continue now analysing the results.

4 RESULTS

The distribution of one year of the "European wind resource" is shown in Figure 2 and the mean plotted versus the standard deviation is shown in Figure 3. A number of interesting observations can be done:

- The variation of the European wind resource is - as expected - significantly smaller than that of individual stations in Europe. This is the case when comparing absolutely as well as relatively, cf Figure 3.

- The distribution is shifted in such a way that there are no wind speeds below 2 m/s. This means that the wind on a European scale never dies: if it quite in one area it will blow in another.

5 ACKNOWLEDGEMENTS

This study was initiated because of a discussion with Dr. L. Soder. Royal Technical University, Stockholm during the defense of my PhD-thesis. The data used have been provided by the Danish Meteorological Institute.

References


ABSTRACT


A short discussion of the limited experiences so far obtained is given.

Finally the future activity of the IEC/TC88 is described.

1. INTRODUCTION

The technical committee no. 88 under the International Electrotechnical Commission (IEC/TC88) has produced a new international standard for wind turbines, Draft IEC 1400-1: Wind Turbine Systems - part 1: Safety Requirements. This 'DIS' is presently going through the - hopefully - final voting to turn it into a valid international standard.

At the same time it is circulated to members of the CENELEC for parallel voting, which could turn the standard into a valid EU standard.

In this paper the code is described.

2. OBJECTIVE OF THE STANDARD

The standard regulates the following areas:
- Mechanical safety (also called engineering integrity), see section 4
- Electrical Safety (or integrity), section 5,
- Installation, assembly and handling, section 6,
- Operation and maintenance, section 7.

Furthermore it regulates the selection of the correct machine type for a definite site by introducing the concept of Wind Turbine Classes (section 3).

3. WIND TURBINE CLASSES

A wind turbine code for international use must be able to handle the very diverse climates, that can be found. This is no easy problem. In very rough climates it is often necessary to build extra strength into a turbine. This extra strength may be very expensive. The same diversity of climates is a problem that the designer has to live with. The committee felt, that a classification of wind turbines according to strength could be a useful tool.

The classification definition came out as shown in Table I.

Table I. Basic wind parameters for IEC Class definitions.

<table>
<thead>
<tr>
<th>IEC Class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{ref}</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>V_{ave}</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td>6</td>
<td>*</td>
</tr>
<tr>
<td>I_{ave}</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>

* values to be specified by the manufacturer.

The classification parameters are the following: $V_{\text{ref}}$, Reference Wind Speed - Extreme 10min-average wind speed at hub height only to be surpassed once in 50 years,

$V_{\text{ave}}$, Annual average wind speed,

$I_{\text{ave}}$, Annual average turbulence intensity.

The idea of the classification parameters is, that the turbine of a certain class shall be designed to withstand climates, for which all three parameters may be up to the corresponding class values. It should be made clear, that the three parameters together describe a design regime for the turbine and does not represent a physical relation between the corresponding parameters evaluated for some selected site climate.

The turbine buyer should then first establish the corresponding parameters for his selected site and then...
check that the turbine considered for the site has all class parameters higher than the site parameters.

Class S is for the manufacturer, that for some reason does not want to select the precise mix of parameters of a numbered class. He will then, however, have to give a more detailed description of design values for his turbine. This is necessary, as the standard-classes - if used - define several other parameters, that must be independently defined, if class S is used.

4. MECHANICAL SAFETY

4.1 Basis for Safety Calculation

The standard prescribes the use of limit state design including the partial coefficients method. This method is the one most commonly used for codes. The background international standard for limit state design is ISO-2394 [1].

A limit state is a state of a structure and the loads imposed upon it, beyond which the structure no longer satisfies the design requirements.

The purpose of design calculations is to keep the probability of a limit state from being reached below a certain value prescribed for the WTGS. The design requirement for the limit state is in many cases expressed by the inequality

\[ R_d = R(x/y_m) \times S_d = S(F_k/y_f) \]  

(1)

In this equation the various symbols designate:

- \( R(x) \) the resistance function yielding the design resistance,
- \( S(x) \) the load function yielding the design load,
- \( y_m \) the partial coefficient for resistance - which modifies \( f_k \) the characteristic strength of the material,
- \( y_f \) the partial coefficient for load - acting on \( F_k \) the characteristic load.

Very simply stated the equation (1) expresses, that the design value of the resistance function of a component should be higher (stronger) than the value of the load, it is subjected to.

The code operates with four kinds of limit states:
- ultimate limit states
- accidental limit state
- serviceability limit state

ISO-2394 treats ultimate and fatigue limit states as one type, but does require fatigue state checking in cases, where it is needed. The IEC code does require fatigue checking.

4.1.1 Safety level. The safety level of a code is defined by the definitions of all four parameters used in (1). The characteristic values of load and resistance are statistical measures. Here the IEC code prescribes the use of 50yr extreme values for climatic parameters. Therefore load values are 98% fractiles, i.e., risk of experiencing a larger value through a year is 2%. 95% survivability for materials, when loaded to the characteristic load value (strength) is prescribed, i.e., the chance that a specific piece of material breaks down, given the limiting conditions, is 5%.

The partial coefficients for loads has to be chosen as shown in Table II.

<table>
<thead>
<tr>
<th>Load Type</th>
<th>IEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamic</td>
<td>1.3</td>
</tr>
<tr>
<td>Functional</td>
<td>1.4</td>
</tr>
<tr>
<td>Gravitational</td>
<td>1.1</td>
</tr>
<tr>
<td>Inertial</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The IEC committee had difficulties with the lack of good international materials codes, and have therefore chosen to allow the use of national codes for materials. It does request the user of national codes to make sure, that the codes used gives a 'level of safety' corresponding to the level the IEC code is aiming at. The IEC Code establishes a minimum level of safety. It does require the materials resistance values to correspond to at least 95% survivability. And it does not allow materials partial coefficients in ultimate limit states under 1.15. It will mean, that most national codes are tougher. For fatigue the IEC prescribes 1.25 for non-fail-safe components. It is actually quite common to leave the final decision on safety level to the decision of the user countries.

In some national safety codes the concept of safety class is used. When used, the definition of a safety class reflects the possible extend of the consequences of a failure, e.g., whether or not personal injury could occur. These consequences of course depends on whether the construction will be used on sites close to or far from concentrations of people. The safety class is often taken into account by means of changes in the partial coefficients for materials. A change of such a partial
coefficient of 10% roughly corresponds to a change of failure probability of a factor of 10. This again often corresponds to shifting from one safety class to the next.

In this wind turbine code it has been decided to use only one safety class, where personal injury or economic or social consequences can occur. This can be assumed to be built into the safety level of the code. Provisions for using a so-called 'special safety class' are given, as the standard opens for the possibility, that the safety level required can be adapted to rules from local authorities or negotiated with the wind turbine buyer.

4.2. Load Cases

Limit state design requires the testing of the strength in 'worst' thinkable situations. These situations are expressed by means of load cases for the construction. See Table III and Table IV for the load cases defined by the IEC standard.

In order to find these worst situations, it is clear, that we should be looking for some extreme load-inducing external conditions. But first we must realize, that - aside from the external conditions - the loads depends which task, the turbine is presently performing. In connection with standards, each of these tasks are actually called design situations. Each design situation may contain critical load cases. The wind turbine has many design situations (operational modes) - production, start, stop, stopped with a fault, etc.

To find the critical load cases, one must look for extremes in external conditions, be it wind or other external conditions. See Table V for the combinations.

It should be added here, that as discussed in connection with the basis for safety calculations, (1), we are aiming at keeping the probability of failure below a certain value. This means, that when combining extremes of different sources, we can look apart from the most unlikely combinations. An overview of the result of these considerations can be seen in Table V, which shows how many load cases comes out of the combination of extremes from turbine faults, extreme climates and other extreme external conditions. The term appropriate shows, that a few cases remains important enough, because they are correlated events, like eg loss of electrical connection together with an extreme wind speed.

### Table III IEC Load Cases, Fatigue.

<table>
<thead>
<tr>
<th>DESIGN SITUATION</th>
<th>DLC</th>
<th>WIND CONDITION</th>
<th>OTHER CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Power production</td>
<td>1.2</td>
<td>NTM $V_{m} &lt; V_{max} &lt; V_{s}$</td>
<td></td>
</tr>
<tr>
<td>2. Power production + occurrence of fault</td>
<td>2.3</td>
<td>NTM $V_{m} &lt; V_{max} &lt; V_{s}$</td>
<td>Control or protection system fault</td>
</tr>
<tr>
<td>3. Start up</td>
<td>3.1</td>
<td>NSW $V_{m} &lt; V_{max} &lt; V_{s}$</td>
<td></td>
</tr>
<tr>
<td>4. Normal shut down</td>
<td>4.1</td>
<td>NSW $V_{m} &lt; V_{max} &lt; V_{s}$</td>
<td></td>
</tr>
<tr>
<td>5. Emergency shut down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Parked (standing still or idling)</td>
<td>6.2</td>
<td>NTM $V_{max} &lt; V_{s}$</td>
<td></td>
</tr>
<tr>
<td>7. Parked + fault conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Transport, assembly, maintenance and repair</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations:
- **DLC**: Design Load Case
- **ECD**: Extreme Coherent Gust and Direction Change
- **ECG**: Extreme Coherent Gust
- **EDC**: Extreme Direction Change
- **EOG**: Extreme Operating Gust
- **ESW**: Extreme Steady Wind Model
- **EWS**: Extreme Wind Shear
- **NTM**: Normal Turbulence Model
- **NSW**: Normal Steady Wind Model
4.3. External Conditions and Load Calculations.

Wind conditions are dealt with quite extensively. Two types of wind regimes are used: normal and extreme wind conditions.

Normal wind conditions are described by the following three 'models':
- Wind speed is Rayleigh distributed,
- Wind speed profile follows a power law with exponent 0.11,
- Normal turbulence is characterized by the 10min average standard deviation, \( \sigma_1 \), from the wind speed \( V_{hub} \) given by
  \[
  \sigma_1 = 1.2 \frac{J_{\infty}}{V_{ref}} (0.75V_{\infty} + 0.16V_{\infty})
  \]  
  (2)

where \( J_{\infty} \) and \( V_{\infty} \) are the class definition values of Table I. The turbulence power spectrum as shown in Figure 1 is specified such that the spectrum follows a \( f^{-5/3} \) law in the upper end. Also the scale parameter that defines the position of the peak is given. As alternatives, a deterministic and a stochastic model is given.

Extreme wind conditions are prescribed as
- a short time average (3sec average) extreme wind speed with a recurrence period of 50yr
  \[
  V_{3E}(t) = 1.4 V_{ref}(t|x_0)^{0.11}
  \]  
  (3)

derived from the class reference wind speed, which is the corresponding 10min average.

- several prescribed deterministic gusts:
  - extreme operating gust
  - extreme direction change
  - extreme coherent gust
  - extreme coherent gust with direction change
  - extreme wind shear

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Design & Wind & Other & Type of \\
Situation & Condition & External & Load case \\
\hline
Normal & Normal & Normal & 4 F \\
Normal & Extreme & Normal & 10 U \\
Normal & Normal & Extreme & 1 F \\
Extreme & Normal & Normal & 3 U + 1 F \\
\hline
\end{tabular}
\caption{Combining design situation and external conditions for load case determination}
\end{table}

* Appropriate means, that several extremes may have to be combined, if a common cause makes the probability high enough.

The extreme wind speed is of course meant to be used for the usual momentary ultimate wind load calculations. The gusts, on the other hand, also tests for loads, that could be created by shortcomings in the control system. The gusts are generally so slow (rise times of 6-10 secs) that they do not cause dynamical excitation of resonances in the structure.

As an example of the meaning of gusts take eg the extreme coherent gust with direction change (Figure 2):

With the direction changing over 12 secs, the yawing system will usually no be able to turn the turbine fast enough, and consequently it must be able to stand running in back-wind for some time.
4.4. Control and Safety Systems

A separate chapter is dedicated to the control and protection systems. The rationale behind strict definitions of these systems is of course, that the different limiting values for the operational limits are essential as input parameters to calculation of the limit state conditions for the various essential load cases.

The control systems should be understood as a system that watches essential function parameters and then takes care of the normal operation, i.e., start and stop, power limitation, yawing, grid connection etc. It must do that such in a way, that the turbine is kept running within its normal operational limits.

The protection system shall go into operation when detecting a fault or breakdown in the wind turbine or its control system or possibly some dangerous event. In such a case it shall be able to keep the turbine in a safe condition.

The regulations do not actually require the systems to be separate, but it does spell out rules, that attempts to make it clear, that the protection system must be able to function when needed.

The protection system must contain at least one braking system, that can stop the turbine from any operating condition and which acts on the low speed side of the gear box. The formulation of this has been a somewhat controversial point for the committee. At least one country requires two systems, with at least one of them being aerodynamic. In this country it is still expected, that if one wants to live up to the safety level (failure probability) implied by this standard, it is not easy to get away with just one system.

<table>
<thead>
<tr>
<th>Design Situation</th>
<th>Load Case</th>
<th>Wind Conditions</th>
<th>Other Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Power production</td>
<td>1.1</td>
<td>NTM $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>ECD $V_{nom} = V_r$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>NSW $V_{nom} = V_r$ or $V_{om}$</td>
<td>External electrical fault</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>EOG, $V_{nom} = V_r$ or $V_{om}$</td>
<td>Loss of electrical connection</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>EOG, $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>EWS $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>EDC $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>ECG $V_{nom} = V_r$</td>
<td></td>
</tr>
<tr>
<td>2. Power production + occurrence of fault</td>
<td>2.1</td>
<td>NSW $V_{nom} = V_r$ or $V_{om}$</td>
<td>Control or protection system fault</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>NSW $V_{nom} = V_r$</td>
<td>Internal electrical fault</td>
</tr>
<tr>
<td>3. Start up</td>
<td>3.2</td>
<td>EOG, $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>EDC, $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td>4. Normal shut down</td>
<td>4.2</td>
<td>EOG, $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td>5. Emergency shut down</td>
<td>5.1</td>
<td>NSW $V_{nom} = V_r$ or $V_{om}$</td>
<td></td>
</tr>
<tr>
<td>6. Parked (standing still or idling)</td>
<td>6.1</td>
<td>ESW $V_{nom} = V_{eh}$</td>
<td>Possibly loss of grid</td>
</tr>
<tr>
<td>7. Parked + fault conditions</td>
<td>7.1</td>
<td>ESW $V_{nom} = V_{el}$</td>
<td></td>
</tr>
<tr>
<td>8. Transport, assembly, maintenance, repair</td>
<td>8.1</td>
<td>To be stated by the manufacturer</td>
<td></td>
</tr>
</tbody>
</table>
5. THE ELECTRICAL SYSTEM

Regulations for the electrical system of a WTGS installation is treated in chapter 6, covering both the electrical equipment inside the single WTGS and the power collection system in a multiple machine installation, that feeds the power from each single unit and feeds it into the electrical network or load.

This chapter makes extensive references to the wealth of existing IEC standards on many aspects of safety of electrical systems. It does, however also contain provisions for WTGS specific uses, e.g., the fact that the mechanical safety of the turbine depends heavily on the availability of the network connection.

Apart from a general definition of what is the electrical system, subchapters treat general rules, that are common for all the complete electrical system, rules specific for the single WTGS unit, and rules that are specific for the power collection system.

6. INSTALLATION, ASSEMBLY AND ERECTION OF THE WTGS

Whereas the first 6 chapters have dealt mainly with the mechanical and electrical design securing the safety of the turbine, chapter 7 also looks into the special problems in connection with the handling of the turbine from it leaves the factory until it is ready to go into operation on its final site. This handling of course has some bearing on the safety discussed above by securing, that the assumed strength of all parts is maintained after the finished installation. But the chapter also is important for ensuring the safety for the work force, that takes care of the installation. The chapter is felt by some to be too detailed and to contain material, that is "common" knowledge. The final result as presented in the chapter is a compromise between different countries, whose needs rests on different traditions. Such compromises are unavoidable, when such differing needs shall be met in an international standard.

The chapter deals with site access, environmental conditions during installation, documentation needed for the installation process, handling, foundation, assembly, erection, lifting equipment and other related topics.

7. COMMISSIONING, OPERATION AND MAINTENANCE

Also the contents of this chapter is a compromise as discussed under installation. The chapter deals with commissioning, testing, operations, handling of faults and diminished reliability, various work procedures plans, manuals needed and records to be kept. Finally it deals with inspection and maintenance needs.

8. EXPERIENCES WITH THE STANDARD

The experience with the new standard is so far rather limited. In the very beginning 'academic' exercises were undertaken to compare the IEC standard with existing national standards in several countries (e.g., in Denmark and the Netherlands). Several manufacturers are of course trying to come to grips with the use this new standard, in the beginning mainly in order to decide how to verify a design according to several standards in one go. This is a sensible approach, as the manufacturer has to find the cheapest way to satisfy every customer, and it will take some time before the national standards abolished. These different comparisons have given rise to a few comments, but by and large it seems, that the IEC has hit a reasonable compromise. Realizing that a brand new standard quite likely is not the final answer, the IEC/TC88 who wrote it has already formed a new working group who are entrusted with gathering experiences and complaints in preparation of a revised edition, which according to the present plan could be ready in about 3 yrs.

9. FUTURE STANDARDS

The TC88 has completed a standard on safety requirements for Small Wind Turbines. It is now going through two voting rounds, which is assumed to turn it into an international standard.

A standard on Acoustic Measurement Techniques has been finished and will go into the voting in a couple of months. A Power Performance Measurement Standard has been discussed at a recent meeting and will hopefully be finished at a new meeting in April next year.

Finally besides the working group on revision of the basic safety standard also Blade Testing Methods are being studied by another working group.

10. CONCLUSIONS

The new international standard for wind turbines seems to be finding rather general acceptance. The problem is now, whether the authorities in many countries will accept this standard rather than their own standards or technical certification rules. Only the future will show that.

11. REFERENCES

EXPERIMENTAL DETERMINATION OF STRUCTURAL PROPERTIES
BY NON-DESTRUCTIVE METHODS

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Risø National Laboratory
DK-4000 Roskilde, Denmark

ABSTRACT Three types of non-destructive tests have been exploited to determine mass distribution, stiffness distribution, and mode shapes of a wind turbine blade in order to improve the test procedures in the Danish certification system.

While the blade is mounted in a rigid test stand for the standard strength and fatigue test, the test programme is easily extended to include an investigation of the above structural properties.

The mass distribution is determined based on the difference in strain gauge signals due to a 180 degrees rotation of the horizontally mounted blade. The stiffness is derived from the static deflection, corresponding to a load applied to the tip, and the mode shapes are determined from registrations of blade accelerations originating from a sinusoidal excitation of the blade, fine tuned to the relevant natural frequency.

The method is redundant, and an easy test of the overall accuracy is performed by comparing the ratio between the generalized mass and the generalized stiffness to the square of the relevant natural frequency.

INTRODUCTION

The mass and stiffness distributions, related to a wind turbine blade, are of vital importance for structural simulation of the wind turbine structure. Usually, these structural properties are derived based on knowledge of the blade geometry and of the structure of the applied composite materials. However, due to the complexities in geometry and in the behaviour of the applied composite materials, together with the uncertainties inherent in the production process, it is desirable to compare the calculated results with experimental data. In addition, the knowledge gained is a prerequisite for validating and improving the analytical methods.

MASS DISTRIBUTION

The method, to be presented, relies heavily on an experimental determined moment distribution originating from the gravity on the structure itself. As some uncertainty is related to these measurements, the method is given a variational formulation, which leaves the total mass and the centre of gravity as invariants.

The mass per unit length is expressed as

\[ \rho(x; \rho_0, \vec{a}) = \begin{cases} \rho_0 & \text{for } 0 \leq x < x_0 \\ f(x; \vec{a}) & \text{for } x_0 \leq x \leq L \end{cases} \]

where \( x \) is the coordinate along the blade axis, \( L \) is the blade length, \( \rho_0 \) is an adjustable parameter, and the parameter vector, \( \vec{a} \), contains the adjustable parameters \( a_i; i = 1, ..., N \).

The total mass of the blade, \( M_T \), and the position of the centre of gravity, \( x_G \), are assumed to be known a priori. The set of possible expressions for the mass per unit length, \( \rho(x; \rho_0, \vec{a}) \), is thus restricted to functions satisfying

\[ M_T = \int_0^L \rho(x; \rho_0, \vec{a}) \, dx, \]

and

\[ x_G = \frac{1}{M_T} \int_0^L x \rho(x; \rho_0, \vec{a}) \, dx. \]

Furthermore, the mass distribution is required to be continuous, whereby the following relation must hold

\[ \rho_0 = f(x_0; \vec{a}) . \]

Based on the expression for the mass distribution, the cross sectional blade bending moments, originating from the gravity on a turbine blade placed in a horizontal position, are easily determined. Denoting the blade bending moment, at the cross section defined by the blade coordinate \( x_j \), by \( M(x_j; \rho_0, \vec{a}) \), we obtain

\[ M(x_j; \rho_0, \vec{a}) = g \int_{x_j}^L (x - x_j) \rho(x; \rho_0, \vec{a}) \, dx, \]

where \( g \) denotes the constant of gravity. It appears that the moment distribution is expressed in terms of the constant of gravity, \( g \), and the adjustable parameters introduced in the expression for the blade mass distribution.

The available measured cross sectional bending moments are denoted \( \tilde{M}(x_j); j = 1, ..., J \), with \( J \) being the
total number of observations. The measuring positions might be distinct or some of them may be identical. It is now presumed that each bending moment registration has an inherent measuring error that is independently random and Gaussian distributed around the true bending moment $M(x_j)$ with variance $\sigma_j$. Under these circumstances it can be shown, Larsen [1], that a maximum likelihood estimation of the adjustable parameters results in a chi-square fit, where the functional

$$U(p_0, \vec{a}) = \sum_{j=1}^{J} \left( \frac{M_j - M(x_j; p_0, \vec{a})}{\sigma_j} \right)^2$$

is to be minimized. The essential boundary conditions for the variation, as expressed by the equations (2), (3) and (4), are taken into account by introduction of the Lagrange multipliers $\delta, \gamma, \text{and } \zeta$. The resulting functional, $V(p_0, \vec{a}, \delta, \gamma, \zeta)$, to be minimized is thus expressed by

$$V(p_0, \vec{a}, \delta, \gamma, \zeta) = \sum_{j=1}^{J} \left( \frac{M_j - M(x_j; p_0, \vec{a})}{\sigma_j} \right)^2 + \delta \left[ M_T - \int_{x_0}^{L} \rho(x; p_0, \vec{a})dx \right] + \gamma \left[ M_T x_0G - \int_{x_0}^{L} x\rho(x; p_0, \vec{a})dx \right] + \zeta \left[ p_0 - f(x_0; \vec{a}) \right]. \quad (7)$$

Let the task be simplified by confining it to the class of linear problems. In the present context, this is to be interpreted as functions, $f(x; \vec{a})$, that result in sectional moments, total mass, centre of gravity, and mass densities that are linear in the components of $\vec{a}$. As the moment operator, expressed by (5), and the operators related to the imposed boundary conditions, expressed by (2) and (3), are all linear, linearity in the above sense imply linearity in $f(x; \vec{a})$, i.e.

$$f(x; \vec{a}) = \sum_{i=1}^{N} a_i F_i(x). \quad (8)$$

The functions $F_i(x); i = 1, \ldots, N$ are called basis functions, and in [1] a general formulation is given for two classes of basis functions – power functions and exponential functions. Both of them has the advantage of being simple analytical functions, making the evaluation of the necessary integrals a simple task. Moreover, these types of basis functions have the potential to generate the shape of a typical mass distribution.

When linearity is assumed, the minimization of (7) results in the following $(N+4) \times (N+4)$ linear system of equations, which has exactly one solution, Cramer [4].

$$\begin{align*}
\frac{\partial V(p_0, \vec{a}, \delta, \gamma, \zeta)}{\partial p_0} &= 0 \\
\frac{\partial V(p_0, \vec{a}, \delta, \gamma, \zeta)}{\partial a_i} &= 0 \quad \text{for } i = 1, \ldots, N \\
\frac{\partial V(p_0, \vec{a}, \delta, \gamma, \zeta)}{\partial \delta} &= 0 \\
\frac{\partial V(p_0, \vec{a}, \delta, \gamma, \zeta)}{\partial \gamma} &= 0 \\
\frac{\partial V(p_0, \vec{a}, \delta, \gamma, \zeta)}{\partial \zeta} &= 0
\end{align*} \quad (9)$$

The method is now applied to estimate the mass distribution of the LM 17 m blade. We select $f(x; \vec{a})$ to be expressed by the finite Laurent series

$$f(x; \vec{a}) = \frac{a_1}{x} + a_2 + a_3x + a_4x^2; \quad x_0 \leq x \leq L. \quad (10)$$

Note, that when power functions with negative powers are present among the basis functions, the value of the transition point $x = x_0$ is restricted to be strictly larger than zero to avoid singularities. As the transition point, in principle, can be chosen to be arbitrary close to zero, this restriction is not severe.

The philosophy behind the above choice is that the term $\frac{a_1}{x}$, to a substantial degree, account for the general shape, whereas the second-order polynomial is intended to adjust for the most significant deviations between the $a_i$-term and the "true" shape. The coefficients of variation are presumed to be identical for all the bending moment recordings, and the total mass, the centre of gravity, and the transition point $x_0$ are specified to 1617 kg, 5.13 m, and 0.4 m, respectively. The maximum likelihood estimate of the mass distribution, resulting from the above assumptions, is shown in Fig. 1, together with the "true" mass distribution obtained from cutting the blade up in suitable sections.

The measured mass distribution is plotted against the "true" mass distribution.

---

**Figure 1:** Chi-square fit plotted against the "true" mass distribution.
The agreement between the fit and the "true" mass distribution is good. However, the humb on the "true" mass distribution, due to the aerodynamic brake mechanism, has not been detected. To investigate whether it was possible to detect the brake, an extreme weighting of the registrations near the tip was tried without success. The conclusion is that the airbrake effect on the moment distribution is modest and of the same order of magnitude as the noise in the measurements. This is supported by Fig. 2, where the moment distributions originating from the fit and the "true" mass distribution, respectively, have been shown.

Figure 2: Moment distributions originating from "true" and fitted mass distribution.

DISTRIBUTION OF FLEXURAL RIGIDITY

The procedure for the determination of the flexural rigidity of a wind turbine blade relies on a static vertical point loading of the horizontal clamped structure and the resulting deflection. Denoting by \( x \) the coordinate along the blade axis with zero at the blade flange, and increasing values towards the tip, the deflection \( u(x) \), due to the applied load, \( P \), is recorded in a suitable number of distinct points. In order to secure sufficient resolution of the deflection in all points on the blade, and, at the same time, to respect the limited load carrying capacity of the blade in the tip region, it may be necessary to apply external point forces at a number of different points of attack. Denoting by \( x_P \) the point of attack of the vertical force, the moment, arising from the external loading, at the position \( x \), \( M_E(x) \), is expressed by

\[
M_E(x) = P(x_P - x) \quad \text{for} \quad x \leq x_P \quad (11)
\]

The corresponding moment, made up by the internal elastic forces, \( M_I(x) \), is expressed by

\[
M_I(x) = E(x)I(x) \frac{\partial^2 u(x)}{\partial x^2} \quad \text{for} \quad x \leq x_P \quad (12)
\]

where \( E(x)I(x) \) is the flexural rigidity of the blade cross section defined by \( x \).

Having determined the deflection \( u(x) \), the flexural rigidity is thus obtainable, for cross sections satisfying \( x > x_P \), from the static equilibrium condition. Applying the expressions (11) and (12), we derive

\[
E(x)I(x) = \frac{P(x_P - x)}{\partial^2 f(x,a_0,\ldots,a_N)} \quad \text{for} \quad x \leq x_P \quad (13)
\]

It turns out that the determination of the second derivative of a measured deflection curve, with its inherent measuring errors, is a highly delicate process. Therefore, the measured deflection field has to be smoothed by a suitable fitting function. In the present investigations, the measured values have been approximated by a fitting function of the form

\[
f(x; a_0, \ldots, a_N) = \exp\left(\sum_{i=0}^{N} a_i x^i\right) \quad \text{for} \quad x \leq x_P \quad (14)
\]

where \( a_0, \ldots, a_N \) denote the adjustable parameters of the fitting function. The maximum likelihood estimates of these, \( a_0^*, \ldots, a_N^* \), are determined by use of the traditional least square technique. Thus, it is implicitly assumed that the measuring errors are independent Gaussian with the identical variance at each measuring point [1].

Having fitted a function \( f(x; a_0^*, \ldots, a_N^*) \) to the measured deflection curve, the flexural rigidity is readily obtained from

\[
EI(x) = \frac{P(x_P - x)}{\partial^2 f(x,a_0^*,\ldots,a_N^*)} \quad \text{for} \quad x \leq x_P \quad (15)
\]

The scatter in \( f(x,a_0^*,\ldots,a_N^*) \) will introduce scatter in the second derivative of the fitted function. A series of tests, with different size of the applied vertical forces, \( P_i \), are performed for each point of attack. Suppose that \( J \) tests are performed with the point of attack defined by \( x = x_P \). The normalized curvature, expressed by

\[
\kappa(x) = \frac{\partial^2 f(x,a_0^*,\ldots,a_N^*)}{\partial x^2} \quad \text{for} \quad x \leq x_P \quad (16)
\]

should, for ideal conditions, be an invariant for all these tests. However, due to the scatter (primarily in the determined values for the second derivative of the fitted function), the realizations \( \kappa_i(x) \); \( i = 1, \ldots, J \) are observed. As a best estimate to the "true" value of \( \kappa(x) \), the mean value, expressed by

\[
\hat{\kappa}(x) = \frac{1}{J} \sum_{i=1}^{J} \kappa_i(x) \quad \text{for} \quad x \leq x_P \quad (17)
\]
is applied, thus finally expressing the flexural rigidity as

$$EI(x) = \frac{1}{\kappa(x)} \quad \text{for } x \leq x_p .$$ (18)

The described method has been applied to determine the flapwise flexural rigidity of the LM 17 m blade. Two series of load cases have been performed - the first with the point of attack defined by $x_p = 11.47$ m, and the second with the point of attack specified as $x_p = 14.90$ m. Both test series consisted of three load cases.

For each of the experiments, a deflection curve was fitted to the measured data according to expression (14) with the polynomial degree $N = 3$.

The distribution of the flexural rigidity, as obtained from expression (15), is given in Fig. 3 for all the load cases contained in the present two test series.

![Figure 3: Flexural rigidities determined based on all the load cases.](image)

As seen from Fig. 3, the two categories of curves, corresponding to the two test series, seem to meet "smooth" in the vicinity of $x = 7.65$ m, and moreover each of the curve categories display very limited mutual scatter. In Fig. 4, the final flapwise flexural rigidity has been estimated by unifying the mean of the two test series, as determined from expression (18), at the point $x = 7.65$ m.

MODE SHAPES

It can be shown, Larsen and Kretz [2], that the normal mode shape values, related to lightly damped linear structures, with well separated natural frequencies, can be approximated by the imaginary part of the transfer function (at resonance) relating the force input to the acceleration response at the particular point, where the mode shape value is to be determined. In order to obtain a reasonable S/N ratio in the measurements, it has proven successful to apply a sinusoidal excitation at the natural frequency of concern.

The method has been applied to the LM 17 m blade clamped in a rigid test stand. The sinusoidal excitation was applied at the blade tip, and the resulting acceleration response was recorded at a number of positions spaced with suitable resolution along the blade. The exciting force was measured by means of a force transducer, and the accelerations were recorded by piezoelectric accelerometers. These recordings were fed into an analyzer which, based on a suitable spectral averaging procedure, offered the possibility of extracting the modulus as well as the phase of the complex accelerance at the resonance frequency.

The experimental results for the first flapwise mode shape, corresponding to the measured natural frequency $\omega_m = 2.08$ Hz, are presented in Fig. 5.

![Figure 5: Measured first flapwise mode of the LM 17 m blade.](image)
The estimated mass distribution has been compared to the "true" mass distribution, obtained by cutting the blade into pieces, in Fig. 1, and good agreement has been obtained. Moreover, the static moment distributions, originating from the above mass distributions, have been compared in Fig. 2, and excellent agreement is revealed. Finally, the dynamic performance of the mass estimate has been investigated. The first natural flapwise frequency of the blade has been calculated by combining a fixed stiffness distribution with the estimated and the "true" mass distribution, respectively. A deviation of the order of magnitude 0.9% was observed, which is considered fully satisfactory.

However, for the other two categories of results, we do not have any key. Instead, the redundance in the data material has been utilized to check the mutual overall consistence between the obtained experimental results. It is well known, see e.g. Larsen et al [3], that a natural frequency can be expressed in terms of generalized mass and stiffness quantities as

\[
\omega_i = \sqrt{\frac{k_i}{m_i}},
\]

with

\[
m_i = \int_0^L m(x)\varphi_i^2(x)dx,
\]

and

\[
k_i = \int_0^L E(x)l(x)\left(\frac{\partial^2 \varphi_i(x)}{\partial x^2}\right)^2 dx,
\]

where \(\varphi_i(x)\) denotes the mode shape corresponding to the \(i\)th natural frequency. The estimated mass distribution, flapwise stiffness distribution, and first flapwise mode shape for the LM 17 m blade can be substituted into the above relations, and the resulting frequency estimate can then be compared with the measured first flapwise natural frequency. The determination of the second derivative of the measured modal shape is critical. Therefore, the measured mode shape has been smoothed according to expression (14) with \(N = 3\). The first flapwise natural frequency has been measured to \(\omega_m = 2.08\) Hz, and estimated from (19) to \(\omega_e = 2.22\) Hz, which equivalent a relative deviation of the order of magnitude 6%. The agreement is considered fully satisfactory, and consequently consistency between the measured quantities has been demonstrated.

REFERENCES


Navier-Stokes Solver for Rotating Wing.

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Abstract: A 3-D/2-D Navier-Stokes solver for incompressible, steady viscous flow is described. The ability of this code to compute aerodynamic flows for wind turbine applications is first tested on an airfoil and a non-rotating wing. Finally, the centrifugal and Coriolis forces are included and a computation of a complete rotating blade is done, showing spanwise flow in the separated region on the suction side radially towards the tip.

INTRODUCTION

Traditionally, the flow past a wind turbine rotor is determined by the blade element momentum method BEM, which relies on two-dimensional lift and drag coefficients for each element of the wing. More sophisticated methods such as the solution of the Euler equations have been used. As the axial inflow increases, the fixed pitch wind turbines operating at constant rotational speed eventually stalls. In this situation, the Euler equations are inadequate, since they cannot take separation into account. It is believed that spanwise pressure gradients, created by the Coriolis and centrifugal forces, causes the BEM to underestimate the aerodynamic loads. Experiments by McCroskey [4] on a rotating blade show no appreciable change from a non-rotating blade in the transition or separation location, but a significant radial flow in separated flow regions. These effects have been investigated numerically by Sørensen [7] and Snel et al. [6]. In [6], an order of magnitude analysis is employed to reduce the three dimensional boundary layer equations so they can be solved with 2-D methods. In [7], the full three dimensional flow past a rotating wing is solved by a viscous-inviscid interaction scheme. Unfortunately, this technique diverges for angles of attack higher than approximately 20 degrees. To resolve all 3-D and deep stall effects it is therefore necessary to solve the full three dimensional Navier-Stokes equations. Recently, a general purpose 2-D/3-D Navier-Stokes solver...
has been developed in a collaboration between The Department of Fluid Mechanics, DTU and Meteorology and Wind Energy Department, Risø National Laboratory. In the present work, which is done in the JOULE II program called Dynamic Stall & 3-D Effects, the Coriolis and centrifugal accelerations have been added to allow the solution in a rotating frame of reference, attached to a wind turbine blade.

CODE DESCRIPTION

The flow solver is based upon the program Basis3D [2], which is a platform to solve PDE's and contains tools for multiblock topology. Furthermore, Basis3D has a multigrid equation solver [3] using Schwarz domain decomposition technique. The solver is basically a plane relaxation method, where each plane is solved with an ILLU preconditioned multigrid solver. The velocity-pressure formulation of the incompressible Navier-Stokes equations are chosen, i.e. the three momentum transport equations and the continuity equation. A cell centered, non-staggered and strong conservative discretization is used. For the velocity-pressure coupling, the SIMPLE method is employed to compute the pressure and to ensure a solenoidal velocity field. Wiggles in the pressure field are avoided by a Rhie-Chow evaluation of the cell face fluxes [5]. To accelerate towards a stationary solution, local time stepping and grid sequencing are applied. Local time stepping means that from convergence considerations an optimized time step is found for each cell. Since the time step is different throughout the computational domain a time true solution is not obtained. In grid sequencing the first iterations are performed on coarse grids. Next, this preliminary solution is interpolated to the final grid, where the computation is finished. Grid sequencing is easy to implement if a multigrid data structure is used. It is possible to chose between the first order upwind, second order upwind and QUICK scheme for the convective terms. Further, the minmod limiter is employed on the fluxes to obtain TVD behaviour. The standard k-ε turbulence model with the logarithmic law-of-the-wall is implemented. This wall law is derived from a channel flow with favourable pressure gradient. It is noted that a favourable pressure gradient is not present on the suction side of an airfoil.

GRID

A grid is generated for an NLF(1)-0416 airfoil. This profile is used on a non-tapered non-twisted test wind turbine at Delft University of Technology, see Bruining et al. reference [1]. The blade is 8.834 chords long. The grid is constructed from 7 blocks of 24*24 cells. For a 2-D computation this is a coarse mesh, but it is chosen since it is used to generate a C-O grid for the wing. An impression of the resolution is given
in figure 1. The C-O grid is constructed by repeating the 2-D grid in the spanwise direction and folding it around the tip. The 3-D surface grid is shown in figure 2.

RESULTS AND DISCUSSIONS

To gain confidence in the code, 2-D computations for the NLF(1)-0416 profile are performed and compared to wind tunnel measurements made by Bruining et al. [1]. For a Reynolds number of \(1 \cdot 10^6\) the flowfield for \(\alpha=4.09, 9.18\) and 19.16 is computed, where \(\alpha\) is the angle of attack. For this profile \(c_{l_{\text{max}}}\) occurs at a value of \(\alpha\) at approximately 13 degrees. The pressure coefficient as a function of the chord is shown in the figures 3, 4 and 5. For \(\alpha=4.09\) and 9.18, i.e. below \(c_{l_{\text{max}}}\), an excellent agreement is found between measurements and computations. At \(\alpha=9.18\) the solution is also found on a grid, where the number of gridpoints has been doubled in each direction. In figure 4 it is seen that the solution is very close to be grid independent. At \(\alpha=19.16\) the solution is still good. The large separation bubble seen in the pressure plot in figure 5 is visualized by making a velocity plot, see figure 6. The flow past the translating wing is solved for an angle of attack of 4.09 degrees. At the root a symmetry boundary condition is enforced. In figure 7 a good agreement is observed between the solution at the root and 2-D measurements. The tip vortex is visualized by plotting the velocities in a plane just behind the trailing edge. A magnification of the tip vortex is shown in figure 8. All these preliminary results are so encouraging, that the fictitious forces stemming from the centrifugal and Coriolis acceleration are included in the momentum transport equations. A global coordinate system as shown in figure 9 is used. An calculation is performed with a tip speed ratio of \(\lambda=9.22\) and the center of rotation four chords from the root section. The dimensionless pressure

\[
C_p(r) = \frac{p - p_{\infty}(r)}{\frac{1}{2}\rho(V_{\infty}^2 + \Omega_y^2r^2)}
\]

is shown in figure 10 for a root, a mid and a tip section. It is seen that the flow is separated at the root. Velocity vectors in a plane \(x=\text{constant}\) on the wing close to the trailing edge are shown in figure 11. It is seen that there exists a significant radial flow towards the tip in the separated part of the wing at the root.
CONCLUSION

A general purpose Navier-Stokes solver including the standard k-ԑ turbulence model has been used to solve aerodynamic flows related to wind turbines. Excellent agreement between measurements and computations is found for a 2-D airfoil below $c_{l_{max}}$. In deep stall the code still produces good results. A translated wing is computed. At the root the flow is in good agreement with 2-D measurements and the tip vortex is clearly visible. The centrifugal and Coriolis terms are added in order to compute the flow past a rotating blade. In the separated region at the root a significant radial flow towards the tip is observed. This effect is verified experimentally by McCroskey [4]. All computations were carried out on a RISC workstation, so it is concluded that it is realistic today to use CFD tools in aerodynamic investigations of flow past wind turbine blades. The object for 3-D computations of rotating wind turbine blades is to provide airfoil data corrected for 3-D effects for the faster BEM model.
Figure 1: Grid detail near airfoil.

Figure 2: Surface grid.
Figure 3: $Re=1 \cdot 10^6$, $\alpha=4.09$.

Figure 4: $Re=1 \cdot 10^6$, $\alpha=9.18$. 
Figure 5: $Re=1 \cdot 10^6$, $\alpha=19.16$.

Figure 6: Velocities at $\alpha=19.16$. 
Figure 7: Comparison between root and 2-D calculation, Re=1 \cdot 10^6 and α=4.09.
Figure 8: Velocity plot behind the tip, $Re=1 \cdot 10^6$ and $\alpha=4.09$. 
Figure 9: Rotating wing

Figure 10: Pressure coefficients for rotating wing, $\lambda=9.22$ and $Re_{root}=3.16 \cdot 10^6$. 
Figure 11: Velocity vectors at trailing edge for rotating wing showing radial flow towards the tip at the root, $\lambda = 9.22$ and $Re_{\text{root}} = 3.16 \cdot 10^6$. 
References


1. SUMMARY

This paper describes the work of the JOULE II project "Dyna­mic Stall and Three-Dimensional Effects". An overview of the work is given.

The goal of this project is to produce engineering methods for the calculation of stalled flow of horizontal axis wind turbines. Engineering methods in this context means that the methods should be suitable for implementation in current programs for aero-elastic calculations.

The project is divided into three tasks:

1. Experiments
2. Calculations with codes that can give detailed information on the flow of a stalled rotor and development of engineering methods
3. Engineering methods

Experimental results for the 75% radius of wind turbines are presented and discussed.

3D calculations are shown to be able to predict the static stall delay at small radius of the turbine.

Calculations with three dynamic stall models are shown to give good agreement with measurements on a NACA 4415, a LS(1)-0421 MOD and a SERI 809 aerofoil.

2. INTRODUCTION

The use of 2D steady state aerofoil data in strip theory codes results in unsatisfactory predictions of wind turbine loads. The maximum power for stall regulated turbines is generally under-predicted using 2D wind tunnel data. To achieve the correct power level and blade bending moments it is therefore common practice to apply empirical corrections to 2D aerofoil data. The inflow conditions relative to the blade are, due to e.g. yaw and wind turbulence, varying with time and for many cases it is inadequate to use quasi-steady aerofoil aerodynamic data.

In order to correctly simulate the loading and performance of a wind turbine operating in stall, it is thus clear that dynamic stall and 3D effects have to be included in calculations of forces and performance. It remains, however, to quantify both the dynamic stall and the 3D effects. Empirical methods for unsteady aerodynamics in stall, developed for helicopters, need to be adapted or modified to the conditions for stalled wind turbine rotors.

3. OUTLINE AND OBJECTIVES OF THE PROJECT

The 12 participants in the project are: FFA in Sweden, Risø and Tech. Univ. of Denmark in Denmark, ECN and Delft Univ. of Technology in the Netherlands, Univ. of Bristol, Garrad Hassan, Imperial College and Cranfield University in England, Nat. Tech. Univ. of Athens and CRES in Greece and Univ. du Havre in France.

The goal of the project is to produce engineering methods for 3D and dynamic stall. Engineering methods in this context means that the methods should be implementable in current programs for aero-elastic calculations.

Much effort in the project is devoted to carrying out and analysing experiments. Calculations will also be used to study 3D and unsteady effects.

The project is divided into three tasks: Experiments, calculations and development of engineering methods. The success of the latter task will depend on the further learning from the aerodynamic information gathered during the analysis of experiments and calculations.

An initial effort is spent to understand and quantify stationary, or at least quasi-steady, 3D effects, because it constitutes the point of departure for superimposed unsteady variations.

Experiments. The experiments consist of measurements of blade section characteristics of seven turbines. The different tests are listed in table 1. Data from the tests will be stored in a data base at ECN available for all participants. The format for the data base will be the same as for the IEA Annex XIV "Field Rotor Aerodynamics" and shared with the participants of this IEA annex. Data from measurements on the NREL combined experiment will also be available for the present project.

Calculations. Calculations are carried out for steady state as well as unsteady cases.

University of Bristol and Garrad Hassan & Partners will, for steady cases, perform viscous/inviscid coupled calculations based on panel methods and 3D integral boundary layer methods.

ECN together with NLR will use the unsteady 2D viscous/inviscid code Ultran V as modified to include the effect of rotation in the boundary layer by Snel et.al. (1). For this project the B.L. equations will be implemented in a time accurate way and the code will be extended with a model for the vortex shedding process to be able to model dynamic stall.

Risø and CRES will make calculations for unsteady flow which is described by Christensen in (2).

The Technical University of Denmark will use a 3D Navier-Stokes solver to make steady calculations of stalled rotating blades, see Hansen (3).

NTUA together with CRES and Universite of du Havre will develop an "advanced tool for dynamic stall of 3D rotating blades". The unsteady inviscid free wake code GENVUP will be used as basis for this. A calculation scheme that can take into account non-linear profile aerodynamics will be implemented into GENVUP.

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Engineering models. Five partners, Rise, Cranfield University, ECN, the Technical University of Denmark and Gerrrad Hassan & Partners will develop engineering methods for 3D steady inflow and dynamic stall.

Empirical methods for dynamic stall have been developed for the helicopter industry and have also been used for some time by the wind energy industry. Examples of dynamic stall models are the Gormont model (4), the Onera model (5), the Beddoes-Leishman model (6) and the model of Øye (7). The input to these models are in principle a set of static aerodynamic data and constants for algebraic or differential equations to model the unsteady response.

The methods of this project will probably be adaptations of existing dynamic stall models to the conditions for horizontal axis wind turbines. The static data to be used will then be 2D data corrected for 3D effects. Also the time constants can be dependent on the three-dimensional character of the flow.

4. THREE DIMENSIONAL EFFECTS

The aerfoil characteristics of rotating blades have been studied in a number of experiments, eg. Madsen (8), Hales (9), Butterfield et al (10), Bruining (11), Ronsten (12) and Graham (13). The experiments of Ronsten and Graham were carried out in wind tunnels during steady conditions. The other experiments are field rotor experiments. The field rotor experiments provide data at unsteady conditions. However, cases with small variations in angle of attack can be chosen and constitute "quasi-steady" data from these experiments.

All tests give the same indication of a stall delay near the root of the blade. There is an angle of attack region above the 2D stall α, were the normal force continuously increases. The maximum 3D normal force coefficient, Cn,max, is thus larger than the 2D value. This is reported in the references above typically for r/R around 30% and is sometimes referred to as the "Himmelskemp effect" after the first reported observations of this effect by Himmelskemp in 1945.

4.1 Measured stall characteristics at r/R = 75%.

At larger values of r/R the effect of rotation on increased Cn,max decreases but measurements show that the stall characteristics can differ from that measured during 2D tests. 2D measurements of aerofoils often show a drop in Cn above Cn,max. As the separation point moves forward the normal force reaches a maximum and then drops before it attaches to the curve for a flat plate of fully separated flow at higher α. The drop in Cn normally becomes larger for high Cn,max aerofoils and is dependent on conditions around the leading edge region of the airfoil. For angles of attack just above Cn,max, Cn can drop to values well below 1. A region of negative Cn, stalled occurs after stall.

Local instantaneous damping of flapwise motion can be written as proportional to the derivative dCn/da. For unsteady motion the Cn(α) curve will differ from the characteristic attained during a slow change of α. Existing dynamic stall models like the Beddoes-Leishman or Onera model use the static Cn data as a basis. The final calculated unsteady normal force will depend on the unsteady motion and values chosen for time constants but also on the static data input of the aerodynamic force coefficients.

Figure 4.1 - 4.4 show the normal force coefficients measured at around 70% r/R of the blade for four of tests of the project.

Figure 4.1 shows data from Risø. Data are shown for three different cases: Rotating and non-rotating blade during the field test and a non-rotating blade mounted in a wind tunnel. For the rotating field tests the data are bin averaged on the angle of attack. For the wind tunnel measurements the data shown are binned over a very short time interval. The angle of attack for all cases was measured with a five hole pitot tube. The measurements in the wind tunnel show quite a lot of scatter. The aerfoil is a NACA 63-215 aerofoil. 2D tests of this aerofoil at the same Reynolds number by Björck (14) show that 2D stall is expected for α = 15° after which Cn drops off and finally following the fully separated flow characteristics for α = 20°. For decreasing α, flow attachment was delayed and a static stall hysteresis is observed.

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Table 1 Measurements of blade section characteristics.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Diameter [m]</th>
<th>Aerofoil type</th>
<th>Chord Reynolds number</th>
<th>Type of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECN</td>
<td>25</td>
<td>NACA 44xx</td>
<td>1.25 million</td>
<td>Field rotor. Pressure measurements at 30%, 60% and 80% radius with maximum 500 Hz sampling rate for pressure distributions.</td>
</tr>
<tr>
<td>DUT</td>
<td>10</td>
<td>NLF(1-0416)</td>
<td>0.5-1.2 million rotating, 0.5-2 million 2D</td>
<td>Field rotor. Pressure measurements at 30%, 50% and 70% radius with maximum 333 Hz sampling rate for pressure distributions. The non-twisted, constant chord blade have also been tested in a wind tunnel as a 2D-test.</td>
</tr>
<tr>
<td>CIT</td>
<td>2.8</td>
<td>NACA 4415</td>
<td>&lt;0.5 million</td>
<td>Rotor towed behind a car. Pressure measurements at 35% and 75% radius. Pressure distributions read every 3° azimuth angle.</td>
</tr>
<tr>
<td>IC/ICAL</td>
<td>17</td>
<td>NACA 63-2xx</td>
<td>0.5-1.1 million</td>
<td>Field rotor. Pressure measurements at 20%, 30%, 40%, 50%, 65%, 70% and 80% radius with maximum 500 Hz sampling rate for pressure distributions.</td>
</tr>
<tr>
<td>Rise</td>
<td>19</td>
<td>NACA 63-2xx</td>
<td>0.9-1.2 million</td>
<td>Field rotor. Force measurements on blade segments at 37%, 68% and at the tip at 25 Hz sampling rate. The same type of blade as for the IC/ICAL test.</td>
</tr>
<tr>
<td>IC</td>
<td>2</td>
<td>NACA 63-2xx</td>
<td>≈80 000</td>
<td>Wind tunnel test. Stationary pressure measurements.</td>
</tr>
<tr>
<td>UB</td>
<td>2</td>
<td>NACA 63-2xx</td>
<td>≈80 000-160.000</td>
<td>Wind tunnel test. Laser Dopple Anemometry measurements of the velocities at the boundary layer.</td>
</tr>
<tr>
<td>FFA</td>
<td>5.35</td>
<td>NACA 44xx</td>
<td>0.5-1.2 million</td>
<td>Wind tunnel test. Stationary data. Pressure measurements at 30%, 55%, 75%, 85%, 92.5%, 95%, 97.5% and 99% radius.</td>
</tr>
</tbody>
</table>
The data for the wind tunnel test of Risø in Figure 4.1 show two levels of $C_n$ at stall and post stall. One at a lower level and one at higher level of $C_n$ values. The different levels were, however, not related to increasing or decreasing $\alpha$. Jumps between the two levels did not occur orderly. The curves for the rotating field test show $C_n$ values that coincide best with the high level of the wind tunnel test. Different levels were found during the rotating tests as well, but over a shorter $\alpha$ interval.

FFA has carried out tests in two wind tunnels of a non-rotating and rotating blade with NACA 44xx airfoils. At 30% radius marked differences were found between rotating and non-rotating conditions and no negative slopes of $C_n$ were found during the rotating test. For the 70% radius, however, a drop in $C_n$ occurred both during rotating and non-rotating conditions as shown in figure 4.2.

Rotating measurements on a blade with NACA 44xx airfoils have also been carried out at Cranfield University. For 35% r/R the same behaviour as for the FFA tests were found with a marked stall delay. The acquired data for runs with a yaw angle less than 5 degrees and for the radial station 75% r/R are shown in Figure 4.3. The Cranfield data show a smaller $C_{n,max}$ than the FFA measurements and a small shift in $\alpha$. However, both sets of data show signs of a drop on $C_n$ at high angles of attack.

Figure 4.4 shows $C_n$ for 70% r/R for tests of Delft. The $C_n(\alpha)$ curve for a 2D test of the section is shown together with field rotor tests of the rotating turbine. The wind speed is measured in a meteorological tower -one diameter away from the turbine. This wind speed is used to determine the angle of attack using Blade Element Momentum Theory. The curve shows a lot of scatter. This is believed to be partly due to poor correlation of the conditions at the met tower and at the turbine. Measurements have more lately also been made with a probe to measure the angle of attack and it is hoped that this will give better $C_n(\alpha)$ results for the field tests. From the data shown in Figure 3.4 it is difficult to draw any conclusions concerning differences between 2D data and rotating 3D data.
conclusions concerning differences between 2D data and rotating 3D data.

With the data analysed so far it is difficult to say anything definite about the difference of stall characteristics of a rotating blade and the 2D case for the 70% radius.

The data of Rise show an increasing $C_{\theta}(\alpha)$-curve for the whole range of $\alpha$ for the rotating cases. The FFA data show rather good agreement between the rotating and non-rotating case. $C_{\theta}\text{max}$ is slightly smaller for the rotating case. Both curves, however, show a drop in $C_{\theta}$ post stall. The Cranfield data show a rather low $C_{\theta}\text{max}$ and a small drop in $C_{\theta}$ post stall.

The SERI 809 aerofoil has been tested extensively by NREL (former SERI). The tests of NREL indicates that a large drop in $C_{\theta}$ due to complete leading edge stall found in 2D test is absent during rotating field rotor conditions.

One important task for the present project is to determine, by analysis of more data, under what conditions, and how stall characteristics, for quasi-steady conditions, differ from 2D stall characteristics for the specifically used aerofoil.

4.2 Calculations of 3D quasi-steady stall.

The calculations of ECN/NLR (1) have shown that the inclusion of the effect of rotor rotation in boundary layer equations leads to results with a stall delay relative to 2D calculations.

The NLR code ULTRAN V has been modified to include effects of rotor rotation in the boundary layer equations. The additional terms for rotation appear to be proportional to the local value of $\alpha$. An additional equation for the radial boundary layer flow is added to the ULTRAN V code. With assumptions on the cross flow the integral boundary layer equations can be solved for a 2D dimensional section. The ULTRAN V code is a code with strong viscous-inviscid coupling and calculations of separated flow can be carried out.

Figure 4.5 shows the computed $C_{\theta}(\alpha)$ for the 30% station of the FFA Stork blade. (The real $\alpha$-value is divided by an empirical factor of 1.5.) Figure 4.6 shows the computed pressure distributions at an angle of attack of 25 degrees with the 2D B.L. formulation and with the effects of rotation. The qualitative behaviour with a stall delay is well captured. The ULTRAN V code is based on the Transonic Small Perturbation modelling for the inviscid flow and results can not be expected to quantitatively capture the measured pressure distribution. However, the trend in calculations shows promise and indicate that the typical excessive behaviour of $C_{\theta}$ at large values of $\alpha$ can be caused by centripetal and Coriolis effects in the B.L. resulting in thinner B.L. and a reduction of the viscous losses.

At the University of Bristol, UB, integral boundary layer equations are used together with a panel representation of the blade and the wake (15). The B.L. equations are strongly coupled with the inviscid flow. The B.L. equations have recently been modified so as to be able to calculate the flow of rotating blades. Calculations can be made with the B.L. terms due to rotation switched on/off. Calculations can also be made in a strip-wise sense neglecting cross flow. Initial calculations have been made on the FFA Stork rotor at a tip speed ratio of 8.2. For this case, $\alpha$ is rather low and the flow is attached and the effect of rotation in the B.L. is rather small, as is also expected. Figure 4.7 shows the calculated B.L. momentum thickness for the 55% r/R section at a tip speed ratio of 8.2.
effect of thinning the B.L. The effect of rotation are, however, expected to be significant for separated flow cases. Such calculations will be made in the near future.

The difference between 2D characteristics and 3D rotational flow is a function of the radial position of the blade. At low values of r/R a stall delay is observed. Closer to the tip, however, even decreased C_{n,m} has been observed (12), (13). The aerodynamic characteristics of airfoils on blades could be different from 2D characteristics due to effects in the boundary layer, but differences can also occur due to the fact that the general conditions of the inviscid flow are different than that of 2D conditions. It is the hope that such effects can be studied using the fully 3D calculations.

4.3 Measurements of boundary layer characteristics for separated flow.

An important part of the investigation of the 3D flow will be measurements of the boundary layer with Laser Doppler Anemometry at University of Bristol. The LDA measurements will be made with the same blade that the Imperial College has used for surface pressure measurements at different radial stations (13). The B.L. measurements will give valuable information on the character of the separated flow of a wind turbine. The measured B.L. profiles will be used to calibrate the B.L. formulation in the viscous calculations.

5. DYNAMIC STALL.

The existence of dynamic stall has been shown in several tests on wind turbines, e.g. (8), (9). Several of the experiments of the current project will yield more data including pressure distributions for unsteady conditions.

Modelling of dynamic stall has been carried out in the JOULE I project "Response of Stall regulated Wind Turbines - Stall induced Vibrations", Rasmussen et al. (15). The Onera model, the Beddoes-Leishman, and the Øye model were used in this project. The inclusion of dynamic stall models considerably improved the agreement between calculated and measured dynamic behaviour of stalled rotors. Simulations of the normal force coefficient from a specific measured time series of a from the measurements on the Risø test turbine (8) were also made. It was then found that the measured aerodynamic force had a larger energy content at higher frequencies than the simulated force. The measured normal force coefficient is shown as a function of angle of attack in Figure 5.1

The calculations in (16) were a first generation application of the models. The lift coefficient has been recalculated using the Beddoes-Leishman model. The new calculations were made by Garrad Hassan with the lift from the shed leading edge vortex included in the model.

The dynamic behaviour in the Beddoes-Leishman model is determined by time lags for the pressure distribution build up, the boundary layer separation process and vortex lift decay. In figure 5.2 a and b a small sensitivity analysis is shown. The time constant for the time lags has been given different values; "standard values" and the values quadrupled. It is seen that the amplitude of the loops varies. However, the frequencies of the normal force variations are rather unchanged.

The inclusion of vortex lift has increased the energy content at higher frequencies to a small degree but the measured and predicted time histories still show significant qualitative changes.

Three aerofoils used on wind turbines have recently been tested at Ohio State University by Hoffmann et al. (17). Static 2D as well as 2D dynamic stall tests were carried out. The unsteady tests were carried out a reduced frequency of maximum = 0.07. The aerofoils are a NACA 4415, a NASA LS(1)-0421 MOD, and a SERI 809 aerofoil.

![Figure 5.1 Lift coefficient versus angle of attack from measurements on a wind turbine by Risø](image1)

**Figure 5.1** Lift coefficient versus angle of attack from measurements on a wind turbine by Risø

![Figure 5.2 Lift coefficient versus angle of attack. Calculations with the Beddoes-Leishman model](image2)

**Figure 5.2** Lift coefficient versus angle of attack. Calculations with the Beddoes-Leishman model
conditions at increasing and high $\alpha$. The measurements show some differences between different revolutions which could be due to the forcing angle of attack motion not being exactly sinusoidal and the same for all revolutions. It could also well reflect the general unsteadiness of stalled flow.

In the current project, the predictions with the existing dynamic stall models will be compared to measurements of aerofoil characteristics during rotating conditions and for aerofoils used on wind turbines for more cases than those shown above. Such tests will guide to the choice of appropriate empirical constants and an appropriate description of static data. Needed modifications of the models will also be identified.

Possible changes to current dynamic stall models in use by the participants could be to include effects of radial dependence of the stall characteristics and better modelling of the effect of varying relative velocity caused by yawed flow and wind turbulence in the turbine plane.

One important question is to find out if the dynamic stall behaviour on rotating wind turbine blades is different than that measured during 2D wind tunnel tests.

6. CONCLUSIONS

The stall-delay near the root seems to be found in all of the rotor test results.

This stall delay is also captured by the calculations of ECN/NLR by including the effects of rotor rotation in the boundary layer equations indicating that the stall delay can be explained by these effects.

At larger values of $r/R$ the measurements do not show an entirely consistent behaviour. However, at large $r/R$ (i.e. small $c/r$) the effects of rotor rotation becomes smaller and the spanwise lift distribution and aerofoil shape becomes relatively more important. The fully three-dimensional calculations are expected to give more knowledge about the stalled flow closer to the tip where spanwise pressure gradients could be important.

The work with the engineering methods has just started. Some preliminary calculations have shown their capability of predicting dynamic stall effects. However, in order to verify their capability on rotating rotors, more experimental data at unsteady conditions with high confidence in the relative inflow, (i.e. angle of attack and dynamic pressure) is needed.

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REFERENCES


Introduction

In the mid and late eighties experimental campaigns were initiated in different countries Butterfield [2], Modern [1], Ronsten [18], Haley [6], Bruining [1] in order to investigate some earlier findings of Rasmussen [16] concerning the importance of the 3D, rotational and unsteady effects on the operational characteristics of HAWTs working in natural conditions.

The above measurements as well as some more recent measurements performed by Madsen [8] show clearly that the 3D, rotational and unsteady effects are indeed the source of the uncertainty in modelling and predicting the aerodynamic loads on the HAWTs.

In order to investigate one of the above mentioned topics we are attempting in this paper to model the unsteady effects in the stalled regime aiming to the understanding of the related physics.

A dynamic stall model which is based on a 2D primitive variables Navier-Stokes solver is used for this reason. Numerical results are compared against experimental and computational results of the open literature, as well as against the experimental results of Madsen [9] for a HAWT setup.

The unsteady Navier-Stokes code

The unsteady 2D Navier-Stokes solver NNSCODE, which is applied hereafter for the dynamic stall solver developed by N. N. Sørensen.

The Navier-Stokes equations are treated in their primitive variables form while a standard high Reynolds K-e turbulence model is used for closure.

These governing equations consists of a Poisson equation for the pressure, p and 4 transport equations for respectively the velocity components \( u \) and \( v \), and the turbulent kinetic energy \( K \) and the turbulent energy-dissipation rate \( \epsilon \). In the region near to solid boundaries the high Reynolds number K-e turbulence model by Hanjalic and Launder [5] is not appropriate to apply. The boundary conditions for \( K \) and \( \epsilon \) are provided by wall functions here.

A first order upwind scheme has been applied for the 4 transport equations.

The equations are discretized using the collocation finite volume methodology on a block structured boundary conforming grid. To avoid the pressure-velocity decoupling Rhie-Chow interpolation is used to obtain the mass flux on the cell faces [17].

The sequential strategy for obtaining the variables at the new time step level is based on the SIMPLE technique by Patankar and Spalding [15].

First the momentum equations are used to predict the velocities at the new time level. Hereafter the pressure equation is used as a corrector to make the field fulfill the continuity constraints. Finally the remaining transport equations for turbulence are solved.

The solution of the momentum equations and the equations for \( K \) and \( \epsilon \) are obtained using a TDMA solver applied successively in alternating directions. The solution of the pressure equation is accelerated using a multi-grid method. The multi-grid method uses the Schwarz alternating method [19] with an overlay of half a block into neighboring blocks (to avoid the degradation of the multi grid efficiency caused by the internal boundaries), and a TDMA solver as smoother.

During the iterative procedure, \( p \), \( u \), \( v \), \( K \) and \( \epsilon \) updates are relaxed using the following relaxation parameters: \( \alpha = 0.2 \), \( \beta = 0.8 \), \( \delta = 0.8 \), \( \gamma = 0.8 \).

Computations shows [6], that if one due to the unconditionally stable implicit scheme, allows the use of large time steps, where \( CFL > 1 \), it will affect the accuracy of the solution. On the contrary, if \( CFL = 1 \), there seems to be no gain in accuracy if one iterates more than one time through the transport equations for each external cycle. For this reason \( CFL = 1 \) was set equal to 1 for all computations presented in this paper.

For dynamic stall computations the code is run in its unsteady mode using a time variable time step, given by the cell with the highest velocity subscribing to the stability criteria of \( CFL = 1 \). Computations presented in this paper was made on the grid around a NACA0012 airfoil of 257 x 32 grid points (8 blocks of 32 x 32 points) shown in Fig. 1.

The NNSCODE is modelling dynamic stall by dynamic inflow, and the inflow boundary conditions are given at a distance of 6 chord lengths in front of the airfoil (see, Fig. 1).

Figure 1. The grid applied by NNSCODE to compute the presented dynamic stall behaviour. The total grid consists of 257 x 32 grid points equal to the 8 blocks of 32 x 32 grid points.

Dynamic stall

Simulating dynamic stall by Navier-Stokes codes like the NNSCODE is time consuming, and leaves a requirement for finding appropriate "test" cases, that on the one hand will give valuable information of the physical effects of dynamic stall related to HAWTs operating in natural conditions, and on the other hand makes it possible and easy to compare results from different dynamic stall codes internally, compare the results from the different experimental test programmes on HAWTs internally, and to compare the results from the numerical simulations and the experimental test programmes.

Most of the research done until present on dynamic stall is due to efforts of the helicopter society, and there exists excellent papers and review reports covering the different physical aspects of dynamic stall on helicopter rotors, e.g. [13] and [2].

Investigations has been made [13] to show the influence of a number of parameters on dynamic stall on helicopter rotors like e.g.

- Reduced frequency
b) Amplitude and mean angle

c) Reynolds number

d) Mach number

e) Airfoil geometry

f) 3D effects

g) Turbulence of the free stream

h) Surface roughness

This study will concentrate on four of the above mentioned effects, important to HAWTs operating in natural conditions: a), b), c) and e)

Types of oscillations

The dynamic stall behavior of an airfoil can be initiated by different types of oscillations. The airfoil can in principle oscillate in a pitching (tangential), plunging (flap wise) or translational (edge wise) motion, the inflow can oscillate in three equal modes or the resulting dynamic stall behavior can be a combination of two or several of these modes.

Most of the experimental results on dynamic stall presented in the literature related to the helicopter are coming from wind tunnel tests of oscillating airfoils.

On the other hand, due to the structural nature of the blade on HAWTs, tangential and edge wise oscillations of the blade sections are not likely to occur. Flap wise oscillations can be seen.

A blade section of a HAWT or a helicopter will typically "see" an oscillating inflow, when operating in normal mode. Regarding the 3D effects which are due to the developing 3D boundary layer and the vortex cones (w'antilging and v'arions), we are interested to investigate whether a 2D model or experiment may simulate within a certain accuracy the basic flow features of a blade section. Since most of the experiments are performed for pitching airfoil rather than plunging inflow conditions, the first needed step is to identify major differences between dynamic stall induced from these two sources.

It is recalled that a 2D dynamic stall model for an oscillating airfoil needs a term in the Navier-Stokes equations, when compared to a 2D dynamic inflow model.

Parker and Mccroskey [14] found that in deep stall, at a Reynolds number of Re = 1.17\times10^6 and \( \alpha = 14.7^\circ + 5.6^\circ \sin(\theta) \) for Re = 1.17\times10^6 and Re = 0.855 (in the operational regime of a section on a HAWT, \( \theta = \pi/3 \)), there seems to be minor differences in the stall characteristics, whereas the oscillations come from the pitching inflow or the pitching airfoil. The comparison can be seen in fig. 2 and fig. 3.

In fig. 4 a comparison is made between the present Navier-Stokes model and the viscous-inviscid interaction model used by Mccroskey [11] for a pitching NACA0012 airfoil in deep stall conditions (\( \alpha = 15^\circ + 10^\circ \sin(\theta) \)) for a Reynolds number of Re = 3.4\times10^6 and a reduced frequency of k = 0.25. It can be seen that the present pitching inflow results compare well with the pitching airfoil results.

A similar conclusion was made by Mccroskey [13] comparing the C_l characteristics of a pitching and a plunging airfoil in deep stall (\( \alpha = 15^\circ + 10^\circ \sin(\theta) \)). The comparison is shown in fig. 5.

In conclusion, it seems clearly that for the deep dynamic stall regime, there are no significant differences in the physical behavior of oscillating inflow or oscillating airfoil.

Airfoil geometry

Mccroskey et al. [10], [11] and [12], found that in the light dynamic stall regime, there were major differences in the dynamic stall characteristics between typical leading edge stalled airfoils (e.g. NACA0012) and trailing edge stalled airfoils (e.g. SC-105). These differences are small compared to changes of the Reynolds number, but highly dependent on the reduced
frequency and the mean angle and amplitude of the oscillation.

On the contrary testing different airfoil shapes in the deep dynamic stall regime has shown that there is a minor influence of the shape itself on the dynamic stall characteristics, compared to the influence of Reynolds number, reduced frequency, mean angle and amplitude.

This remark is very important, implying that in deep dynamic conditions relevant dynamic stall characteristics of different airfoils may be directly compared (at a certain extend).

If this is true one may extrapolate the results obtained for a specific HAWT, to other HAWTs with different geometries.

Initiation of dynamic stall simulations

Recalling the previous conclusion, that for oscillating inflow and oscillating airfoil, there are no major differences in the airfoil characteristics in deep dynamic stall, which make it easy to compare computational and experimental results from HAWTs (oscillating inflow) with oscillating airfoil data available in the helicopter literature.

In deep dynamic stall results from HAWTs applying different airfoil geometry on the blade sections can easily be compared internally and with results from dynamic stall modelling for different airfoils, because changing the airfoil geometrical shape gives raise to minor changes in the airfoil characteristics.

These temporary findings lead to the idea that, making initial dynamic stall simulations with the application of the code on the NACA0012 airfoil, could simulate features in dynamic stall, that could be compared to open literature and to experimental results from HAWTs.

Some numerical studies have been performed for the NACA0012 profile with harmonic variations of the inflow boundary conditions. These studies cover a Reynolds number interval $Re \in [1-3 \times 10^6]$ and the reduced frequency interval $k \in [0.05-0.2]$ experienced by airfoil sections on HAWTs operating in natural conditions.

Finally two experimentally obtained time series of the dynamic inflow parameters for angle of attack $\alpha(t)$ and relative velocity $V(t)$ measured on the HAWT test setup, were applied as input for the dynamic stall model, and comparisons of the normal coefficients $C_n(\alpha,t)$ from the experiment and the simulations were made. Time series no. 1 was measured on the HAWT operating in normal natural condition. Time series no. 2 was measured on the HAWT when the rotor was highly yawed. The two time series are presented in respectively fig. 10 and 14.

Results from harmonic dynamic inflow simulations

A series of simulations was made for harmonic inflow conditions, where the Reynolds number was fixed at $Re = 1.5 \times 10^6$ and the mean angle, the amplitude and the reduced frequency were changed.

Such a simulation where the mean angle $\alpha = 10^\circ$ is below stall and the amplitude is large ($10^\circ$) is presented in fig. 6. The reduced frequency $k = 0.175$ is in the range of IIAWTs operating in natural conditions. An open hysteresis loop is seen for the lift coefficient $C_l(\alpha)$.

Figure 6. A harmonic dynamic inflow computation of a NACA0012 airfoil at a Reynolds number of $1.5 \times 10^6$ and a reduced frequency of $k=0.175$; $\alpha$ is given by $\alpha = 5 \times 10^\circ + 2^\circ \sin t$.

A simulation where the amplitude is small is shown in fig. 7. The expected small hysteresis is seen at this point below the static stall angle.

Figure 7. A harmonic dynamic inflow computation of a NACA0012 airfoil at a Reynolds number of $1.5 \times 10^6$ and a reduced frequency of $k=0.175$; $\alpha$ is given by $\alpha = 5 \times 25^\circ + 25^\circ \sin t$.

The setup of the HAWT experiment

The setup of the HAWT blade is done in a way that 3 segments of the blade can measure locally unsteady but spatially integrated airfoil characteristics. The velocity and angle of attack of the incoming flow is measured 1 meter in front of the mid blade segment by a five hole pitot probe. The instrumentation of the HAWT blade can be seen in fig. 9.
Comparisons between experiment and simulation are done in terms of the normal coefficient $C_N(a,t)$ and is presented in fig. 11, fig. 12 and fig. 13.

Figure 9. The experimental test setup of the LM 8.5 m blade on the Tellus HAWT

Comparison of results from experiments and sim.

As a final set of simulations the dynamic stall model where set up with unsteady inflow boundary conditions for angle of attack $a(t)$ and relative velocity $W(t)$ (also named $V(t)$) from the time series previously mentioned.

The time series no. 1 given in fig. 10 is a typical time series for a HAWT operating in natural conditions. The $a(t)$ variation arise from the misalignment of the rotor to the incoming flow (the rotor is yawed).

The time series no. 2 is from the HAWT operating under more extreme yaw conditions and is given in fig. 14.

Figure 10. Measured angle of attack $a$ and dynamic inflow velocity $V$ as function of time. This time series no. 1 is representative for a HAWT operating in the normal regime. $a$ are taken at a frequency of 50 Hz by a 5 hole pitot probe mounted 1 meter in front of the mid blade segment (given as a NACA 63,218 airfoil) of a HAWT wing (LM 8.5 m) operating in natural stall conditions. The averaged Reynolds number is $1.3 \times 10^6$ and the reduced frequency is $k=0.05$, equivalent to the low rotational $k$ for the HAWT rotor on 37 rev/min.

The first simulation applying the time series no. 1 is using the given $a(t)$ and a constant $V(t) = 27$ m/s for the inflow boundary conditions. The simulation is for 2 revolutions of the blade equal to a real time of 3.54 sec.

Figure 11. The dynamic inflow computations performed by the Navier-Stokes code NNSCODE on a NACA60012 airfoil with experimental input parameters $a(t)$ and $V(t)$ from time series no. 1 given in fig. 10. The first simulation applies $V(t)$ constant, $V(t) = 27$ m/s, and the given $a(t)$ for the incoming flow. The second simulation applies the given variation on both $V(t)$ and $a(t)$.

With the exception of the first quarter period, where the computation is "transitional", the simulation of the general flow aspects is fair (See fig. 11). The comparison of the corresponding hysteresis loops is shown in fig. 12 and fig. 13.

In the second simulation with time series no 1, the inflow boundary conditions are given in terms of both $a(t)$ and $V(t)$. The simulation is performed for nearly one revolution of the rotor.

Figure 12. The dynamic inflow computations and experiment given by the time series no. 1 shown in fig. 10. $C_N(t)$ is given as $0$ of $a(t)$ shown for the time period equal to the 1st rotor revolution (1.62 sec). Sequentially solving the five governing equations in 8,221 grid points, simulating the real time period of 3.54 seconds and subscribing to the CFL-stability criteria of CFL=1, the Navier-Stokes solver NNSCODE applies 195,800 time steps. On an IBM Risc RS 6000/590E Work Station, with a MFLOPS-performance of 11.8, this simulation takes 18,998 CPU-hours and 41 CPU-minutes (approximately 14 days), leaving these 2D unsteady turbulent Navier-Stokes simulations, at time present, as tools for physical studies of dynamic stall in order to construct proper engineering models.

For the time series no. 2 only one simulation is performed. The measured
NNSCODE V Constant
NNSCODE
HAWT experiment

$C_n$ vs $\alpha$

Figure 1. The dynamic inflow computations and experiment given by the time series No. 1 from fig. 10 $C_n(t)$ is given as 0 of $\alpha(t)$ shown for the time period equal to the 2nd rotor revolution.

$\alpha(t)$ and constant $V(t) = 35$ m/s were used as inflow boundary conditions. Since the time series is to short, the simulation is characterized by the initial transitional effect, thus, fails to capture the typical "figure 8" shape of the experimental $C_n(\alpha)$ hysteresis loop.

Figure 2. Measured angle of attack $\alpha$ as function of time. This time series No. 2 is for a HAWT operating in a more extreme yaw regime. The averaged Reynolds number is $1.3 \times 10^6$ and the reduced frequency is $k=0.05$, equivalent to the low rotational $0$ for the HAWT rotor on 37 rev/min.

When comparing the results from the time series of normal operational mode and the time series where the rotor is yawed (the simulations with $V(t)$ constant), it is evident that for both time series the highest errors between the experimental and the simulated data lay within the period of the first second. Both simulations are initiated with a converged solution to the steady equations for a Reynolds number equivalent to a mean velocity of the time series and with an incidence $\alpha$ equal to the starting value of the incidences in the time series data. This means that the start of the simulations is strongly affected by transitional effects, different from flow situations, where the inflow boundary conditions are the same, but where the simulations has been started earlier. The estimation of the time interval in which these initial effects are dying out is not possible at the moment.

Conclusion

For oscillating inflow and oscillating airfoil in 2D, there seems to be no major differences in the airfoil characteristics in the deep dynamic stall regime. Comparisons between measurements of airfoil characteristics on a HAWT operating in natural conditions and similar results from a 2D dynamic stall simulation (when applying a Navier-Stokes model) shows that the simulations capture general features of the measurements.

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References


INFLUENCE OF TRANSVERSAL TURBULENCE ON LIFETIME PREDICTIONS FOR A HAWT

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ABSTRACT. The paper presents work concerned with investigation of the quality of synthetic generated turbulence used as input to aeroelastic simulation programs. Measured and synthetic turbulence generated by two models, which basically differ in the number of represented wind components, is compared. The turbulence is represented as the local wind vector at a cross section of a rotating wind turbine blade in natural wind. The results confirm that the transversal turbulence component is important for realistic representation of the local wind vector and subsequently for derived quantities as e.g. fatigue damage.

INTRODUCTION

The presented work addresses investigation of the turbulence in the rotor plane of a horizontal axis, stall regulated wind turbine at wind speeds just below stall onset. The considered terrain is uniform and neutral atmospheric stability conditions are prevailing. A detailed coverage of the work is presented in [1].

The main aim of the work is

- to investigate the quality of selected full field turbulence simulation methods by comparing simulated and measured components of wind in a rotating frame of reference, taking the presence of the turbine blades into consideration,
- to investigate the importance of the transverse turbulence components and
- to evaluate effects of the turbulence quality on fatigue predictions.

The comparison is primarily on the level of second order statistics of the resulting wind speed vector at a blade cross section and of the resulting normal force on a blade segment, which is derived from linearized relations between angle of attack and normal force coefficient. The results provide preliminary information about the quality of the methods, and identify areas of great importance for prediction of fatigue load and for further model development.

At present it is widely realized that both performance and strength and fatigue of wind turbines are strongly affected by turbulence, and that predictions have to include some appropriate modelling of turbulence. It is important that the modelling includes an adequate representation of the temporal and spatial distribution of turbulence, in particular because the movement of a point on a rotating blade in a vertical plane perpendicular to the mean wind direction gives rise to the phenomenon denoted rotational sampling of turbulence, resulting in general redistribution of energy from lower to higher frequencies and in concentration of energy at frequencies corresponding to multiples of the rotational frequency of the rotor.

Scope of the Present Work

At The Test Station for Wind Turbines at Risø full scale measurements of aerodynamics and structural dynamics on sections of a rotating blade of a stall regulated wind turbine in natural conditions have been going on for some years. The measurements were initiated in 1986 with the objective to "identify the main mechanisms controlling the aerodynamic forces on a rotating HAWT blade in natural, turbulent conditions. In particular the measurements should be used to quantify the importance of 3D flow effects, unsteady effects and rotary wing effects", Madsen [2,3,4,5]. The measurements have been carried out on a specially designed test set up of a 19 m rotor of a stall regulated Tel I us rotor. These measurements offer an excellent opportunity to validate the performance of different models used for predictions of loads on wind turbines. The present work makes use of the measurements and aims at investigating the performance of time domain models for simulation of turbulence, because these models are very important for the research work going on right now in the area of nonlinear aerodynamics and structural dynamics and for evaluation of the influence of turbulence on fatigue loads. An important part of the work is the investigation of the effect of including all three velocity components in the turbulence simulation. Previous work has indicated that especially the transversal component might be of crucial importance. The methods proposed by Veers [6] and Mann [7,8] have been selected for the investigation. Below the methods are referred to as the Veers and the Mann model, respectively. The Veers model is chosen because it is widely in use at the moment and the Mann model because it is capable of including all three turbulence components, and seems to be a promising method for future work. It should be mentioned that the original one component model proposed by Veers has been extended by some researchers to include all three components as well, for example by Kelley [9], but we use the model with only one component, because this has been common practice. The parameters needed as input to the simulation models are derived from free field measurements obtained with ultrasonic anemometers.
The main result of the work is the comparison of the measured and the simulated resulting wind speed vector at a rotating blade cross section. Further, the normal force on a blade segment - derived from the wind speed vector - has been compared in order to evaluate model performance with respect to fatigue load prediction. The simulations include full aeroelastic models [10,11] in order to obtain calculated results as realistic as possible.

**COMPARISON OF MEASURED AND SIMULATED TURBULENCE AT A BLADE CROSS SECTION**

Below, comparison of the measured and the simulated wind vector at a cross section of the midspan blade segment is carried through. The pitot measurements at radius 6.83 m provide the size and direction of the relative wind, which below is compared with the corresponding wind vector simulated by aeroelastic codes. Ideally, agreement should be obtained - at least at higher frequencies, where the statistical uncertainty is small - since the models intend to simulate both wind turbine dynamics and flow field. Only the projection of the relative wind on the blade cross section is considered. All spectra presented below are obtained with approximately 16 statistical degrees of freedom (DOFs).

**Figure 1:** Power spectra of measured relative wind velocity at the blade cross section.

**Pitot Measurements**

The pitot measurements are separated in stochastic and deterministic parts by use of azimuthal binning. Power spectra are generated for both the total signal and the stochastic and deterministic parts. The results for the relative velocity are shown in Figure 1 and the results for the angle of attack in Figure 2. The stochastic part corresponds to the part of the total signal, which originates from the influence of turbulence, and it is observed that the turbulence gives by far the biggest contribution to the signal. The effect of rotational sampling is clearly observed. The deterministic contribution is only significant at frequencies corresponding to multiples of the rotational frequency, and originates from wind shear, tilt, tower influence and average yaw error.

**Results From Simulation with the One Component Veers Model**

In the present application of the Veers model, the turbulent wind field is generated at 3 radial stations - located at radii 6.0, 6.83 and 8.0 m - and 32 azimuthal stations. The rotational speed of the rotor is constant (0.8 Hz) and the sampling of turbulence takes place at the stations where it is generated (sample frequency 25.5 Hz), thus avoiding interpolation. The simulation covers a 10.7 min. time period, resulting in 16384 samples.

**Figure 2:** Power spectra of measured angle of attack at the blade cross section.

In order to examine the importance of the transversal wind speed and the possibility of compensating for the neglected transversal component, a simulation has been carried through with temporal change of wind direction - assumed to be coherent over the rotor disk - corresponding to the measured angle of the horizontal wind component at one of the sonic anemometers. In total, two aeroelastic calculations have been performed, one without and one with the change of wind direction.

Below, only the stochastic parts of the signals - obtained by subtraction of the azimuthal average - are presented.
Relative velocity. The power spectrum of the simulated relative velocity is presented in Figure 3 together with the power spectrum for the corresponding measured signal. The corresponding plots of the cumulative variance are presented in Figure 4.

The Veers simulation, which only includes the longitudinal turbulence component, severely underestimates the relative velocity variation over the whole range of frequencies. Inclusion of the coherent wind direction change, which is a somewhat arbitrary approach aiming at adding a transversal turbulence component, results in a significant improvement of the simulated spectrum, although the power is still underestimated. However, this approach should be viewed with care, especially when it is used for calculation of loads, which results from integration of the influence of turbulence over the whole rotor disc, because the real turbulence is known to be coherent only for low frequencies and small separations.

Results from Simulation with the Three Component Mann Model

The simulated Mann turbulence field is generated in a rectangular box with a quadratic cross section, covering the rotor. The distance between points on the quadratic grid is approximately 2 m in all directions. All the presented time series - measured and simulated - cover a time period of approximately 600 sec. sampled with a rate of 28 Hz, giving a total of 16384 samples.

Angle of Attack. The angle of attack is analyzed in the same way as the relative wind speed in the previous section. The power spectrum of the simulated angle of attack is shown in Figure 5 together with the power spectrum of the measured signal. The corresponding plots of the cumulative variance are presented in Figure 6. The results show that the Veers simulation severely overestimates the angle of attack variation. Furthermore, the inclusion of the coherent wind direction changes does not improve the simulation result. In fact, the change, when the wind direction variation is included, can hardly be recognized.

The time series are resolved in a stochastic and a deterministic part by azimuthal averaging, defining the stochastic part as the total signal minus the azimuthal average.
Relative velocity. The power spectrum of the sampled relative velocity (stochastic part) is shown in Figure 7, and the corresponding cumulated variance in Figure 8. The peaks at multiples of the rotational frequency are almost identical for the measured and the simulated results. The difference in variance is mainly attributed to the low frequency part of the spectra, which can be expected because of the relatively high statistical uncertainty in this frequency range.

The general underestimation observed at higher frequencies is caused by the actual finite grid resolution, resulting in adequate representation of frequencies in the turbulence model only below 0.8-1.0 Hz. Otherwise, the differences can easily be explained by the randomness of the samples.

Angle of attack. The power spectrum and the cumulated variance of the stochastic part of the sampled signal is presented in Figures 9-10. Again, good general agreement is observed. The main differences are located to the low frequency range.

COMPARISON OF DERIVED NORMAL FORCE

In the previous sections we have been concerned with investigation of the quality of the simulated wind speed vector at the blade cross section. In itself this quality is important for validation and development of the models including the load calculation models, which use the wind speed as input. However, the ultimate aim with the models is to predict the loading and use this prediction in the design process in order to obtain proper dimensioning of structural members with respect to strength and fatigue. Therefore, it is of interest to know how the discrepancies observed on the wind speed influence the load.

In the present context we only intend to calculate this influence in a simplified way, by use of a linearized relation between angle of attack and normal force coefficient, thus avoiding discussion of implemented load calculation models.

Such a linearized relation has been obtained from the measurements performed previously on the Telius turbine as reported by Madsen in [3 pp. 66-71]. Here the angle of attack range is divided in two subranges, and the corresponding normal force coefficients are each approximated with a straight line:

\[ C_N = 0.3180 + 0.0050 \alpha_r \quad \text{for } \alpha_r < \alpha_{\text{stall}} \]  
\[ C_N = 0.8023 + 0.0253 \alpha_r \quad \text{for } \alpha_r \geq \alpha_{\text{stall}} \]

where \( C_N \) is the normal force coefficient, \( \alpha_r \) is the angle of attack [°], and \( \alpha_{\text{stall}} \) is the angle corresponding to stall onset (approximately 7°).

The normal force on the segment is then obtained from:

\[ F_N = 0.195 u_r^2 C_N \]

where \( u_r \) is the relative velocity [m/s].
The angle of attack for the case we are considering in the present context is only momentarily below \( \alpha_{\text{stall}} \), so the \( C_N \)-curve from Equation (2) covers the actual situation. The results for this case are presented in the following section. Generally, the results include measurement, Veers simulation and Mann simulation. Only the stochastic part — obtained by subtraction of the azimuthal binned signal from the total signal — is included in the analyses presented below.

With the purpose to illustrate the implications for fatigue, rainflow counting is performed on the signals, and equivalent normal force fatigue ranges are calculated in order to obtain some quantification of fatigue influence. Only the normal force variation is considered, and the results are merely dependent on the slope of the normal force coefficient. It would be of interest to see how the relative velocity deviations influence the results for the below stall onset situation as well, corresponding to the \( C_N \)-curve in Equation (1), which has a higher slope.

Now, with that purpose it is assumed that the local variations in relative velocity for the situation treated above can be considered representative for a situation with angle of attack below stall onset, and the above calculations are repeated by use of \( C_N \) from Equation (1). The absolute size of the obtained force ranges might be unrealistic, but still the relative range size and distribution on frequencies should be realistic.

Practically, the calculation is carried through by offsetting the angle of attack with \(-8^\circ\) thus forcing the angle of attack variation to lie within the range of the wanted \( C_N \)-curve. The results of the calculations for this case are presented in the section below.

Results with Force Coefficient Slope above Stall Onset

In this section the results from comparison of normal force, obtained by use of the force coefficient from Equation (2), are presented.

The results of the rainflow counting are presented in Figure 11 as accumulated range plots, where a value on the abscissa expresses the number of ranges having a range greater than or equal to the corresponding ordinate value. The rainflow counting results show fairly good agreement between measurement and Mann simulation, whereas the Veers simulation underestimates the number of small range cycles. In order to quantify the relative influence of the deviations with respect to fatigue, an equivalent normal force fatigue range is calculated according to

\[
F_{N, eq} = \left( \frac{\sum n_i k_i}{\text{range interval no.} i} \right)^{1/2}
\]

where \( F_{N_i} \) is the normal force range corresponding to range interval \( i \), \( n_i \) is the number of ranges in range interval no. \( i \), and

\[
k = \frac{F_{N, eq} (\text{actual})}{F_{N, eq} (\text{measured})}
\]

The relative normal force fatigue range, \( k \), is calculated by normalization with the equivalent range of the measurement, and serves as a quantification of the relative importance with respect to fatigue.

Results with Force Coefficient Slope Below Stall Onset

In this section the results from comparison of normal force, obtained by use of the force coefficient from Equation (1), are presented.

The results of the rainflow counting are presented in Figure 12 as accumulated range plots. The rainflow counting results show fairly good agreement between measurement.

Table 1: Absolute and relative equivalent normal force range, corresponding to stall onset slope

<table>
<thead>
<tr>
<th>( m )</th>
<th>Measurement ( F_{N, eq} ) [N]</th>
<th>( k )</th>
<th>Mann simulation ( F_{N, eq} ) [N]</th>
<th>( k )</th>
<th>One comp. simulation ( F_{N, eq} ) [N]</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>67.0</td>
<td>1.00</td>
<td>65.9</td>
<td>0.98</td>
<td>61.7</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>67.4</td>
<td>1.00</td>
<td>69.0</td>
<td>1.02</td>
<td>69.3</td>
<td>1.03</td>
</tr>
<tr>
<td>5</td>
<td>69.6</td>
<td>1.00</td>
<td>73.9</td>
<td>1.06</td>
<td>78.7</td>
<td>1.13</td>
</tr>
<tr>
<td>10</td>
<td>84.4</td>
<td>1.00</td>
<td>98.3</td>
<td>1.16</td>
<td>114.7</td>
<td>1.36</td>
</tr>
</tbody>
</table>

\( n_{eq} \) is the equivalent number of ranges, arbitrarily chosen here as the number of complete rotor revolutions during the 10 min. period, and \( m \) is the reciprocal value of the SN-curve slope in a logarithmic plot.

Figure 11: Rainflow count on normal force, corresponding to stochastic part. Experimentally derived force coefficient above stall onset.
The aim with the present work has been the investigation of the quality and the adequacy of selected full field turbulence simulation methods, used for response simulation on horizontal axis wind turbines in the time domain. The work has been carried through partly by comparison of simulated turbulence at a section of a rotating blade with corresponding measured turbulence and partly by comparison of derived resulting force on a blade segment. Two methods have been selected for turbulence simulation and comparison. One is the widely used Veers method, which simulates only the longitudinal turbulence component. The other is the recently at Risø developed Mann method, which simulates all three turbulence components and includes the influence of shear. The resulting relative wind vector at the cross section has been investigated by comparison of its magnitude and the angle of attack, both represented as power spectra and cumulated variance functions.

The simulated Mann turbulence gives excellent agreement with the measurements, both with respect to size and direction of the resulting relative wind vector. Using the turbulence simulated with the Veers method results in significant underestimation of the variance of the size of the relative velocity and significant overestimation of the variance of the angle of attack. It has further been demonstrated that substantial improvement of the relative velocity variance can be obtained by including a wind direction change, which is coherent over the rotor disc, aiming at adding a transversal component to the turbulence. The wind direction change has only negligible influence on the angle of attack. However, this approach should be viewed with care, when the purpose of the simulation is to calculate loads, which are obtained by integration of the turbulence field over the rotor disc, because the transversal component is known to be coherent only for small separations and low frequencies.

In order to evaluate the quality of the simulation methods, when they are used for dimensioning of structural members against fatigue, the influence of the discrepancies on the calculation of the normal force on a blade segment has been investigated. The normal force has been derived – both for measurements and simulations – by use of linearized relations between angle of attack and normal force coefficient for two situations, one with a coefficient slope corresponding to angles of attack below stall onset and another corresponding to angles of attack above stall onset. Rainflow counting has been performed on the derived normal force and an equivalent normal force range has been calculated with reference to different SN-curves. This range has been used as a measure of the resulting simulated fatigue damage relative to the fatigue damage caused by the actual normal force derived from the measured wind vector. The calculation has been carried through with different slopes of the SN-curve.

The comparison shows that the Mann method gives results which for the below stall case deviates from —2% to +8% from the measurement depending on the selected SN-curve slope. The negative deviation corresponds to steel material and the positive deviation to fibre glass composite material. The corresponding deviation is from —2% to +16% for the above stall case and generally the results are comparable for the below and the above stall case. The results for the Veers simulation show much bigger deviations and behaves differently whether the below stall or the above stall case is considered. For the below stall case the deviations – corresponding to the ones mentioned above for the Mann simulation – are from +37% to +62% and for the above stall case they are from —8% to +36%.

Thus, the results show that an adequate representation of turbulence in a simulation model, used for calculations on a horizontal axis wind turbine, should include all three turbulence components in order to obtain reliable results. It has been shown here that it is important tor prediction of the local wind vector and for fatigue calculations.
and it is likely that such improvements of the turbulence field will be advantageous for future development of load calculation models, e.g. dynamic stall models.

ACKNOWLEDGMENTS

The work has been funded, partly by the EFP program under the Danish Ministry of Energy, and partly by the Commission of the European Communities, Directorate General XII for Science Research and Development DG12. Many colleagues have contributed to the accomplishment of the presented work. They are thanked collectively for their valuable support to the project, as mentioning everyone would be very comprehensive. A project like this depends heavily on the availability of reliable measurements and the authors therefore find it important to express their thanks to the colleagues, which have performed the often anonymous work with carrying out the measurements and making them available for model development and verification.

REFERENCES


EXPERIMENTAL AND NUMERICAL RESULTS FOR A SERIES OF TIP SHAPES

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ABSTRACT: The blade tip region is of high importance for the rotor power production, the blade loading and the noise emission. Wind turbine performance can thus be significantly influenced (improved) by the choice of the right tip shape. In this report experimental and numerical results are presented. The experimental results comprise load and inflow measurements conducted on a 100 kW wind turbine Tellus T-1995 which has been used as a test bed. The results from the different tips are to be compared to those of the rotor's standard tip. The numerical results presented have been reached by using the commercial Navier-Stokes code FIDAP and comprise calculations of the laminar flow field around the tips.

1. INTRODUCTION

The tip region has traditionally been considered as the part of the blade which houses the aerodynamic brakes (to provide overspeed protection), or the means for providing active power regulation or as the area where various attachments can provide power augmentation (tip vanes, e.g. Shimizu et al [1]). Today the importance of the tip region and the tip shape for wind turbines blades in relation to power production, blade loading and noise emission is recognized by many authors. This is due to the high speeds encountered and the formation of the tip vortex.

Most of the existing information on blade tips comes from tests on helicopter rotors both in full scale and in wind tunnels (e.g. Phillipe and Vuillet [2], and McVeigh and McHugh [3]). The research on helicopter blade tips aims to control the vortex roll-up process in order to improve the noise emission and the blade loading together with achieving savings in power.

As the corresponding experience with alternative tip shapes, for turbine blades, is limited to the noise issue [4-5], this project started with the objective to study the aerodynamic behavior of a series of tip shapes. Their shapes have been chosen following a helicopter literature review and their main common property is their ability to produce a more diffused tip vortex. Regarding the numerical part of the paper, the laminar velocity fields around some of the tips are presented.

2. THE EXPERIMENTAL SETUP AND INSTRUMENTATION

The main points are presented here, while a detail description can be found in ref. (5) and (6). The three bladed stall regulated HAWT has a diameter of 19m. The blades used are commercial LM 8.2m of the 63,2nn profile series and have both twist and taper. One of the blades is modified so that three blade segments, 0.5m in span, are suspended each from the end of a three component balance whose other end is attached to the main spar of the blade (Fig. 1).

Fig. 1. The Test Blade Layout

One balance is situated at the tip area and thus the blade can easily accommodate new tips which are fastened directly on the balance. The number of channels to be transferred through the rotating system and sampled on the ground was limited. Therefore the rotor signals measured during the tests are:
the normal to the blade segments force $F_n$, the chordwise force $F_t$ and the pitching moment $M_p$ from the mid and the tip segment,
- signals from two accelerometers which are mounted close to the tip and the mid section in order to enable the subtraction of the inertia force component from the measured balance force,
- the flapwise root bending moments of the three blades and finally,
- the local inflow using a five hole Pitot tube.

**Calibration of the setup.** Full bridge strain gauges were used for all force and moment signals. The gauges for both the normal and the tangential forces on the blade segments are mounted each on two separate cross sections of the balance. They are coupled so that only the resulting differences in the bending moments between the two cross sections are measured while constant contributions are compensated. Thus the influence from constant moments is avoided. This is important since it means that the measurements are not influenced from tips of different length and weight. The calibration of the response of the strain gauges and the accelerometers took place in the workshop. To compensate for the offsets of the sensors due to drift or because of mounting a new tip, the turbine was rotated slowly under light to zero wind conditions and the offsets of the signals were fitted relative to the blade's azimuthal position.

![Fig. 2 The blade and Pitot aoa](image)

**The five hole Pitot tube.** The five hole Pitot tube was adopted for the measurement of the local inflow velocity vector. The Pitot tube was mounted just outside the mid segment towards the tip, on a tube bent to the pressure side of the blade while the corresponding differential pressure transducers were embedded in the blade close to the pitot tube location. Its distance from the leading edge of the blade was one chord length. The Pitot tube measures the local velocity, the angle of attack (aoa) and the sideslip angle. As one of the objectives of this experiment has been to produce data so that comparisons could be made with calculations and wind tunnel data, the accuracy of these measurements was a matter of concern. Later wind tunnel measurements, during which the blade was placed in a wind tunnel and measurements took place under the same configuration (7), confirmed the accuracy of this approach.

![Fig. 3 The blade and Pitot aoa, dynamic conditions](image)

The results in Fig. 2 show binned values of the geometric aoa while the blade rotates slowly and its aoa increases at a rate of 0.16°/sec. No corrections of any kind have been applied. Even at high aoa beyond stall - where blockage is encountered - the two signals agree well. A dynamic situation is shown in Fig. 3 where the time series of the two angles are shown while the blade is subject in periodic motion around its axis. The agreement is still considered good. Corresponding observations from lower aoa (e.g. up to a mean value of 10°) revealed no differences, while at higher aoa the agreement became poorer but was still reasonable. The results are presented as functions of the measured aoa. The reason for this is the high correlation to the other measured parameters. This is important for two reasons: a) a limited number of data are needed in order to cover a wide spectrum of operating conditions (typically $3 \times 10$ minutes) and b) the good correlation and low standard deviation achieved makes visible small differences.
A final argument is needed for the Pitot position which is 2.2m away from the tip region. This fact alone is a matter of concern, namely how real is the correlation between the tip signals and the aoa? The pitot tube at its chosen position measures an aoa which, according to the theory, is the angle the blade sees during its operation. Had it been possible to place the Pitot tube to the tip region, the results would have been of limited interest due to the complicated local three dimensional conditions encountered that do not hold for the rest of the blade.

3. PRESENTATION OF THE TIPS

The tip shapes studied are shown in Fig. 4. All tips have the same planar area which as seen from the figure has resulted in small differences in length. The geometry of the blade, (i.e. profile, thickness distribution and twist) has also been retained in the tips. A more detailed presentation along with some of their acoustical behavior can be found in (5). Concerning their aerodynamic merits a great number of tests exist on series of different shapes. These tests aimed also in checking and calibrating developed numerical codes.

Fig. 4. The Tips chosen for this study

After testing seven tip configurations at Boeing-Vertol, McVeigh and McHugh (7) report increased cruise efficiency (rotor lift/effective drag) for a tapered tip. On the other hand Strout, Rabbot, and Nieback (8) after testing four different configurations at Scorsky report that a swept tapered tip showed improved performance combined with reduced bending loads.
Alike results have been reported for the ogee tip while the elliptic tip is considered to combine merits of the tapered and the swept tip.

4. RESULTS

**Power curve measurements.** In Fig. 5 the power curve measurements for all five tips (high rpm) are presented. For every power curve are typically used three to four time series of ten minutes duration and the data before binning are pre-averaged over one revolution. The data have been chosen so that most of them come from the same wind direction. A detail of the power curves is given in Fig. 6. It is seen that the peak power is found for all tips at the same aoa (except for the elliptic tip due to lack of data). All power curves with the exception of the swept tapered tip are systematically higher than that of the standard tip. This difference reaches a maximum at peak power. The tapered tip shows by far the highest production of all, which at maximum turbine efficiency (around 10°-12°) would result in an increase in production by around 7.5kW provided all three tips were changed.

**Load measurements.** In Fig. 7 the lift and drag coefficients are presented for all five tips. The inertia force components, measured by the accelerometers, are subtracted from the normal force measured by the balance. The minimum $C_t$ coefficient was during data reduction arbitrarily set equal to -0.01 for angles around zero, as a zero compensation for it proved difficult. In the same data 2D wind tunnel data for the same airfoil are presented (11). Clearly the behavior of all the tips has strong 3D characteristics. The slope of the $C_L$ curves compared to the 2D data is much lower and the maximum $C_{L_{\text{max}}}$ values are also below the maximum values for the 2D case. Their behavior after stall also differs from the 2D case which is characterized by a large negative slope. Important differences occur also between the tips. Three of them (elliptic, swept tapered and tapered) have alike slopes in the pre-stall region. The ogee tip slope is intermediate between the above ones and the standard tip, whose slope is the lowest. The same observation holds for the $C_{L_{\text{max}}}$ values. The various tips are also seen to reach stall at different aoa, with the swept tapered to reach first and the standard last. Differences exist also in the post-stall region. Notice the sudden transition of stall for the swept tapered tip (which is followed by an almost constant normal force coefficient, not shown here), and compare it to the more gradual one of the rest. This situation is especially interesting for stall regulated wind turbines.
Flap bending moments. In Fig. 8 the flapwise bending moments are shown for three of the tips (high rpm). They are presented as pairs derived from the same time series. Data for the ogee tip are not available while data for the elliptic tip are not available at high AoA (high rpm). The curves begin to diverge behind the stall region and the most significant fact is that lower bending moments (lower loads at the root of the blade) occur for the swept tapered tip. At low rpm (Fig. 9) the same trend is observed for the swept tapered tip. Data for the elliptic tip show a slightly better behavior, while the tapered tip does not show any differences from the standard.

5. CALCULATIONS

Different numerical models have been used for the investigations of the influence of the tip shape on the aerodynamics. A model based on a combination of the standard strip theory with a lifting line model was developed and serves as a quick tool for estimating the influence of the variation of the chord and twist on e.g. the distribution of the bound circulation and the strength of the tip vortex. However, this type of model cannot take into account the details of the planform such as the geometrical positions of the leading and trailing edge. A fully three dimensional model is
necessary for a detailed analysis of the tip flow and in the present case a Navier Stokes (NS) code has been applied. It is the commercial code FIDAP which is based on the finite element principle.

So far, a simple rectangular tip shape has been investigated. A grid with a total number of around 36000 nodes was created using a non-structured grid in the base plane, Fig. 1. The spanwise length of the model is only about two chordlengths and realistic boundary conditions cannot really be applied on the plane towards the rest of the blade. However, as it will be seen below the tip vortex is concentrated within a rather narrow region at the tip and the incompleteness of the boundary conditions is thought to be of minor importance for the details of the tip flow.

Fig. 10 The grid for the Navier Stokes simulations of the tip flow. Number of nodes around 36000.

The calculations have been run with an angle of attack of 4 degrees, laminar flow and a Reynolds number of 100.000.

The velocity vectors in a plane perpendicular to the free stream are shown in Fig. 11 at a position mid between the leading and trailing edge and in Figure 2b at 0.1 chordlength behind the trailing edge. The flow around the tip from the pressure side to the suction side forming the tip vortex is clearly seen in Fig. 11. From Fig. 12 it appears that the center of the vortex is just inboard of the tip.

With the assumption of laminar flow and a Reynolds number of 100 000 the numerical results cannot be compared directly with experiment. However, the objective with this kind of simulations is to get a basic insight into the flow for different tip geometries. For example to see what difference it makes if the leading edge is turned towards the trailing edge and opposite the trailing edge turned to the leading edge. It is therefore expected that this type of calculations can clarify why the swept tapered tip seems to differ considerably from the tapered tip.

Fig. 11 The velocity vectors in a plane perpendicular to the free stream and through a point mid between the leading and trailing edge. Laminar flow, Re. = 100.000, aoa = 4deg.

Fig. 12 The velocity vectors in a plane perpendicular to the free stream and through a point 0.1 chordlength behind the trailing edge. Simulation parameters the same as in Fig. 11
6. CONCLUSIONS

A series of different tip shapes have been studied during which four alternative tips have been compared to the blade's standard tip. The use of the Pitot tube in these tests reduced the amount of data needed for obtaining reliable results. The study confirmed the importance of the tip region in the performance of a wind turbine. Higher production and lower loads are possible by careful design of the tip.

Concerning the tips tested, they exhibited different behaviour in the pre-stall region expressed by differences in slope and maximum values of the lift coefficients, although the differences in maximum values should partly be influenced by their planform and the fact that it is a bending moment we measure. The different tips are seen to reach stall at different aoa and to exhibit differences in the stall process and post stall behaviour. No clear evidence of influence was observed in the mid section of the blade from changes in the tip area. All of the tips showed increase production relative to the standard with the tapered being the most effective.

For the swept and the tapered tip, an improved effect to flap load ratio was clearly observed. Specially for the swept tip, reduced loads were observed in the post stall region.

Although the tip data demonstrate the differences, they are not enough to attribute to the reasons for it. Therefore a CFD investigation of the problem could contribute to a better understanding of the flow around the tip area.

REFERENCES


CONCEPT TESTING OF WIND TURBINES

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1. INTRODUCTION

The Danish certification system for wind turbines has requirements to testing of wind turbines which is described as basic and system testing. It has been the practice in the past few years that the loads on the 500 kW wind turbine generation were verified for each wind turbine type by measurements, which has meant system testing of quite a number of wind turbines. Therefore, it was decided to put up a testing program that incorporates calculations with aeroelastic codes into the certification process. The present paper describes a testing procedure, called concept testing, which is based on the applicability of aeroelastic codes to reduce the number of system tests necessary to perform on wind turbines of the same concept.

2. SCOPE OF CONCEPT TESTING

The idea of concept testing is to make a comprehensive test of a wind turbine of a certain concept (with a certain type of blades), then to calibrate or "tune" an aeroelastic model to the measurements. The "tuned" model can then be used to calculate loads on wind turbines of the same concept: a wind turbine with same number of blades, same type of blades, but with variations in blade setting angles, rotational speed, rotor diameter and structural eigenfrequencies. The concept testing includes: comprehensive load measurements on a wind turbine, detailed measurements on the blade mass- and stiffness distribution and an aeroelastic code to make detailed calculations on wind turbine types of the same concept. The procedure also includes basic testing of wind turbine types of the same concept in order to tune the calculations. The concept testing is about to be implemented in the Danish certification system.

A basic test comprises:
- power performance measurements
- noise measurement
- test of safety systems
- yaw efficiency measurement
- eigenfrequencies at standstill
- grid load at cut-in and cut-out
- function test

A system test comprises:
- a basic test
- eigenfrequencies during operation
- measurements of blade and rotor loads

The basic idea is to supplement a concept test with aeroelastic calculations to calibrate the code, then subsequently to utilize the information gathered in order to verify loads on another wind turbine. On the "First Wind Turbine", the following shall be carried out:

Concept test
- system test
- blade load distribution on WT
- blade mass distribution
- blade stiffness distribution

Fitting of aeroelastic calculations
Calculations based on:
- WT data
- measured blade mass and stiffness distribution
- fitting of WT stiffness to measured modal frequencies on WT
- fitting of aerodynamic 3D data to measured blade load distribution on WT
- fitting of other parameters in aeroelastic model to fit measured load data on WT

On a second type of wind turbine, being within the same concept (having the same type of blades), the following shall be carried out:

Basic test
see above

Aerelastic calculations
Calculations based on:
- WT data
- measured blade mass and stiffness distribution
- fitting of stiffness of WT to measured modal frequencies on "second WT"
- aerodynamic 3D data from "first WT"
- otherwise fitted parameters in aeroelastic model from "first WT"
3. TESTING PROGRAM

The idea of concept testing is being verified by a concept test on a Nordtank 500 kW wind turbine with LM17 blades. A system test, a measurement of the blade load distribution on the turbine and measurements of blade mass- and stiffness distributions were performed. The information were implemented in an aeroelastic code.

Concept testing of Nordtank 500 kW

The system test of Nordtank 500 kW (NTK500) is reported in Petersen[1] and briefly described in the paper. Main information on the turbine is given in Table 1. The instrumentation of NTK500 included measurement of main meteorological and wind turbine operational parameters. Yaw- and tilt-moments were recorded in the fixed frame of reference (tower) and in the rotating frame of reference (main shaft). Flapwise bending moments at blade radii of 75%, 50%, 25%, flapwise and edgewise blade root moment, and rotor shaft torsion were measured. The system test provided information on dynamic response analysis with emphasis on structural vibration modes and response during operation. The statistics of the structural loads are calculated and the fatigue loads are evaluated for blade, rotor and tower loads using rainflow counting. The equivalent load ranges are calculated at different wind speeds, turbulence intensities and forced yaw misalignment. For comparison the natural frequencies at standstill are provided in Table 2. The blade mass- and -stiffness distributions were reported by Larsen[2] and Larsen et al.[3], respectively. A paper presented at this conference by Larsen[4] concentrates on these subjects. Larsen[4] found the first flapwise mode shape natural frequency from a bench- mark test, on the LM17m blade, as 2.08 Hz.

Basic test of Wind World 500 kW

The content of the basic test is described by Tripod[5], and main information is shown in Table 1. The natural frequencies at standstill were measured and reviewed in Table 2, from Tripod[6].

Load measurements on WW 500 kW

The test program is described in Paulsen[7]. The instrumentation of the Wind World 500 kW (WWLD500) is almost identical to the instrumentation on NTK500, with exception of the measurement of flapwise blade load distribution and the tower top bending moments.

4. DESCRIPTION OF THE AEROELASTIC CODE

The aeroelastic code can be any aeroelastic code that includes the turbulent wind input to the rotor and takes all the measured modal eigenfrequencies into account. The aeroelastic calculations to be presented are based on simulations with Riso’s aeroelastic code DBP2, described by Larsen et al.[8]. Basically DBP2 is a fully integrated model of a horizontal axis turbine with all essential couplings between tower, transmission system, generator and blades taken into account. At present the model is limited to standstill situations and to normal operation of the turbine, and the model work either in the frequency domain or in the time domain. The code do not include a detailed stall hysteresis model. However, the stall load cases can be approximated by a simple gradient method. By calibrating the profile characteristics to measurements, the stall load performance may be further improved. The structure of the model is illustrated in Figure 1. The load models comprise volume forces (gravity-, centrifugal-, Coriolis forces, and inertia forces due to elastic deformations of the structure) and surface forces caused by the wind field. The wind field contains a deterministic as well as a stochastic component, thus inducing elastic deformations comprising both a deterministic and a stochastic part. Taking into account geometric stiffness and weakening contributions in the structural model, all the volume forces comprises a deterministic as well as a stochastic load part.

The wind load due to the mean wind (including wind shear, tower influence, yaw error, and inclination of the ground) comprises the deterministic part of the wind, whereas the temporal wind speed variation caused by turbulence is introduced in terms of a stochastic process model. The aerodynamic model is used to transform the wind flow field to loads on the structure. Here an extended version of the two-dimensional blade element theory has been applied. Inclination of ground surface, tilt, yaw-error and coning can be taken into account. As illustrated in Fig. 2, the structural model comprises two degrees of freedom on each blade, one degree of freedom on both asynchronous generator and main shaft, and four degrees of freedom related to the tower. The common small-deformation assumption is adopted, and the mechanical behaviour of the generator is described only in terms of damping and inertia quantities. In formulating the dynamic equilibrium equations the modal decomposition technique is adopted for the components tower, transmission system and blades. Thus, the resulting equations are formulated with a mixture of generalized coordinates (modal amplitude functions) and physical coordinates as the unknowns.

5. VERIFICATION OF LOADS

Two specific load cases at 10 m/s and 16 m/s are simulated and the results are compared with the correspondent experimental data sets.
Inputs to the aeroelastic code

Two classes of input data are required for numerical simulation of the behaviour of a wind turbine structure: data characterizing the dynamic behaviour of the structure, and data specifying the load cases to be investigated. The data interrelated directly to the structure are: the main data of the turbine (tilt, coning, number of blades, etc.), the stiffness properties and the mass distribution of the involved elastic components, the total mass and centre of gravity of the nacelle system (inc. gearbox, generator, yaw system, main axis and bearings, but ex. rotor and hub) and the inertia of the nacelle system. Moreover, it includes generator and gearbox characteristics. These data were obtained from available drawing material originating from the approval of the wind turbine. The structural input data has finally been fine tuned to yield the measured tower-, tilt-, and yaw natural frequencies obtained from the basic test of the wind turbine (Table 2). Due to lack of time, the 3D aerodynamic adjustment based on blade load distribution measurements was not performed. The relevant data related to the description of the load cases are the mean wind speed V, the turbulence length scale L, the coherence decay factor A (assuming a Davenport coherence decay model), the turbulence intensity factor I, the roughness length of the terrain (z_0 = 0.001), and the yaw error Φ. These data were obtained from an analysis of the wind measurements related to the relevant structural measurements and put in, Table 3.

Load statistics

From the wind statistics and operational conditions of the turbines, a set of input data to the code is provided in Table 3. Statistics based on 10-minutes time series of flapwise root bending moment M_3 and tower top torsion moment M_4 are shown for the Nordtank in Tables 4&5 and for the Wind World in Tables 6&7. The variance and the range from the load statistics differ not significantly except for the stalled conditions at load case 16 m/s of WWLD500 (M_3) and NTK500 (M_4).

Power density plots

The results for the flapwise bending moments corresponding to the load case 10 m/s are shown in Fig.3&4. The model estimates of the M_3 spectra shows in general a variance which is close to those obtained from measurements (see Tables 4&6 for comparison). However, the figures indicate that a better agreement is achieved for the WWLD500 in the high frequency part of the spectrum. Deviations between the measured and fitted spectra in the high frequency range are likely inferred by misfit of the coherence (see Table 3 foot-note).

The fundamental rotational frequency of 0.5 Hz (1p) and higher harmonics (up to 8p) are represented in the spectra. There is reasonable agreement between fitted and measured energy at 1p, although the simulations underestimate moderately for the NTK500. The predicted peaks at 2p and 3p are more evident and steeper than those corresponding to the experimental data. This indicates that the damping in the simulations is less than the damping in the structure. In addition peaks are observed at the two asymmetrical rotor modes and at the symmetrical mode. They are identified at frequencies displayed in Table 2. The prediction is quite close to the measured spectra. The 1st tower bending mode at 0.72 Hz (WWLD500) is in Fig.4 amplified in the code, but not significantly in the measured spectrum. In case of NTK500, the 1st tower bending mode is difficult to detect in the predicted as well as in the measured spectra.

The mode shapes at higher frequencies are in general more complex and uncertain than at lower frequencies: the code estimates peaks in the range of 3-4 Hz which are not measured for NTK500. However, the energy content at those frequencies is small.

Concerning WWLD500 there seems to be experimental evidence for expecting some energy at the high frequency part of the spectrum (7p). The results for M_3 corresponding to 16 m/s are displayed in Figs.5&6.

The predictions are quite close to the measurements, considering the missing 3D aerodynamic properties. The 1st tower bending mode is visible both for fitted and measured data, although the calculated peaks are underrated. WWLD500 displays smaller measured peaks than fitted. The amplification is partly explained by the influence of the -14° yaw misalignment. In this situation the code does not account for stochastic variations of the wind direction. There is a significant difference in variance between the measured and simulated results for the WWLD500 as displayed in Table 6. The explanation is believed to depend on the background turbulence. For the simulations a slow variation in the time series occurred, which was not present in the measurements.

The spectra of the tower top torsion M_4 at load case 10 m/s, are shown in Fig. 7&8. The fitted spectra are close to the measured spectra with exception of the NTK500 at the 1st tower bending mode. The measured peak at 1p is expected due to strain-gauge sensitivity from bending, but should not be present in the tower torsion response. Amplification of peaks at 3p and 6p is consistent with the observation, that the turbulence input to the rotor causes harmonics of 3p in the fixed frame of reference. It is evident from the figures that the asymmetrical rotor modes contribute to the broad and high energy level just below 2 Hz.
The modelled spectra are below the correspondent experimental spectra for both types of machines, except at 3p and 6p. As for the load case 10 m/s, the yaw misalignment introduces a periodic variation of the flapwise blade loads and a amplification of 3p harmonics in the fixed (tower) frame of reference. Concerning the NTK500, the differences in variance between measured and simulated correspondents is due to a slowly varying component in the simulated time series. This component might be removed by selecting a smaller decay factor in the coherence model (this decay factor was not estimated from wind measurements).

Rainflow spectra

Rainflow counting is carried out on the flapwise root bending moment signals $M_\alpha$ and on tower top torsion $M_{\theta}$, with a 3p cps reference, for the determination of equivalent load ranges. The total range is limited to 310 kNm for $M_\alpha$ and 275 kNm for $M_{\theta}$, in order to get comparable counts for measurements and simulations, respectively. In order to investigate the influence on the life-time consumption originating from variations in the Wöhler exponent $m$, equivalent load ranges have been estimated for $m=4$, $8$ and $12$. The determination of the equivalent load ranges was based on optimum resolution for the individual signals.

In Fig. 9&10, the rainflow spectra for $M_\alpha$ corresponding to NTK500 and WWLD500 at 10 m/s, are shown. In analogy, Fig. 13&14 display the results for the wind condition 16 m/s.

The fitted values are consequently overestimated. However, the shapes are very alike except for WWLD-500 at 16 m/s. The result of the rainflow counting of $M_\alpha$ are shown in Fig. 15-18.

The model adequately estimates the trend and the magnitude of the counts of the correspondent measured spectra at 10 m/s. Differences in the graphs are obtained at low loads where measurement uncertainty in general is high. However, the contribution at the low ranges have minor effect on the life-time consumption for construction details.

The NTK500 rainflow spectra at 16 m/s demonstrate a difference between fitted and measured results, which will significantly influence the life-time.

A comparison of equivalent load ranges for NTK500 and WWLD500 are performed in Tables 8&9.

Concerning the 10 m/s load case, the displayed difference between simulated and measured equivalent load ranges for the flapwise moment $M_\alpha$, are within 5% and 12% for the NTK500 and the WWLD500, respectively. A deviation of this order of magnitude is considered fully satisfactory.

As for the 16 m/s load case, the difference for the NTK500 is of the order of magnitude 10%, whereas a difference for the WWLD500 of 40% is found. A considerable difference was also observed in the variance for this signal, and the explanation is a misfit of the background turbulence as stated earlier.

Generally the form of the rainflow spectra for $M_\alpha$, regarding the load case 10 m/s display a satisfactory agreement between measurements and simulations. For NTK500 differences of the order of magnitude 18% are displayed for glassfibre materials and for steel. As for WWLD500 the corresponding differences are 1% and 9%, respectively.

Concerning the equivalent load ranges for $M_\alpha$ at the load case 16 m/s, differences of the order of magnitude 4% are revealed for WWLD500. As for NTK500, differences of the order of magnitude 34% are observed. These significant differences were also observed in the variance, and the explanation is believed to be caused by the missing coherence fit for this turbine. Moreover the missing 3D aerodynamic profile data fitted from blade loading measurements may contribute.

CONCLUSIONS

The paper describes a procedure, concept testing, how to reduce the extent and content of wind turbine tests and at the same time to preserve the quality of the verification standard. By combining simulations and basic test measurements on a wind turbine, detailed information on the structural behaviour are facilitated on conceptual alike wind turbines.

Simulations are made with the aerelastic code DBP2 on a Nordtank 500 kW and on a Wind World 500 kW horizontal axis wind turbine. The results were compared with experimental data collected from concept test, basic test and load measurements on the turbines. Power spectral density functions were derived and discussed for simulated and measured conditions. Rainflow counting analysis was done and it was demonstrated, how the simulated results will influence rainflow spectra and equivalent load ranges.

The subjects covered reveal satisfactory agreement between results derived from simulations and from the correspondent experimental load measurements. Divergence between experiment and theory can be explained and accounted for. It is believed that an adjustment of aerodynamic profile data fitted from blade load distribution measurements will contribute positively on additional convergence. Concept testing has thus, so far shown promising results of combining detailed measurements with aerelastic code.
REFERENCES


---

Key parameter: Make

<table>
<thead>
<tr>
<th></th>
<th>NTK500</th>
<th>WWLD500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Diameter</td>
<td>37.0m</td>
<td>37.1m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>35m</td>
<td>35m</td>
</tr>
<tr>
<td>RPM</td>
<td>30.2 rpm</td>
<td>30.1 rpm</td>
</tr>
<tr>
<td>Tilt</td>
<td>2°</td>
<td>4°</td>
</tr>
<tr>
<td>Tip angle</td>
<td>-2°</td>
<td>-1.8°</td>
</tr>
<tr>
<td>Tower Height</td>
<td>33.8m</td>
<td>33.5m</td>
</tr>
<tr>
<td>Weights Rotor in. hub</td>
<td>8010kg</td>
<td>9500kg</td>
</tr>
<tr>
<td>nacelle, ex. hub</td>
<td>15400kg</td>
<td>21000kg</td>
</tr>
<tr>
<td>tower</td>
<td>22500kg</td>
<td>18100kg</td>
</tr>
</tbody>
</table>

Tab. 1 Technical specifications for NTK500 and WWLD500, from Ref. [1] and [6], respectively.

<table>
<thead>
<tr>
<th>Model/Make</th>
<th>NTK-500</th>
<th>WWLD-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 st tower bending</td>
<td>0.81 Hz</td>
<td>0.72 Hz</td>
</tr>
<tr>
<td>1 st asym. rotor/torsion</td>
<td>1.63 Hz</td>
<td>1.72 Hz</td>
</tr>
<tr>
<td>1 st asym. rotor/2. nd tow.</td>
<td>1.72 Hz</td>
<td>1.84 Hz</td>
</tr>
<tr>
<td>1 st sym. rotor/ flapw.</td>
<td>2.07 Hz</td>
<td>3.12 Hz</td>
</tr>
<tr>
<td>1 st sym rotor/edgew.</td>
<td>3.43 Hz</td>
<td>3.5 Hz</td>
</tr>
</tbody>
</table>

Tab. 2 Natural frequencies at standstill for NTK500 and WWLD500, from Ref. [1] and [6], respectively.

<table>
<thead>
<tr>
<th>MAKE</th>
<th>V [m/s]</th>
<th>I [%]</th>
<th>L [m]</th>
<th>A</th>
<th>( \phi [^\circ] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTK 500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.73</td>
<td>14.4</td>
<td>800**</td>
<td>7.15**</td>
<td>+6</td>
<td></td>
</tr>
<tr>
<td>16.00</td>
<td>11.5</td>
<td>800**</td>
<td>7.15**</td>
<td>+0</td>
<td></td>
</tr>
<tr>
<td>WWLD 500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>12.5</td>
<td>900</td>
<td>8.38</td>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>16.05</td>
<td>12.7</td>
<td>1200</td>
<td>13.57</td>
<td>-14.4</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 3 Load characteristics data input to DBP2.

**Note: This figure is not adjusted to the actual wind situation, but standard values for the site have been applied."
<table>
<thead>
<tr>
<th>NTKSOO</th>
<th>10 m/s</th>
<th>16 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>M, [kNm]</td>
<td>SIM.</td>
<td>MEAS.</td>
</tr>
<tr>
<td>average</td>
<td>160.6</td>
<td>215.2</td>
</tr>
<tr>
<td>st. dev.</td>
<td>26.26</td>
<td>27.35</td>
</tr>
<tr>
<td>max</td>
<td>346.3</td>
<td>301.2</td>
</tr>
<tr>
<td>min</td>
<td>70.2</td>
<td>116.5</td>
</tr>
<tr>
<td>range</td>
<td>176.0</td>
<td>184.7</td>
</tr>
</tbody>
</table>

Tab. 4 NTKSOO flapwise root bending load statistics at 10 and 16 m/s.

<table>
<thead>
<tr>
<th>WWLD500</th>
<th>10 m/s</th>
<th>16 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>M, [kNm]</td>
<td>SIM.</td>
<td>MEAS.</td>
</tr>
<tr>
<td>average</td>
<td>153.6</td>
<td>116.6</td>
</tr>
<tr>
<td>st. dev.</td>
<td>22.67</td>
<td>19.56</td>
</tr>
<tr>
<td>max</td>
<td>229.5</td>
<td>195.7</td>
</tr>
<tr>
<td>min</td>
<td>69.5</td>
<td>53.7</td>
</tr>
<tr>
<td>range</td>
<td>160.0</td>
<td>142.0</td>
</tr>
</tbody>
</table>

Tab. 6 WWLD500 flapwise root bending load statistics at 10 and 16 m/s.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m/s</td>
<td>4</td>
<td>56.62</td>
<td>59.70</td>
<td>80.29</td>
<td>65.91</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>81.68</td>
<td>83.85</td>
<td>106.26</td>
<td>86.19</td>
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<tr>
<td></td>
<td>12</td>
<td>101.69</td>
<td>102.81</td>
<td>127.48</td>
<td>103.87</td>
</tr>
<tr>
<td>16 m/s</td>
<td>4</td>
<td>82.71</td>
<td>72.01</td>
<td>114.35</td>
<td>77.07</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>112.72</td>
<td>100.32</td>
<td>148.27</td>
<td>98.25</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>134.56</td>
<td>122.72</td>
<td>178.88</td>
<td>115.80</td>
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</table>

Tab. 8 NTKSOO equivalent load ranges at 10 m/s and 16 m/s.

<table>
<thead>
<tr>
<th>WWLD500</th>
<th>10 m/s</th>
<th>16 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>M, [kNm]</td>
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<td>MEAS.</td>
</tr>
<tr>
<td>average</td>
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<td>9.7</td>
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<tr>
<td>st. dev.</td>
<td>22.55</td>
<td>23.81</td>
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<td>max</td>
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<tr>
<td>min</td>
<td>80.1</td>
<td>129.1</td>
</tr>
<tr>
<td>range</td>
<td>169.3</td>
<td>169.1</td>
</tr>
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</table>

Tab. 7 WWLD500 tower top torsion load statistics at 10 and 16 m/s.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m/s</td>
<td>4</td>
<td>49.49</td>
<td>55.20</td>
<td>60.25</td>
<td>65.51</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>68.37</td>
<td>77.54</td>
<td>80.88</td>
<td>83.23</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>82.64</td>
<td>94.96</td>
<td>98.59</td>
<td>98.14</td>
</tr>
<tr>
<td>16 m/s</td>
<td>4</td>
<td>80.77</td>
<td>114.07</td>
<td>109.73</td>
<td>95.54</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>105.21</td>
<td>142.90</td>
<td>138.68</td>
<td>119.63</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>123.31</td>
<td>163.60</td>
<td>160.85</td>
<td>140.30</td>
</tr>
</tbody>
</table>

Tab. 9 WWLD500 equivalent load ranges at 10 m/s and 16 m/s.
Figure 1 Elements of the model.

Figure 2 Degrees of freedom and component coordinate systems.

Figure 3 Power spectra for flapwise bending moment, NTK500, 10 m/s.

Figure 4 Power spectra for flapwise bending moments, WWLD500, 10 m/s.
Figure 5 Power spectra of flapwise bending moments, NTK500, 16 m/s.

Figure 7 Power spectra of tower top torsion, WWLD500, 10 m/s.

Figure 6 Power spectra of flapwise bending moment, WWLD500, 16 m/s.

Figure 8 Power spectra for tower top torsion, WWLD500, 10 m/s.
Figure 9  Power spectra of tower top torsion, NTK500, 16 m/s.

Figure 11  Load spectra of flapwise bending moment, NTK500, 10 m/s.

Figure 10  Power spectra of tower top torsion, WWLD500, 16 m/s.

Figure 12  Load spectra of flapwise bending moment, WWLD500, 10 m/s.
Figure 13 Load spectra of flapwise bending moment, NTK500, 16 m/s.

Figure 15 Load spectra of tower top torsion, NTK500, 10 m/s.

Figure 14 Load spectra of flapwise bending moment, WWLD500, 16 m/s.

Figure 16 Load spectra of tower top torsion, WWLD500, 10 m/s.
Figure 17 Load spectra for tower top torsion, NTK500, 16 m/s.

Figure 18 Load spectra of tower top torsion, WWLD500, 16 m/s.
SPOT CHECK ON OPERATING WIND TURBINES

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ABSTRACT: As a part of the Danish Type approval and certification system for wind turbines, the Test Station for Wind Turbines has since 1988 been doing spot checks on randomly selected wind turbines that have been approved and erected in Denmark. This paper describes the objectives, procedures, methods, results and the considerable experience obtained with this type of tests.

2. BACKGROUND

Wind turbines installed in Denmark have been regulated through a public systems approval scheme as a part of the administration of the Danish subsidy scheme for renewable energy installations. This approval scheme has been in force since 1979. In connection with the decision to stop the subsidy scheme for wind turbines in Denmark, a new system for type approval of wind turbines and certification of the quality assurance systems for production and installation was established in 1991. The background for the establishment of a new approval scheme in Denmark is a common desire from manufacturers and users that a coherent set of rules and a quality control system for wind turbines should be created covering the complete process from design to installation. Approval is in Denmark mandatory for grid connected and non grid-connected wind turbines with a rotor diameter larger than 6 m. It is the aim with the approval scheme to ensure compliance with current safety requirements and to ensure that quality aspects such as performance and noise emission is properly documented. It is the goal that the system shall satisfy as far as possible those requirements set by both producers, wind turbine owners, insurance companies and authorities. The approval scheme has been adapted to requirements and procedures needed in the future with a view to the technical harmonization within the European Community.

One of the elements in the approval system has since 1988 been spot checks on operating wind turbines. The spot check system is seen as a follow-up on the type approval and certification and is carried out by the Test Station for Wind Turbines.

3. OBJECTIVE

The objective of spot checks is to do an conformity assessment of the operating wind turbines against the type approval specification of the wind turbine. The spot checks assesses both the conformity of the components in the wind turbine and of the manufacturing quality with the type approval specifications. Furthermore the objective is to give a feedback on the status of the wind turbines after a certain operation period and on the quality of the O&M-status of the wind turbines to the Test Station for Wind Turbines and the Energy Agency. The overall expectation is through the spot checks together with the strengthening of the requirements in the type approval system continuously to improve the quality of the wind turbines. For one thing, the spot checks help to obtain a higher degree of conformity of the wind turbines with the type approval specifications.

4. THE SPOT CHECK SYSTEM

In the autumn 1988 the Test station started developing the spot check system. First forms and procedures were developed and spot checks were carried out on 6 wind turbines. After this first phase the procedures, specifications of measuring methods and forms were made.

4.1 Procedure

The selection of wind turbines for spot check is partly random and partly based on information available for the Test Station for Wind turbines and for the Energy Agency. The wind turbine manufacturer in informed 2 weeks in advance of a spot check on one of his wind turbines scheduled for a specific date. He is informed about the type of machine to be checked, but not about the specific machine to be checked. The manufacturer is...
obliged to send a representative that can operate the wind turbine hereunder test the safety systems.

A few days before the spot check the manufacturer is informed about which specific wind turbine will be checked. Thereafter the manufacturer is responsible for making an appointment with the wind turbine owner about the spot check on the wind turbine and make appointments about responsibilities for possible damage on the wind turbine under the tests of the safety system. An engineer and a technician from the Test Station for Wind turbines carries out the spot check together with the representative from the manufacturer. Occasionally, also the wind turbine owner is present during the spot check.

4.2 The spot check action

At the spot checks general information about the wind turbine is registered. The relevant information is e.g. wind turbine type, wind turbine owner, the text on the wind turbine nameplate, manufacturing time, erection time, production since erection, relevant. The Crew from the Test Station for Wind turbines then examines the wind turbine. As mentioned above, the spot check investigation of the wind turbine includes 1) the conformity with the type approval specification including both the components used in the wind turbine and the manufacturing quality and 2) the present status for the machine O&M in form of manufacturing quality and wear and tear. The crew looks at the following:

- foundation, bottom tower flange, strength of the door opening, weldings in the tower, flanges in the tower
- yaw system
- bed plate
- main bearings, bearing housing and connection to bed plate
- other bolt connections, e.g. in connections to hub and blades, gearbox mounting etc.
- rotor blades
- gearbox, hereunder slip in shafts and bearings. Occasionally the gearbox cover is removed and tooth wheels and bearings are investigated
- mounting of the generator
- the transmission system and possible coupling unbalance
- the mechanical brake system

During the investigation, the turbine is investigated for cracks, tolerances, unbalance, slip, and all nameplates and components are registered. Photos are taken of the nameplates, and of details leading to remarks etc. A photographic method is used for determining the blade tip angles.

Furthermore, the site is documented by photographs of the surroundings of the wind turbine.

During the spot check the labour safety is investigated and compared with general requirements in Denmark. Also the noise emission around the turbine is analyzed and an attempt is made to identify the noise emission sources.

Finally the safety system, hereunder the aerodynamical brakes is tested. The tests of the safety system are recorded with a video camera.

Check data are recorded by means of the spot check forms and compared with the type approval specification of the components and the manufacturing quality. The spot check report is handed to the wind turbine owner, the manufacturer and the Energy Agency.

5. EXPERIENCES WITH THE SPOT CHECKS OF WIND TURBINES

Since 1988 the Test Station for Wind turbines has carried out 70 spot checks on wind turbines erected in Denmark, Ref. 1. The results from the compliance assessments with the type approval specification is given in table 1. Numbers in the table for each spot check year are the number of spot checks during the year, and the number and percentage of the wind turbines that did not comply with the type approval specification. For most of the turbines where there are deviations from the type approval specification, only one component in the turbine deviates from the specification. Only two manufacturers had more than one component-deviation per turbine and these two manufacturer went broke around 1990 and 1991.

Tab.1 Wind turbines not complying with the type approval specification.

<table>
<thead>
<tr>
<th>Year</th>
<th>Turbines checked</th>
<th>Turbines not complying</th>
<th>Percentage not complying [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>13</td>
<td>7</td>
<td>54</td>
</tr>
<tr>
<td>1989</td>
<td>19</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>1990</td>
<td>6</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>1991</td>
<td>8</td>
<td>3</td>
<td>38</td>
</tr>
<tr>
<td>1992</td>
<td>13</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>1993</td>
<td>0</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>1994</td>
<td>11</td>
<td>7</td>
<td>64</td>
</tr>
</tbody>
</table>

The years 1988 and 1989 showed a high percentage of turbines not complying with the type approval.
specification. As a consequence of this finding, actions were taken to achieve compliance with the type approval specification.

The years 1990 and 1991 the wind turbines which did not comply with the type approval specification was from one manufacturer. The manufacturer stopped his operation around 1991.

The one wind turbine in 1992 which did not comply had a tower which was not type approved. The manufacturer was requested to apply for approval of the tower or to change the tower to the type approved tower.

The 2 wind turbines in 1994 was from the same manufacturer. On both turbines there were 3 instead of 2 breaking calibers on the mechanical breaking system. The turbine was approved with 2 calibers. The wind turbine is now approved with 3 calibers.

As can be seen, the conformity with the type approval specification has over the year reached a satisfactory level. Of course it is difficult to measure why the degree of compliance has improved, but we are sure that the spot check systems has played an important role. One of the experiences is that the manufacturer sometimes fails to realize, when a changes in the design have to be approved (eg. same bolt quality but a different bolt supplier shall not have an approval).

Spot check results on the conformity assessment of the production and installation quality combined with comments about unsatisfactory O&M, are given in table 2. The seriousness of the quality failures is best illustrated by the observation, that the improvements requested to remedy the weaknesses, are mostly obtained through ordinary O&M on the turbines.

Tab. 2 Quality deviations in production and installation of the turbine and missing O&M observed by spot checks in 1992-94.

<table>
<thead>
<tr>
<th>Problem</th>
<th>In percentage of turbines checked (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower and foundation</td>
<td>16</td>
</tr>
<tr>
<td>Oil- and hydraulic oil leakage</td>
<td>17</td>
</tr>
<tr>
<td>Transmission system</td>
<td>6</td>
</tr>
<tr>
<td>Yawing system</td>
<td>3</td>
</tr>
<tr>
<td>Safety system</td>
<td>6</td>
</tr>
<tr>
<td>Blade cracks (small)</td>
<td>1</td>
</tr>
<tr>
<td>Cable fixing</td>
<td>1</td>
</tr>
<tr>
<td>Labour safety</td>
<td>7</td>
</tr>
</tbody>
</table>

It can be seen in the spot-check reports that the problems mentioned in table 2 in 1992-1994 are mainly gear-box oil and hydraulic oil leakage problems.

The spot checks reveals the improvements of the wind turbines. During the first years the spot checks found more serious production-quality and O&M problems. Today problems revealed are usually minor problems as eg. oil leakage.

Tab. 3 The number of observed quality and O&M problems over time in percentage of the number of spot checks per year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Wind turbines with quality or O&amp;M problems [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>117</td>
</tr>
<tr>
<td>1989</td>
<td>95</td>
</tr>
<tr>
<td>1990</td>
<td>83</td>
</tr>
<tr>
<td>1991</td>
<td>40</td>
</tr>
<tr>
<td>1992</td>
<td>46</td>
</tr>
<tr>
<td>1994</td>
<td>45</td>
</tr>
</tbody>
</table>

The level 30-40% of the machines, we think is very realistic. It means that it is very difficult to make a wind turbine without minor oil- or hydraulic oil problems. And in the best wind turbines today we see leakage problems at that level.

For comparable machines we think the level is very realistic. On the other side the statistics shows that there still is something to be gained with respect to solving the leakage problems.

6. CONCLUSION.

The experience since 1988 with a spot check system as a part of the danish approval system is, that the spot check is a very useful tool together with the requirement for a certified quality assurance system in order to achieve compliance between the wind turbines erected in Denmark and the type approval specification. Furthermore the spot checks shows an significant improvement in the production and installation quality. Finally we can recommend the spot check as a very useful feed back mechanism revealing the quality of the wind turbines erected and also the quality of the O&M being carried out on the machines. And finally the spot check system in relation to wind turbine owners, financiers, insurance companies and the general public creates confidence to the technology which is seen to be very important for the future utilization of wind energy.

REFERENCES.

INTRODUCTION

Before describing the data analysis, let us briefly outline some wind flow characteristics presumed important when dealing with fatigue loading within a wind farm. Several approaches have been applied in the prediction of loads, however in all cases the flow inside the wind farm or in the wake of one wind turbine results from both the conditions of the ambient flow and the presence of the wind turbines themselves. The characteristics of the ambient flow - relevant when discussing wind loads - are mean wind speed, vertical wind gradient, turbulence intensity and the scale of turbulence. These characteristics remain important to fatigue in wind farms and in addition horizontal gradients in wind speed and inhomogeneities in turbulence intensity caused by surrounding wind turbines must be considered. Also, a fair amount of measurements have been carried out on various aspects of loads in wind farms.

Thus, in advance of these measurements, it was known that wind load conditions inside and outside a wind farm are different. So the basic question before this analysis is, whether the effects of the wind farm combined cause a reduction of lifetime of the wind turbines: on the one hand horizontal gradients, vertical gradient of turbulence and/or increased turbulence and higher load frequency decrease lifetime, but on the other hand does the decreased mean wind speed increase lifetime.

In this paper we analyze the change of fatigue loading caused by the wind farm itself by comparing the so called equivalent load on a wind turbine at the edge of the wind farm to one placed deep inside the wind farm. Before that, we analyze the change in flow conditions inside and outside the wind farm by comparing wind speed and turbulence measurements from the two meteorological towers erected for the purpose.

THE TEST SITE

Fig. 1 shows the layout of the wind farm. The 42 machines - Nordtank 300kW, hub height 31m and D=28m - are numbered A1 through F7, the instrumented machines being A1 and F6. The two wind turbines are amongst others instrumented for measurement of flatwise bending moment of blades. Meteorological towers, 58m of height, are placed close to these two machines; wind speed and turbulence are measured in 7 heights. Data are sampled at 25 Hz and selected time series stored. Also, statistics - including fatigue parameters - for the 30 min. series are calculated and stored. In this analysis only statistical data are employed, and then only data where 40 out of 42 machines are operating. A total of about 4000 half-hour periods satisfy this condition.

![Fig. 1 Layout of wind farm site; water surface to the north and otherwise farmland. One met tower in the SW corner and one to the west of the F6 machine.](image-url)
AVERAGE FLOW CONDITIONS

To shed light on what can be expected when the wind turbine spacing is fairly large, let us consider the global flow conditions. In fairly flat homogeneous terrain boundary layer similarity theory tells that in neutral atmospheric stratification the change of wind speed \( u \) with height \( z \) is logarithmic:

\[
\frac{u}{u_*} = 1 + \kappa \ln \left( \frac{z}{z_o} \right)
\]

where \( u_* \) is the so called friction velocity and \( \kappa \) the von Karman constant (measured to be 0.4). With neutral stratification is meant that the air temperature variation with height is such that mixing of air is only generated mechanically. The influence of a large array of wind turbines has first been modelled by Templin (1974), referred by Newman (1976), and in a modified way by Frandsen (1992) and Emeis and Frandsen (1993). The basic assumption in Frandsen and Emeis (1993) is that 1) the vertical wind profile is logarithmic over and under hub height with a discontinuity in slope at hub height, and 2) the impact of the turbines on the flow is a discrete-layer, horizontally evenly distributed shear stress at hub height (h):

\[
I = \rho \, c_t \, u_h^2
\]

where \( u_h \) is the wind speed at hub height, and the term \( c_t \) is the average drag from the wind turbines per m² of occupied land:

\[
c_t = \pi C_T/(8 s^2)
\]

where \( C_T \) is the wind turbine drag coefficient and \( s \) is the average number of rotor diameters separation. The surface-layer flow is linked to the geostrophic wind speed by the geostrophic drag law:

\[
\frac{u_o}{G} = \frac{\kappa}{\ln \left( \frac{f}{z_o} \right) - 4}
\]

where \( G \) is the geotropic wind speed and \( f \) is the Coriolis parameter. Combining the assumptions and equations leads to the following apparent roughness for the flow above hub height:

\[
z_{e,app} = h \cdot \exp \left[ -\frac{1}{\sqrt{c_t \cdot (\kappa \ln(h/z_o))^2}} \right]
\]

The friction velocity for the outer flow layer, \( u_{e,outer} \), is determined by [4], and for the layer below hub height in turn by \( u_{e,bottom} = \frac{u_{e,outer} - I}{I} \). Turbulence is assumed to be proportional to the friction velocity and consequently according to the model, the turbulence has increased above hub height and decreased (similarly) below hub height.

The modelled reduction and increase factors, respectively, for wind speed and turbulence \( R_s \) and \( R_T \) are shown in Fig. 2, together with ratios of measured averaged wind speeds (at hub height) and turbulence (at 58m) in the two towers. The measured values are averaged over a wind direction sector of ±30° around the diagonal direction, see Fig. 7. In the model, the applied rotor thrust coefficient, \( C_T(u) \), was computed, having a maximum at 5-6 m/s of 0.8 decreasing to 0.2 at 20 m/s. It is seen that for low wind speeds, the wind farm has maximum effect on the flow, increasing turbulence with 40 % above rotor height, and decreasing hub height wind speed with 10-20 %. While the model's prediction of turbulence above rotor height is excellent, the speed reduction shows significant deviations. When the wind speed decreases, more and more wind turbines stop and the two ratios approach 1.

![Fig. 2 Ratios of wind speed at hub height (31m) and turbulence (58m) inside and outside the wind farm, as a function of wind speed.](image-url)

Figs. 3 and 4 show measured vertical profiles of ratios of wind speed and turbulence. The data were averaged over the same wind direction as in Fig. 2. For low wind speeds (and high \( C_T \)) the turbulence level at the top of the rotor is increased - as said - with 40 %, but at the bottom virtually unchanged. For high wind speeds the wind speed reduction is less pronounced, and it is noted that in this case there is a turbulence reduction below the rotor of approx. the same magnitude as the increase above the rotor, which in turn supports the model.
Thus, what can be expected inside the wind is - apart from near-wake situations - a rather uniform decrease in wind speed and an increase in turbulence at the top of the rotor, and unchanged or decreased turbulence at the rotor bottom.

**STRUCTURAL LOADS - FATIGUE**

As indicated above, fatigue loads have been evaluated on basis of data from the two instrumented wind turbines in opposite corners of the wind turbine array. The smallest machine separation is 6D, and therefore large deterministic wake effects are not expected.

The flatwise blade root bending moment has been chosen to represent loads on the wind turbine. Flatwise and lead/lag strain signals (blade root moments) are measured on the two turbines, A1 and F6, Fig. 1. For selected wind direction sectors one of the two turbines will be fully exposed to the wind-generated flow field, with the other turbine basically being exposed to the undisturbed flow. The computed load range distributions are reduced to pairs of "equivalent" frequencies and load widths, as outlined below.

In order to get suitable measures of the dynamic loading we are using the concepts of the simplified load description in the new Danish code of practice for wind mills, Norm for last og sikkerhed for vindmøllekonstruktioner (1992), also described briefly below.

Evaluation of fatigue loads is done in two ways. First, the dependency on the wind direction of the so-called equivalent load width is studied to detect special causes of increase. Then estimates of increased life time consumption in the wakes is made from the measurements and the fatigue life is determined by weighting the sector-by-sector fatigue life consumption. Secondly the fatigue life consumption is found by simple summation over a representative wind sector ranges.

**The Danish Code Load Distributions.**

In the Danish code of practice for design of wind turbines, the fatigue-inducing part of the dynamic load is described in terms of an accumulated load width distribution. Fig. 5 illustrates a typical blade root lead/lag moment width distribution. The distribution is calculated as the sum of two distributions. One is a deterministic, constant amplitude (e.g. gravity) load acting on a rotating blade. The corresponding accumulated load width distribution is a simple step function, in Fig. 5 the curve marked 'gravity only'. It contains N, = 3.4 \times 10^6 widths (i.e. 1P cycles during a 20 yr lifetime of the wind turbine). The other distribution is a standardized shape multiplied with a constant depending on the turbine design and climatic conditions (Fig. 5, 'air forces only'). This distribution represents a stochastic load pattern, caused by the atmospheric turbulence. The sum distribution in Fig. 5 is marked 'all forces'. The resulting width distribution is a blade root lead/lag moment distribution, where the deterministic gravity load dominates. The discontinuity at N, = 3.4 \times 10^6 cycles corresponds to the number of rotations of the rotor over the 20 yr design life time. These N, largest widths consist of deterministic gravity induced widths superimposed with stochastic widths induced by air forces.

The standard distribution used as a basis for defining the stochastic distribution can be expressed by the following two equations with \( I \) being the turbulence intensity and \( A \) the Weibull scale factor:
\[ \hat{F}_a(N_r) = \beta (\log(N_r) - \log(N_0)) + 0.18 \]
\[ \beta = 0.11 (1 + 0.1) (A + 4.4) \]  

\( N_r \) is the number of load cycles in the wind turbine's lifetime. This design load-range distribution is a simplification but it has been found to represent real-life cases well.

The flatwise bending moment is predicted in a similar way, but the gravity part is absent. For an experimental example of the two distribution types, see Fig. 6.

**Definition of Equivalent Load**

On the basis of these definitions we can introduce two different measures of dynamics. Fig. 6 shows an example plot of a Rain Flow counting width distribution obtained from the two blade root moments (flatwise and lead/lag). The lines fitted to the distributions for the largest widths are used for determining the slope. The slope of the stochastic distributions is expected to depend on \( \beta \) (Eqs. 6) and through that on the turbulence.

Another measure of the dynamics is the so-called 'damage equivalent load' (DEL). The measured width distribution is described by \( N \) points, where we have found \( n_i \) widths of size \( L_i \) in point no. \( i \). The rotor has made \( N_p \) rotations during the scanning period. The DEL is defined as the one distinct width \( L_i \), which if it appeared \( N_p \) times during the period would have the same damage effect as calculated by means of the Miner sum. Therefore the DEL can be found by equating the Miner sums calculated for the DEL and

\[ N_{i_p}/n_{i_p} = \sum_{i=1}^{N} (n_i/n_{i_p}) \]  
\[ N_{i_p}\Delta \sigma^m_i = \sum_{i=1}^{N} (n_i\Delta \sigma^m_i) \]  
\[ N_{i_p}L_i^m = \sum_{i=1}^{N} (n_iL_i^m) \]  

[8] has been found from [7] by introducing the SN-curve expression (without change of \( m \))

\[ n_{i_p} = k_{i_p}/\Delta \sigma^m_{i_p} \]  

and in [9] we have multiplied the \( \sigma \)'s in [8] by the same resistance moment in order to convert from stresses to loads.

Thus the DEL can be found as

\[ L_i = \left( \sum_{i=1}^{N} (n_i \sigma_i^m)/N_{i_p} \right)^{1/m} \]  

In these measurements we will use this damage equivalent load width (with \( m = 5 \)). Fig. 6 (which is quite typical for measured spectra) shows, that the fit to the Danish Design Code distribution works very well. It should be remarked, however, that on the basis of a 30min series we cover only the upper 3 out of 8 decades.

**FATIGUE LOADING - MEASUREMENTS**

In this section we will show results from the attempts at mapping specifically the influence of the
"nearest wakes" on fatigue loading. Without going into details, it should be mentioned that excessive work has been done in modelling wake deficit, e.g. Jensen (1983) and Lissaman and Bates (1977), and in modelling of turbulence in wakes, e.g. Crespo and Hernández (1993).

The wind direction in the following plots have been shifted such that 0° in the plots corresponds to the main diagonal wake direction, here the A1/C3 or the D5/F7 wake, or in the usual measure of wind direction (Wd), 216.7° from North (see Fig. 7). Thus the angle WdA1 is (Wd-216.7). The resulting directional angles shown in these plots correspond to the wind along the 6-row and the F-row, respectively. We will be concentrating on wind directions between ±90° from this zero direction. In this direction interval, the A1 turbine is in the free stream zone, only disturbed by the mast M1 and of course by the surrounding terrain.

![Fig. 7 Main features of the surroundings.](image)

Figs. 8 and 9 show the behaviour of the dynamic loading in the form of bin-averaged equivalent widths (ew) recorded on the flatwise bending moment on each of the two turbines A1 and F6, as a function of the wind direction in degrees from the main diagonal. Also the ratio between the widths ew_F6 and ew_A1 is shown. The y-axis scale for the ew's is arbitrary, but comparable for the two machines. The scans used in Figs. 8 and 9 have been selected according to power in the A1 turbine. The case of Fig. 8 is for power less than 200 kW and Fig. 9 for power larger than 200 kW. For the two wind directions, -52° and +40°, the wind flow is along the rows with A1 being exposed to the free wind and F6 in one of the major wake directions.

![Fig. 8+9 Ratios of equivalent widths. 8: P<200 kW, 9: P>200 kW. Line: ratio ew_F6/ew_A1. ▲: ew_F6, □:ew_A1.](image)

The ew-ratio shows the following wake conditions (geometry in Fig. 7):
- F1/F5-row on F6 (-52°)
- main diagonal on F6 (0°)
- A6/E6-row on F6 (40°)

The wake angles are not ±45° as the site pattern is not quite rectangular. The angles stated are calculated from geometry. As seen in Fig. 8 and 9 they fit quite well with observation.

In Fig. 8, the increase in equivalent width in the case of flow along the 6-row and the F-row is 10-15 % (higher in F6) for the flatwise bending moment. Fig. 9 is hampered by bad statistics. This actually shows how difficult it is to get data enough for this type of detailed examinations. The data gathering was run for 1 year, but the difficulty of making
sure, that all data are good, together with the need for selections means, that we barely have data enough for good statistics. In particular the wake structure at -52° in Fig. 9 is badly covered with very few scans. The remainder of Fig. 9 does, however hint, that the wake effect is smaller at higher wind speed, i.e. the park gets more transparent. Other data selection criteria have been employed, leading to approximately the same result. Actually the main reason for the difficulty of measuring the precise wake effect is, that the surrounding terrain induces variations in dynamics, that are as large as the wake effects. It is striking, that at -52° the A1 turbine has a wake-like structure in spite of being in free flow. As hinted in the site geometry (Fig. 7), we think, that a hill at about 1.5 km distance from A1 is the reason. Similarly in the region around 50-60° is disturbed by a house with some trees around at 500 m distance and possibly an older wind 2 km away. These features will probably make sure to induce extra turbulence (and dynamics). This brings us to the somewhat surprising conclusion, that the wake effects (at least in the present experiment) is not stronger than the effects of inhomogeneities in a seemingly nice, flat and undisturbed terrain.

Finally we can conclude, that the diagonal row wake effect is quite a bit smaller than that of the 6-row and the F-row, because of the larger distance between the turbines in the diagonal (9D rather than 6-8D).

Fatigue Life Consumption. Method 1.

One way of providing a simple evaluation of the wake effects on dynamic loading is to simply weight each read from the previous figures. The result has a rather high uncertainty because of the difficulty in singling out the wake effects from the topography, however the calculation is obvious.

The increase in dynamic loading in the wake can be expressed through the equivalent width and can be measured from Figs. 8/9 as follows: the difference in $n_w$ factor for flow along the rows is conservatively estimated to 15%, i.e. \( \frac{n_{w,\text{ave}}}{n_{w,\text{free}}} = 1.15 \), with a half-width of 20°. Using the S-N curve for fatigue:

\[
n_w = k / \sigma^n
\]

[12]

the relative fatigue increase in the wake can be expressed as by lifetimes $t_{\text{ave}}/t_{\text{free}} = 1/2$ times worse than outside ($m = 5$). We can also get an idea, how strong the influence for different positions in the may be as follows. With only one possible wake, life time changes by:

\[
\frac{20/360}{n_v} + \frac{340/360}{n_v} = \frac{1.06}{n_v}
\]

deep into the with 4 wakes (diagonal wakes are much weaker and can be neglected):

\[
\frac{80/360}{n_v} + \frac{280/360}{n_v} = \frac{1.22}{n_v}
\]

[13] [14]

I.e. a decrease of lifetime of a factor of 1.2 deep inside a wind corresponds to 4% in fatigue load level. Applying a higher exponent for the S-N curve will lead to slightly larger increase of fatigue level.

Fatigue Life Consumption. Method 2.

Finally, from sets of statistics, data for wind from the north-east and south-west, respectively, have been averaged to investigate whether the reverse results for the two wind directions are obtained, Table 1. These data are not all simultaneous. As seen, the wind speed is lower from the north-east, which for the present purpose is inconvenient. To make comparison possible, lifetime consumptions for the two cases have been transformed to the same wind distribution and distribution of turbulence. The result is shown in the two bottom lines of Table 1. Assuming that the distribution of wind directions within the chosen sectors are representative, it is now found that the difference in fatigue loading for wind coming from the land to the south-west (roughness length: 0.01-0.02m) is negligible, whereas for wind coming from the water side of the wind to the north-east (roughness length =0.001-0.002m) the equivalent load on the A1 (deep inside the park) is app. 10% higher than for the free-stream F6.
**CONCLUSION**

The analysis presented dealt with fatigue loading and causes thereof in the large wind turbine array Nørrekor Skor Enga II, with machine spacings of 6-8 rotor diameters. The major findings concerning turbulence and fatigue loading "deep inside" the wind were:

In a seemingly flat homogeneous area, features (small hills, roughness changes etc.) of the terrain have a large influence on fatigue loading as the strongest wakes.

Disregarding turbulence in the near-wakes, turbulence in a wind is increased at a height corresponding to the top position of the blades, and unchanged or even decreased at the bottom position of the blades, relative to the terrain with no wind.

With wind along the rows of machines, there is a detectable wake effect on fatigue loading.

With wind from terrain with surface roughness corresponding to land, the integrated effect of the wind on fatigue loading is small.

For wind from the sea side of the wind - extremely low surface roughness - there is an increase in the fatigue-inducing equivalent load of approx. 10 % for the machine in the wind.

**REFERENCES**

[1] Frandsen, S., On the Wind Speed Reduction in the Center of Large Clusters of Wind Turbines; Jour. of Wind Engineering and Industrial Aerodynamics, 39 (1992) 251-265


**Table 1.**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SOUTH-WEST</th>
<th>NORTH-EAST</th>
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</thead>
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<td>2 - 79°</td>
</tr>
<tr>
<td>No. of runs</td>
<td>544 ½ hours</td>
<td>504 ½ hours</td>
</tr>
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<td>$\langle Power, AI \rangle$</td>
<td>48.2 kW</td>
<td>13.9 kW</td>
</tr>
<tr>
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<td>19.6 kW</td>
</tr>
<tr>
<td>$\langle Speed, AI \rangle$</td>
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<td>9.3 kW</td>
</tr>
<tr>
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<td>9.1 kW</td>
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</tr>
<tr>
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<td>12 %</td>
</tr>
<tr>
<td>Lift-consumption increase</td>
<td>- 6 %</td>
<td>+ 75 %</td>
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VINDEBY OFFSHORE WIND FARM - FATIGUE LOADS

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INTRODUCTION

The main objectives of the project are to 1) complement the existing base of wind farm data by gathering information on wind speed deficit, turbulence and structural loads at the Vindeby offshore wind farm to investigate the structure of single and multiple wakes under the ideal homogeneous, low-ambient turbulence conditions found offshore, and thus be able to model wake behavior more correctly, and 2) to be able to characterize turbulence and shear in the incoming flow as a function of upstream turbine separation to be utilized in design standards for calculation of loads on wind turbines to be located offshore.

From a statistical point of view few data are available. However, it is possible to get some indications of the flow environment in and around the wind farm. First, we take a brief look at some efforts made in modelling wind speed deficit and turbulence increase in wind farms and thus what could be expected in the presumed low-turbulence flow at sea. Secondly, measurements of wind speeds and turbulence made at the two offshore meteorological towers is presented, and finally measurements of the so-called equivalent stress width - calculated from flapwise root bending moments of the two instrumented wind turbines - are presented.

VINDEBY WIND FARM

Measurements at the offshore Vindeby Wind Farm consisting of 11 450kW BONUS machines (3-bladed, stall regulated, rotor diameter 35m and hub height 37m above average sea level) located 1.5 km off the coast of the island Lolland provide the input to the data analysis. The wind farm was commissioned and set into operation in September 1991. The 11 machines are arranged in two rows, with 6 machines in one row and 5 in the other, Figure 1. The orientation of the rows is 140° azimuth so as to minimize wake effects (the predominant wind direction is west-southwest). The distance between the turbines in each row is 300m (8.5 rotor diameters) and the distance between the rows is likewise 300m. The water depth varies between 3 and 5m.

Two machines, 4W and 5E, are instrumented for structural measurements: flap- and edgewise bending moments on one blade, bending moment in tower base, active and reactive power (voltage and current), yaw position and status. Three 48m meteorological towers have been erected: one is located on land (to provide information on the change of wind characteristic when the wind is coming from land), one (SMW) is placed at an imaginary wind turbine position in the western row (to provide data on multiple wake situations). All meteorological towers are equipped with cup anemometers at least 5 levels, wind direction and temperature sensors. Also, two 3-D sonic anemometers are employed. At the base of one of the seabottom-based towers wave heights are measured.

Sensor signals from the offshore meteorological towers are fed through multi-core cables to one of the instrumented wind turbines from where they are relayed - together with sensor signals from the wind turbines - through an optical fiber cable to the central data storage and processing computer, which is placed in a cabin at the base of the inshore meteorological tower. Structural and meteorological data are sampled continuously at 25 Hz and stored as 30 minute records.
Statistics such as mean, standard deviation, maximum and minimum of all signal and for the structural measurements also damage "equivalent stress-width" are computed on-line and stored. And finally, each 30 minute record is categorized (binned) according to wind speed and wind direction and stored until an adequate number of time series has been accumulated in each bin.

Meteorological data has been sampled from all three meteorological towers since November 1993, and data from the two instrumented wind turbines since March-April 1994.

WAKE AND WIND FARM MODELLING

Several models for the flow speed reduction in the rotor wake have been developed. However, here we shall only mention one developed by Jensen (1993). Assuming linearly expanding wake with a circular, uniform reduction of wind speed and considering mass conservation, he arrives at the following expression for the speed reduction factor:

\[ R_{u,m,w} = 1 - a y^2, \quad y = \left( \frac{1}{1 + \alpha s} \right) \]

where \( \alpha = 0.51 \ln(h/z'_w) \) is a constant, basically proportional to the "ambient" turbulence intensity, \( s = x/r \), where \( x \) is the normalized downstream distance from the turbine and \( r \), the radius of the wake immediately downstream of the rotor. The induction factor \( a \) is defined in the footnote. For an infinite row of wind turbines, the speed reduction factor becomes

\[ R_{u,m,w} = 1 - \left( \frac{y}{1 - (1-a)y} \right)^2 \]

Figure 2: Model prediction of wind speed reduction and turbulence increase factors; assumptions: \( z_w = 0.0001m, \) rotor diameter 35m, hub height 37m, and computed \( C_T \)-curve.

This expression is known, Courtney and Frandsen (1992), to apply well already for number 3 machine and onwards in a row. \( R_{u,m,w} \) is plotted in Figure 2 together with the hub height (37m) reduction obtained with a boundary layer model, Frandsen and Christensen (1994), employing the actual machine spacing in the Vindeby Wind Farm, a surface roughness of \( z_w = 0.0001m \) and a (computed) \( C_T \)-curve for the turbines in the wind farm. It has been demonstrated, Frandsen (1992), that the two very different models agree well with each other and with data in the case of wind along the rows of wind turbines. In other cases with larger distances to the nearest obstructing machine the Jensen-model works better, reflecting that the nearest machines have a major influence on the resulting flow characteristics.

As for turbulence increase in the wake of a single turbine, an expression for the additional, maximum turbulence intensity, \( I_{\text{add, max}} = I_{\text{ambient}} \cdot e^2 \cdot l^2 \), where \( I_{\text{ambient}} = \sigma_{w}/u \), and \( l_{\text{ambient}} = \sigma_{w}/u \), is the ambient turbulence intensity, has been proposed by Crespo and Hernández (1993):

\[ I_{\text{add, max}} = 0.51 a^{0.83} I_o^{0.032} \left( \frac{r}{l} \right)^{-0.32} \]

(The expression appears slightly different due to the alternative induction applied in this paper and due to the use of \( r \) instead of \( D \)). The wake center-line added-turbulence intensity is found to be some 20% lower. The expression is utilized for calculation of \( R_{u,m,w} \) in Figure 2 (applying the same input data as when plotting the speed reduction factor) together with the result obtained with the boundary layer model for turbulence above the top position of the blade tips. It is seen that the wake model decreases more rapidly with decreasing \( C_T = C_T(u) \).

Also, in Figure 3 the ambient turbulence, \( I_o = 1/\ln(h/z'_w) \), is plotted together with the two different predictions of turbulence intensities described above, for the geometry of the Vindeby Wind Farm, but as a function of terrain roughness. It is seen that according to the models - under the specific conditions with very low terrain roughness: \( z_w = 0.0001m\) - the wind turbines alone generates turbulence corresponding to what would be experienced by a wind turbine not exposed to wind farm effects in flat, inshore terrain at roughness length \( z_w = 0.03m \) which corresponds to a turbulence intensity at hub height of approx. 13-14%. Thus, while for inshore-farmland conditions the increase in turbulence due to wake effects is approx. 50%, the corresponding increase offshore is approx. 200%.

Figure 3: Model prediction of turbulence intensity with and without wind turbines, as a function of ground surface roughness; \( u = 8.5m/s, \) and \( C_T = 0.7 \).
PRELIMINARY RESULTS

It is expected that the low ambient turbulence at sea will cause less dynamic loads and thus less fatigue loading than under inshore conditions. But the low turbulence may also mean that the wakes are preserved longer and therefore cause more pronounced wake effects than seen inshore. For a preliminary analysis, approx. 8,000 half-hour statistics for wind data is available, and for fatigue loads about 700 half-hour values of the so-called equivalent stress width, see Frandsen and Christensen (1994), of acceptable quality have been recorded. In the present analysis, we have chosen to center on data with wind speeds in the vicinity of 8.5 m/s because here the rotor thrust coefficient, \( C_T \), is high and presumably wind farm effects large - even though this further limits availability of good quality data. Thus, with the limitation in available data, the present analysis should be considered preliminary.

Ambient turbulence offshore

The ambient turbulence can be investigated directly from the measured data. Figure 4 shows turbulence intensities measured at hub height, 37m, at the sea-mast-west (SMW) for wind directions (260° - 280°) where basically the upstream sea flow is unobstructed by land and wind turbines. Though there is some scatter, the bulk of measuring points are in the range \( I = 6-10\% \), and for higher wind speeds more close to 8\%. An often applied expression for turbulence intensity under neutral atmospheric stratification, \( I = 1/\ln(h/z_0) \), suggests that at hub height \( I = 8\% \) with an applied surface roughness of \( z_0 = 0.0001\)m. The large scatter mainly toward higher values implies that unstable conditions are frequent, at least for low wind speeds \( u < 10-12 \) m/s. For inshore conditions (farmland, \( z_0 = 0.03 \)m) the turbulence intensity would be \( I = 15\% \), i.e. twice the offshore turbulence intensity.

![Figure 4](image)

**Figure 4** Measured turbulence intensities as a function of wind speed at 37m (SMW), for wind directions 260° < dir < 280°.

Wake Turbulence

As mentioned, two 48m meteorological towers are placed so as to measure wind characteristics similar to what is experienced by the wind turbines. The south mast (SMS) is located at south end of the west-row of turbines. Thus for wind directions around 320° the SMS tower is exposed to roughly the same flow field as the instrumented 4W wind turbine. For directions 310° to 30° SMS records various wake conditions, and for directions 70° to 300° it may serve as free-flow reference tower. The west tower (SMW) serves for wind directions 150° to 310° as reference for predominant winds, and for directions 310° to 150° different wake conditions are experienced, including the situations, where SMW is in direct double wake of 3E-3W and 5E-4W, respectively.

As a preliminary investigation we have calculated the ratios of hub height wind speeds \( \sigma_{SMW}/\sigma_{MW} \) and turbulence \( \sigma_{SMW}^{2}/\sigma_{SMW} \), for wind speeds 7.5 < \( u < 9.5 \) m/s, for which wind speeds the thrust coefficient is high. \( C_T = 0.7 \), see Figure 5. The curves are wind direction bin-averages. The following should be noted:

1. For wind direction = 80°, SMW is in double-wake; here the speed reduction factor is \( R_s = 0.9 \), whereas models predict less than 0.8. Turbulence amplification is \( R_t = 1/0.6 = 1.7 \); here models predict 1.8.

2. For wind directions = 180°-270°, both towers are outside wakes; nevertheless are wind speeds less and turbulence higher at SMS, apparently because SMS is closer to land.

3. For wind direction = 320°, SMS is in 5-double wakes from the west row of machines; Speed reduction factor for SMS is \( R_s = 0.9 \), and turbulence increase factor \( R_t = 1.7 \).

It seems that while models predicts speeds deficits poorly for the large separation (\( s = 8.5D \)), wake turbulence is well predicted and not significantly different for 2 and 5 wakes, respectively.

![Figure 5](image)

**Figure 5** Ratios of wind speeds, \( R_s \) and turbulence, \( R_t = \sigma_{SMW}^{2}/\sigma_{SMW} \), measured in mast to the west (SMW) and mast to the south (SMS), at hub height; wind speed 7.5 < \( u < 9.5 \) m/s.

FATIGUE LOADING

Increased fatigue loading in wind farms is generated by increased flow shear across the rotor and/or increased turbulence level(s) and changed scale(s) of turbulence. An opposite
factor may be the decreased mean wind speed inside wind farm. The relative importance of each factor is not been satisfactorily clarified at present. Here, it is investigated if it is possible to explain increased equivalent width (ew) simply by increased turbulence/decreased wind speed.

Figures 6 and 7 show ew of flapwise blade root bending moment on machine 4W, as functions of wind speed and turbulence, respectively. Only data with wind directions from south to west have been used, i.e. no wind farm effects. It is seen that fatigue loading increase strongly with wind speed, and seemingly less pronounced with turbulence intensity. A simplified formulation of the change due to wake effects of ew can be written as

\[ \Delta(\text{ew}) = \text{ew} - \text{ew}_a = \delta u \frac{\partial(\text{ew})}{\partial u} + \delta I \frac{\partial(\text{ew})}{\partial I} \]

where the sensitivity factors - acknowledging the uncertainties involved - may be read from Figures 6 and 7:

\[ \frac{\partial(\text{ew})}{\partial u} = 7 \text{ units/(m/s)}, \quad \frac{\partial(\text{ew})}{\partial I} = 7 \text{ units/1\%} \]

In Figure 5, for wind direction 80° and wind speeds 7.5-9.5 m/s, we found that SMW experienced double-wake situation with amplification factors for wind speed and turbulence of \( R_u = 0.9 \) and \( R_I = 1.7 \). For the present base case - assuming that only mean wind speed and turbulence are of importance - with \( u = 8.5 \text{ m/s} \) and \( I = 8\% \), a double-wake situation should result in an increase in ew of

\[ \Delta(\text{ew}) = (0.9-1) \cdot 8.5 \cdot 7 + (1.7-1) \cdot 8 \cdot 7 = 32 \text{ units}. \]

Figure 8 shows ew of flapwise blade bending moments for machines 5E and 4W, as function of wind direction. For directions 200° and 255°, wind turbine 5E is in single-wake of 5W and 4W, respectively. The increase in ew is = 50 units for direction 200° and 50-80 units for direction 255°, in both cases considerably more than expected from the simple sensitivity analysis. In Figure 9 the same quantities are shown for higher wind speeds (lower \( C_f \)). Here, the differences have shrunk, though still being 20-30 units for wind direction 200°.

The lack of consistency could indicate that other parameters - e.g. increased horizontal/vertical and turbulence scales - play important roles in the low turbulent offshore flow. However, data are still sparse and the results should be read with caution.

---

**Figure 6** Equivalent width as defined in Frandsen and Christensen (1994) on flapwise blade root bending moment on machine 4W, as a function of wind speed for wind directions: 180-270°.

**Figure 7** Equivalent width of flapwise bending moment on machine 4W as function of turbulence intensity, 7.5 < u < 9.5 m/s.

**Figure 8** Equivalent width of flapwise bending moment of both instrumented machines (4W and 5E), as function of wind direction, for 7.5 < u < 9.5 m/s.

**Figure 9** Same as for figure 8, but for wind speeds u > 11 m/s.
CONCLUSION

A preliminary analysis of wake/wind farm turbulence and fatigue loading in the offshore Vindeby Wind Farm has been carried out. It was found that

- Turbulence intensities as expected is of the order 8% or half the typical inshore turbulence,
- The increase in wake turbulence, relative to ambient turbulence, can be expected to be much higher offshore than inshore,
- Increase in hub height turbulence intensity in double-wake situations (with \( C_T = 0.7 \)) is up to 60%, from approx. 8% to 13-14%, and
- Seemingly the increase in fatigue loading is higher than can be explained by increase in turbulence. This could simply be due to limitation in availability of data, but the possibility exists that the low-turbulence environment offshore preserves the wakes longer and thus creates pronounced horizontal gradients of wind speed.

ACKNOWLEDGEMENT

The work is funded by EU and national Danish research funds (EFP).

REFERENCES


NOTE

1) According to actuator disk theory the speed of the flow when passing the rotor plane is \( u_r = (1-0.5a)u_0 \), behind the rotor, \( u_0 \) being the ambient wind speed and a the induction factor. To maintain continuity, the "initial" diameter of the wake must be

\[
r_1 = r \sqrt{\frac{1-\frac{1}{2} a}{1-a}}
\]

With this definition of a the relation to the rotor thrust is

\[
a = 1 - \sqrt{1-C_T}
\]
ABSTRACT: Power system expansion planning should determine the optimal power system mix including wind power, ideally containing cost of energy comparisons as well as estimates of economics for the society, including externalities. The analyses should be made for all relevant expansion scenarios supplying power at similar and acceptable reliability throughout the lifetime of equipment. This paper addresses the requirements to modelling in general and suggests a modelling approach attempting to take adequate account of statistical variations and uncertainties in input and assumptions as well as influence of future development scenarios. The paper particularly studies the question whether a change of or large uncertainty in the assumed development of consumer loads over a 20 year period has or should have an influence on decisions to invest in wind power capacity up to high penetration levels. A dedicated model for power system performance modelling when studying the impact of wind power up to high penetration levels, WINSYS, is presented and described in the paper. Recommendations regarding need for methodologies for studying system expansions with wind power are discussed for both small and large power systems.

1. INTRODUCTION

Planning and feasibility studies for high wind energy penetration systems consist to a large extent of the same subsudies as for low wind energy penetration. Results are therefore considered acceptable for these subsudies, provided they are performed according to established standards and guidelines, e.g. for cost comparisons between wind power and other sources of energy in accordance with Tande and Hunter [1].

For high wind energy penetration, it is not evident that all studies are trusted, and development of reliable and generally accepted models are needed. Analyses of high wind energy penetration systems include the combined power system design, operation, performance and its dynamic behavior. These are the possible additional sources of uncertainties as compared to traditional grid connected low penetration wind farms.

Provided, however, that appropriate design and performance modelling assumptions are made, the analysis and conclusions of Hansen and Tande [2] indicate that feasibility studies for high wind energy penetration systems may be just as reliable as for traditional grid connected wind farms, at least for small power systems. High wind energy penetration can be achieved using technically reliable design and equipment at a predictable investment cost, but what about the above mentioned design and modelling assumptions. A main assumption is that additional control systems required for high wind energy penetration are kept simple and at a low cost relative to the cost of the wind turbines. For high wind energy penetration, the costs of control systems may however in certain cases be significant and maybe a highly non-linear function of the installed capacity. Furthermore, such a control system may sooner or later become redundant depending on the growth in power system loads. This fact, together with the known difficulties in predicting demand and load development in many types of communities, is a major concern for investors and funding agencies when considering their involvement in high wind energy penetration projects.

This paper therefore presents a model for analysis of high wind energy penetration including uncertainty and sensitivity analysis in general, and it suggests a method to study the above problem of uncertainties in load forecasting.

Firstly, a power system performance model, WINSYS, is presented. Secondly, WINSYS is applied to studying investment decisions’ sensitivity to uncertainties in load forecasts for a relatively small power system at which high wind energy penetration may be feasible. Thirdly, WINSYS is applied to a large power system with similarities to the Danish system for illustration of its general applicability.

2. MODELLING REQUIREMENTS

The basic problem is to establish a basis for planning the best possible power system expansion to enable a reliable supply of sufficient quality of the forecasted demand of electricity at a minimum of costs to the society - all considered. Feasibility studies and expansion planning of combined power systems with wind power requires modelling and comparison of the power system performance of different relevant development scenarios and expansion alternatives.

Particular attention should be given to

- system performance and mix optimization’s dependency on the wind energy penetration level and the future development
modelling of the wind power production and its fluctuating nature and climatic variations
management of the increased number of operational conditions and modes
inclusion of externalities in cost of energy calculations
uncertainties and sensitivity to variations in assumptions, in particular
- costs of fuel (avoided costs)
- investments
- cost of capital and
- development of consumer loads

Provided that appropriate system design and modelling assumptions are made as discussed in Hansen and Tande [2], the only special modelling requirements for wind farms at high penetration levels compared to low penetration levels may be limited to calculating a) the annual utilized energy production of the wind farms and b) the adequate conventional gen-set mix at any given time as well as its production and fuel consumption, with special attention to the above, i.e. modelling

- variations in time of wind power output and consumer loads
- dissipation of excess wind power
- operational performance, requirements and strategies of the conventional power station, including conditions regarding spinning reserve and technical minimum loads on the individual generating sets.

Furthermore, economic data including investments, running costs and social costs should be estimated and described for the specific high wind energy penetration system.

3 THE MODEL

WINSYS is based on a model originally developed for small scale power systems, now modified so that it handles power systems in general with a limited number of wind farms in similar wind climate and up to 20 different conventional power units individually specified in combined operation.

The objective of developing WINSYS was to enable analyses of the consequences of introduction of wind power to high penetration levels in conventional power systems for planning and investment decision purposes.

WINSYS is a code developed and run in a spreadsheet type of programme with its built-in user friendliness and flexible interface to input and output media. WINSYS can easily be adapted to a particular need and has thus been developed as a core code aiming at being time efficient for the specific cases solved rather than setting up a complete and bullet-proof guided way to all answers regarding high wind energy penetration. Inputs and outputs are graphically illustrated in Fig. 1.

Below is a brief description of inputs, outputs and the simulation technique used.

3.1 Inputs

Power system loads

The base year is described day by day with hourly average values for the 24 hours of the day. This daily load pattern is then scaled year by year in the entire analysis period to fit the assumed average load for the day. The load can be split in two types of loads if needed to enable exact description, e.g. if the expected annual increase in domestic and industrial consumption with very different daily load patterns are expected to be significantly different.

In order to reduce the need for computer capacity and to save run-time for the model, days with similar characteristics are grouped and modelling results will be applied for the appropriate number of that kind of a day.

Fuels

Characteristics of fuels used by the gensets in the power system are described in terms of heat value and density. The cost of the fuels are specified year by year for the analysis period.
Conventional generating sets

Up to 20 gensets are specified with their individual technical specifications, known or expected commissioning and decommissioning year as well as investment, operation and social costs. The technical specifications include rated power, technical minimum allowable load and specific fuel consumption as a function of the load including no-load operation consumption.

Wind farms

Different types (p.t. maximum 2 types) of wind farms are specified in accordance with Tande and Hunter [1]. Specifications include: number of wind turbines and specification of the type in terms of rated power, rotor diameter, hub height, power curve and expected technical lifetime. For energy production estimation purposes, performance reduction factors due to rain, dirt, site, obstacles, array efficiency, technical wind turbine and grid availability and transmission losses are included. Furthermore information regarding all related investments and costs of land and project implementation as well as costs of operation and maintenance including retrofit costs and time are entered together with the expected salvage value if any.

Climate

The wind climate is described as the climatologically expected wind climate at the site day by day for a year as for the power system loads. Typically it will be sufficient to describe the daily wind climate for four types of days, namely one for each of the four seasons - winter, spring, summer and autumn.

In order to enable modelling of the effect of the correlation between wind power and power system loads, the wind climate for the day is given as a Weibull type probability density distribution of 10 minute average values for each of the 24 hours of the day for each type of day to be modelled. Furthermore temperature and barometric pressure is given.

3.2 Simulation

The simulation technique is an hour by hour time series simulation for each type of day in each year of the analysis period using a statistical approach to handling the fluctuating wind power within the hour. It is assumed that power system regulation basically is taken care of by the conventional gensets.

In each step of the simulation, the appropriate power system mix of available units to obtain the required spinning capacity according to the operational strategy is determined. Knowing the spinning capacity and the technical allowable minimum load of the conventional units and calculating the probability density distribution of the wind farms' power production, the need for and amount of dissipation of energy in the high wind energy penetration system can be determined. The resulting net load distribution to be shared between the conventional gensets and the amount of utilized wind energy output is thus found from the above. Assuming that the gensets specific fuel consumption specifications are valid at the different levels of load fluctuations experienced with and without wind power, fuel consumption and fuel savings can be determined.

3.3 Output

The model as it is offers a large number of output options depending on the users needs. Below is a selection of some possibilities.

Resulting wind energy and conventional production, fuel consumption and unit commitments of the individual gensets are available year by year as 24 annual average values, i.e. hour by hour of the average day. Based on this load duration curves with and without wind power useful for mix reoptimisation as well as total energy production and fuel savings for the analysis period are available. Graphs of hourly average values of spinning capacity, total power system load, wind energy production, net load and wind energy penetration are easily produced.

The costs and benefits with and without wind power are calculated year by year, giving directly the cash flow of the high wind energy penetration project or development scenario analysed. Using the specified discount rate, levelised production values and levelised production costs, LPC ($/kWh), are calculated by discounting each year's results to the start of operation of the wind farm being studied. Furthermore, the net profit and internal rate of return (IRR) of the investment in the wind farm are calculated.

Finally WINSYS offers a sensitivity analysis of the results of the economic analysis, i.e. an analysis of the sensitivity of the LPC, the IRR or the net profit to a selection of parameters such as the assumed wind conditions, the investment, the fuel costs and the power system loads. The results are available as tables or as a spider type graph.

4 MODELLING AND PLANNING UNCERTAINTIES

The uncertainties associated with modelling high wind energy penetration systems may be divided according to the main reason of uncertainty as follows

- uncertainties in general economic data
- uncertainties in technical specifications and assumptions for conventional gensets and the power system in general
- uncertainties in the estimation of the energy production of the wind farm
- uncertainties in the performance modelling of the power system with high wind energy penetration, and
- uncertainties in community development and power system load forecasts

Uncertainties in economic data and the power system design, specifications, assumptions and modelling in general are basically the same for all types of power systems, but much depending on the model and
assumptions used as concluded in Grubb [3], and more important when comparing technologies than when choosing the optimal solution within one technology. The uncertainties in the estimation of the energy production of the wind farm can be estimated as described in Frandsen and Christensen [4]. The benefits of wind power, however, can in this context all in all be considered to be similar for high and low and high wind energy penetration at the assumptions in Hansen and Tande [2]. Two of the critical assumptions are that the investment costs are estimated for an appropriate technical system design and that costs per installed kW wind power are not too different for low and high wind energy penetration systems, i.e. a low sensitivity to the growth rate in power system loads.

Now, costs of control systems for high wind energy penetration systems may differ and the planner's, the political system's or the private investor's conclusion regarding the attractiveness of expanding the power system with wind to high penetration levels has to be seen in the context of the development of their community. An overview of the consequences of different development scenarios can be provided by applying WINSYS to different development scenarios and assumptions.

The consequences of uncertainties to load forecasts are studied below for a case of a relatively small power system using real data from Praia, the capital of Republic of Cape Verde.

The main data and results at an annual increase of the power system loads of 2.5% and a total wind farm capacity of 3.5 MW, giving a levelised wind energy penetration of 30%, are seen in Table 1. The Internal Rate of Return (IRR) of the investment in wind power to this penetration level is for the power system and assumptions made estimated to 9.9%. Fig. 2 shows the results of the sensitivity analysis to some key parameters for this case in terms of amount of wind power capacity and annual increase in loads.

Different wind energy penetration levels and different forecasts of loads have been assumed and modelled for the purpose.

<table>
<thead>
<tr>
<th>Table 1: Main data and results from WINSYS modelling of a small power system at 30% wind energy penetration and an annual load increase of 2.5%.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind Data</strong></td>
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<tr>
<td>Investment (year: 31 Dec.)</td>
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<tr>
<td>Total Investment (€/MW)</td>
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<td>Wind Investment (€/MW)</td>
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<td>Other Investment (€/MW)</td>
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<td>Total Investment (€/MW)</td>
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<td>Present value (€)</td>
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<td>Estimated wind (%)</td>
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<td>Machinery factor</td>
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<td><strong>WIND COSTS AND BENEFITS</strong> (%)</td>
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<td>Wind consumption</td>
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<td>Debt excluding load</td>
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wind power or more (corresponding to 40% wind energy penetration at 0% annual load increase) and loads do not increase. Other investments in the community may be financially or economically better than the high wind energy penetration, but in this respect it is reminded that this analysis has not assumed any social costs for wind and conventional gensets.

![Fig. 3 Daily patterns for the Praia power system with 3.5 and 5 MW wind power, both at 2.5% annual increase of loads, all for a typical winter, non-weekend day](image)

![Fig. 4 Annual load and wind energy output for the small power system with 5 MW installed wind power capacity at 2.5% annual increase in loads in the period 1996-2005](image)

![Fig. 5 The resulting Internal Rate of Return of an investment in wind power to different penetration levels as modelled by WINSYS for the Praia power system](image)

It should be mentioned that WINSYS facilitates an optimization of mix using the screening curves for the conventional gensets and choosing the lowest cost type of gensets. The optimal mix depends on the wind energy penetration level as can be seen from Fig. 6 showing the load duration curves for different wind energy penetration levels at the small system. Using the screening curves for heavy fuel and gas oil gensets, with heavy fuel being cheaper for durations higher than 1400 h/year, it is seen that the optimal installed capacity of base load units is decreasing from 5.6 MW to 4.2 MW with wind energy penetration increasing from 0 to 30%.

![Fig. 6 Load-duration curves for different wind energy penetration levels with indications of optimal sizes of gas oil and heavy fuel diesel gensets](image)

5. LARGE SYSTEMS

The complexity of large power systems should not underrepresented, but on the other hand WINSYS might be a useful planning tool. At least the approach used in WINSYS might be able acceptably accurate modelling of certain development scenarios with wind power in large power systems, which may previously have involved extensive use of computer capacity for time series simulations to obtain statistically representative results.
For illustration, a similar analyses to the example for a small system has been performed for a large power system with certain similarities to the Danish situation. Key data and results are shown in Table II and Fig. 7.

Table II Main data and results from WINSYS modelling of a large power system at 25% wind energy penetration and an annual load increase of 1.7%

<table>
<thead>
<tr>
<th>LOAD DATA</th>
<th>ELECTRIC DATA AND RESULTS</th>
<th>Large system</th>
<th>1.7%</th>
<th>Analysis year</th>
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<tr>
<td>Description</td>
<td>Wind investment</td>
<td>995</td>
<td>1.7%</td>
<td>2090</td>
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<td>Description</td>
<td>(GWh/year)</td>
<td>5000</td>
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<tr>
<td>Description</td>
<td>Demand</td>
<td>10000</td>
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<td>Description</td>
<td>Total investment</td>
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<tr>
<td>Description</td>
<td>Total demand</td>
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<td>Description</td>
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6 CONCLUSIONS

Planning and feasibility study tools for high wind energy penetration must be developed and validated so that results are reliable and can be trusted by investors and funding agencies.

A model, WINSYS, has been developed which reasonably detailed models high wind energy penetration systems using a minimum of computer capacity and time. The model is user friendly and the interface is flexible.

Known uncertainty sources can be handled by using recommendations, standards and guidelines which enables comparison of different power system expansion scenarios and assessment of the economics on a common basis.

The sensitivity to uncertainty in growth rates of electricity consumption at different wind energy penetration levels can be analysed and the problem seems manageable.

An example applying WINSYS to a small power system shows a potential for wind energy penetration up to 40% at uncertainties comparable to uncertainties for traditional grid connected wind farms. Furthermore it has been illustrated how WINSYS might assist the planning process for larger power systems.

The real hurdle is validation of models which either can be done by internationally comparing available models or even better by getting some high wind energy penetration systems built and by testing the models against those systems.

REFERENCES


ON POWER QUALITY MEASURES FOR WIND-DIESEL SYSTEMS: A CONCEPTUAL FRAMEWORK AND A CASE STUDY

H. W. Bindner, Test Station for Wind Turbines, Risø National Laboratory, Roskilde, Denmark

Per Lundsager, Darup Associates Inc. CAT Science & Technology Park, Roskilde, Denmark

INTRODUCTION

By their definition wind diesel systems are electrical power supply systems with variations of both voltage and frequency of the grid. In order to evaluate prospective systems designs in terms of power quality and compare with alternatives in a rational way it is necessary to work within an agreed framework of definitions for the measures to be applied.

Measures for power quality of wind diesel systems should include measures for both slow and fast variations of both frequency and voltage, slow variations to be understood as variations of 'mean' values. Previous work has concentrated on voltage variations in large grids with essentially constant frequency, and therefore the existing framework as expressed in e.g. CENELEC standards (1) does not include any detailed specification of frequency variation in weak grids.

This paper contributes to the development by presenting a conceptual framework for power quality in terms of both grid frequency and voltage in a time scale, where system dynamics in the usual sense is included, but switching and harmonics are not considered. Concerning voltage variations the proposed framework rests on previous work (e.g. CENELEC) and current work (DEFU/Risø and Mayer/Joule II (2)), and the main contribution of this paper concerns frequency variations.

The framework consists of definitions of power quality measures, a set of criteria for the power quality and a technique for modelling the system. In addition to this, when possible, measurements are made to calibrate the model or verify the predicted behaviour of the system.

The definitions are based on statistical measures for the frequency of occurrence of instantaneous and mean values. The paper will outline criteria in a qualitative way. The modelling technique referred to in the paper is the one used in the JODYMOD Dynamic Wind Diesel Simulation Package, Infield et. al. (3) developed by a European team with support from the JOULE I programme.

The paper includes a case study, in which the framework is applied on the simple and robust experimental wind diesel system at Risø National Laboratory, Lundsager & Bindner (4).

FRAMEWORK

It is significant for a wind diesel system, and indeed any local power supply system, that it operates its own local grid and that the grid is entirely controlled by the controllers of the system.
Measures and Criteria

In both cases the power quality should be expressed and evaluated by the same framework of measures and criteria. Fig 1 outlines the components in this scenario: Inputs in terms of Wind speed and Consumer load inputs. System definition in terms of hardware specifications or a system model with controllers, and outputs in terms of Voltage variations and Frequency variations. The figure indicates measures for slow and fast variations of wind speed and consumer load input.

An extensive set of measures and criteria exists for voltage variations in strong grids, i.e. grids with essentially constant frequency. These measures and criteria could probably be used for soft grids as well, i.e. grids with significant frequency deviations, although the mathematics of several of the voltage measures is developed for constant fundamental frequency.

The established measures and criteria only deal with frequency deviations in terms of a simple set of upper and lower limits for the grid frequency. This is not enough for a satisfactory description of power quality in soft grids. Fig 1 indicates the measures for frequency variations proposed in this paper.

WIND SPEED

The wind speed influences the power balance of the system through the wind turbines connected to the grid. The wind speed affects the system by slow variations that influence the instantaneous 'mean' or quasistatic power balance, and fast variations that influence the dynamics of the system around the quasistatic power balance. Agreed measures exist for both fast and slow variations, and both of these measures are statistical.

Slow Wind Speed Variations. The agreed measure for the 'mean' wind speed is the 10 minute average value, the meteorological standard used for decades. A vast record of wind speeds is available worldwide in this format, and this is the measure relevant for measurement and prediction of wind turbine power production.

The Weibull distribution is used to specify the occurrence of 10 minute wind speeds at any given site and height. Therefore the prediction of Weibull parameters (A,k) or (C,A) form the basis for all wind energy assessment techniques used today, the most prominent example being the WASP Code, Petersen et. al (5). Therefore the probability density function of the 'mean' wind speed input for the power quality input should be this accepted measure.

Fast Wind Speed Variations. The agreed measure for fast wind speed variations, as applied in wind turbine technology context, is the 'turbulence intensity'. This is generally expressed in terms of the standard deviation of an assumed Gaussian distribution of the instantaneous wind speed around the 10 minute average wind speed.

This measure is used in wind turbine design procedures to account for fatigue related loads. The measure is a crucial part of the wind turbine gearbox design procedure proposed by Thomsen & Petersen, (6). Therefore the probability density function of the instantaneous wind speed input for the power quality input should be this accepted measure.

CONSUMER LOAD

The consumer load influences the power balance of the system through the power plant components connected to the grid, e.g. diesel generators, wind turbine generators, dump load. The consumer load affects the system by slow variations that influence the instantaneous 'mean' or quasistatic power balance, and fast variations that influence the dynamics of the system around the quasistatic power balance. In contrast to the wind speed, no agreed measures exist for neither fast nor slow variations, but it would seem sensible to apply similar statistical measures for consumer load variations.

Slow Consumer Load Variations. In order to work together with the Weibull distribution for wind speeds, 10 minute average consumer loads should be applied. That is straightforward in case of measured loads for evaluation of actual Wind Diesel systems. For assessment of future prospective systems this is more difficult, as no single family of probability distribution functions will probably fit all consumer load patterns.

Therefore, for modelling of prospective systems there is a need for an agreed procedure to establish distributions \( f(CL_{10}) \) of the 10 minute average consumer load. Maybe a set of 'typical' agreed distributions, established to describe various types or classes of communities, would be a feasible way to do this.

Often, when doing technical-economical assessment of remote power supply systems, assumed consumer loads are constructed as hourly consumption patterns for 'typical' days, based on known consumption patterns for 'typical' consumers. If nothing else this technique could be extended to establish \( f(CL_{10}) \) distributions.

Fast Consumer Load Variations. Similar to the fast wind speed variations, it would seem logical to apply a measure in terms of standard deviations of the variation of the instantaneous consumer load around the 10 minute average consumer load. Until otherwise proven it would seem natural to assume a Gaussian distribution.

Consumer Load Types: The concept of the measures described above are developed for consumer loads that may be described as purely resistive loads, i.e. they do not represent features of electrical machinery such as inertia.

POWER SYSTEM

The representation of the system will of course depend on whether the power quality framework is used to evaluate an existing hardware system or to assess the performance of a prospective future system.
Analysing Existing Systems: A description of the system is not really needed in order to describe the recorded power quality of the system. It may be useful, though, to list a specification of the system in terms of component and controller specifications, to use as an identification of the system. These specifications are necessary to interpret and understand the recorded power quality.

Modelling/Prediction of Future Prospective Systems: A dynamic electromechanical model is necessary in order to predict the response of the system to the wind speed and consumer load input. The model must include models of the controllers used in the system.

For this study the JODYMOD model (3) is used. The model was developed as the dynamic part of the JOULE I project: European Wind Diesel Software Package, the other part being a logistic modelling toolbox. JODYMOD is a flexible model that allows the user to build his own model by combining electromechanical elements (bus bar, generators, rotating inertias), controllers and other components into a tailor made system model. Jodymod then builds the dynamic equations and performs a time history simulation JODYMOD is designed to work in a range of time scales that are specifically chosen to suit dynamic power quality assessment.

VOLTAGE VARIATIONS

As already mentioned in the introduction there exists an extensive set of measures for the quality of the grid voltage. A survey is given by Nørgård et al. (7) in a note prepared for the Joule II project (2). A total of 15 measures for voltage quality are included in the CENELEC standards (1), but only one frequency measure in included. Many of the measures are based on a frequency analysis of the voltage response, assuming a fixed grid frequency of 50 Hz.

These measures are all deterministic in the sense that the measures are linked to criteria in terms of numerical values or predefined curves that must not be exceeded. At the moment it is investigated how statistical measures can be used for voltage variations for grid connected wind turbines.

The present paper will not separately propose voltage variation measures. It is proposed to use the measures developed elsewhere. Since the frequency deviation measures proposed below are statistical, it would be natural to apply the statistical voltage deviation measures in the framework.

FREQUENCY VARIATIONS

Measures

Simple maximum deviation measures for remote power supply systems are not adequate. Tight limits will be exceeded frequently, and wide limits are generally not acceptable. Therefore statistical measures must be applied.

Frequency Distribution: The basic consideration in remote power supply is that the acceptance of a given frequency deviation will be seen in relation to how often it occurs. Even large frequency excursions may be acceptable if they do not occur very often, but if they occur very frequently only small deviations will be accepted.

It is proposed to use the most straightforward statistical measure, the probability density curve. In practice this will be measured by a binning of the time trace of the frequency, be it measured or computer simulated. Based on this measure it can be predicted, how often the frequency will exceed a given limit.

By integration of the probability density curve (in practice by summations) the duration curve is obtained. This curve directly answers the question: How often does the frequency deviate how much?

The significance of this is not always clear, i.e. the consequences of a given frequency deviation on a given component or appliance is not always clear. This is for the supplier of the component or appliance to state. For wind turbines on soft grids the consequences may be significant, and two examples are given below:

For a stall regulated wind turbine the power is proportional to the rotor speed cubed. Thus, if the grid frequency deviates 5% upwards the power will increase by roughly 15%. This may tend to increase the frequency deviations and, depending on the system controllers, it may cause system instability.

For any wind turbine the fatigue life of the gearbox depends on the duration curve of the generator torque, (6), given a constant rotational speed, i.e. constant grid frequency. Frequency variations will tend to reduce the gearbox fatigue life, firstly by increasing the power as described above, and secondly by increasing the number of load cycles on the gears. This twofold increase of the gearbox fatigue loads may lead to significant reduction of gearbox life.

Rate of Change Distribution: Electric machinery connected to a grid represent so many rotating inertias, and each machine may be connected to other inertias. For remote power supply systems the inertias may be significant.

The torque involved in a change of the rotational speed of a rotating inertia is proportional to the inertia and to the rate of change of speed. In a remote power supply system the rate of change of the grid frequency therefore may be of interest.

It is proposed to use the most straightforward statistical measure, the probability density curve for the rate of change. For a measured or simulated time history of the grid frequency the rate of change is simply the time derivative of the frequency. In practice the time derivative will be represented by a simple difference scheme, and the probability density curve will be measured by a binning of the time trace of the frequency. Based on this measure it can be predicted, how often the frequency rate of change will exceed a given limit.

Whether or not the rate of change is a significant measure is not entirely clear at the moment. For a wind turbine with induction generator, connected to a soft grid, a change in grid frequency caused by other machinery or consumer loads will cause the generator slip and hence the generator torque to change.
Criteria

If the statistical measures proposed above are applied, acceptance criteria are needed. These criteria should be expressed in terms of the measures they are used to evaluate, i.e. the criteria must also be statistical.

No such agreed criteria exist at the moment, and they are not treated further in this paper.

CASE STUDY: THE SIMPLE & ROBUST WIND DIESEL SYSTEM AT RISØ

The System

Fig 2 shows a diagram of the simple and robust wind diesel system at Risø (5). It is a No-Storage wind diesel system with the diesel engine running continuously. It is implemented using standard components. The diesel generator set consists of a 35 kW diesel engine connected to a 60 KVA synchronous generator. The wind turbine is a standard 15 m diameter stall regulated wind turbine with a 55 kW induction generator. A 75 kW dump load is included. All components are coupled to a 1 kV bus bar, connected to a computer controlled load simulator with resistive and inductive load.

Thus the system controllers control grid voltage and frequency. The system controllers are the diesel governor, the dump load controller and the voltage controller. Frequency is controlled by the diesel governor (downwards) and the dump load controller (upwards), both of them P-controllers. Voltage is controlled by the compound type voltage regulator of the synchronous generator of the diesel set, which also compensates the VAR requirements of the induction generator of the wind turbine. It requires only a minimal supervisory system.

More details on the system and its controllers are given in (4).

The Model

The model used to predict the power quality in this case study is the JODYMOD model described above. JODYMOD was developed for use in the European Wind Diesel Toolbox (3).

JODYMOD is a flexible dynamic simulation model. It is based on a modular design with fairly complex models of electrical machines, rotating inertias and controllers. JODYMOD contains a number of components that may be combined by the user to simulate different system configurations and controller parameters influence on e.g. grid voltage and frequency. The software consists of an easy to use simulation set up program and the simulation program that includes graphics for displaying the simulation results.

Fig 3 shows how models of electrical machines, controllers, load types and rotating inertias and shafts are combined by JODYMOD into dynamic electromechanical models of a wind turbine generator and a diesel generator to simulate a complete wind diesel system. It is seen on fig 3 that there is a vast array of outputs (the right hand side of the lower part of each component).

The Scenario

The basis for the case study is a series of three runs reported by Bindner et al. (9) The performance of the system is measured during three different wind speeds and at the same constant consumer load. This leads to three different operating modes. Each of the three runs are about an hour long and are sampled at 8 Hz. The run used in this paper is the run with medium wind speed.

10 minutes of this run is used for comparisons with simulations. The measured wind speed from these 10 minutes are used as input for the simulation model. The simulation are also sampled at 8 Hz. All data points in both the simulations and the measurements are used without averaging. Two simulations are carried out. One with nominal values for all parameters and one where the inertia of the flywheel placed between the diesel engine and the synchronous generator is reduced by a factor of five. This second simulation illustrates how the measures can be used when designing systems.
Results

The results of using the proposed measures for frequency variations are shown in figures 4 and 5.

Measure no. 1, the absolute frequency variation, is shown in Fig. 4. With the chosen controller set points the measured frequency varies between 48.5 and 51 Hz, with a pronounced peak in the occurrence around 50.4 Hz. The simulated frequency distribution is fairly close to the measured one, although the simulated distribution extends to 51.5 Hz while the peaks at 49.5 and 50.0 Hz are missing. Assuming a frequency set point of 50.0 Hz Fig. 4 may also be seen as a probability density curve for the deviation Δf Hz from the 50.0 Hz set point. This is indicated by the secondary x-axis in Fig. 4.

Measure no. 1 gives a useful representation of the pattern of the frequency variation. Fig. 4 shows that if the system is not yet built, the JODYMOD dynamic model will predict the frequency variations close enough to be useful in a comparison between alternative system layouts and to choose the one to be preferred.

Typically the issue is how often the frequency deviates how much from the set point. This information is available in a normal duration curve based in integration (summation) of fig 4. By separating the duration curve in two, one for positive and one for negative deviations, the duration curve may be displayed as shown in Fig. 5.

Fig. 4. Measured and simulated probability density curves for frequency variation (Measure no. 1)

Fig. 5. Duration curve for frequency deviations

Fig 5 directly shows how often the frequency deviates a certain amount or more. It appears that also here the JODYMOD predictions are fairly accurate. It also appears that in this case the system frequency deviates +1 Hz or more in 0 (measured) 5% (simulated) of the time, and -1 Hz or more in 10% of the time. It is noticed that the size of the inertia does not have significant influence on the grid frequency distribution in the simulations.
Measure no. 2: Rate of change in frequency is shown in figs 6 and 7.

![Probability Density Curve for Rate of Change of Grid Frequency](image)

**Fig 6.** Measured and simulated probability density curves for rate of change of grid frequency (Measure no. 2)

As shown in fig. 6, with the chosen controller set points and gains the measured rate of change in grid frequency varies between -0.25 Hz/sec and +0.25 Hz/sec. The simulated rate of change in grid frequency has a wider distribution, from -1 Hz/sec to +1 Hz/sec. The duration curves, obtained by integration (summation) of the curves in fig 6, are shown in fig 7. The influence of the size of the inertia is very pronounced on these curves and as expected the rate of change increases as the inertia decreases.

![Duration Curve for Rate of Change of Grid Frequency](image)

**Fig 7.** Duration curves for rate of change of grid frequency

Unfortunately the time trace for the grid frequency was measured with a lower resolution than desirable for a representation of measure no. 2. This tends to narrow the measured distribution. The measured signal is filtered due to the filtering in the measurement and data acquisition systems and there is a filtering effect due to the averaging of the wind speed fluctuations over the wind turbine rotor area. Therefore there are higher frequencies in the system than we see in the measurements, and these frequencies are present in the simulated time trace. To some extent this explains the deviations between measured and simulated results, but there are also real differences between the measured and simulated measures.

**Stability** The proposed measures do not contain direct information about system stability. The measures deal with variability, i.e. the pattern of frequency deviations from the nominal value. The question of stability, i.e. the possibility that the frequency may get out of control and deviations may continue to increase until the system breaks down, must be dealt with separately. It may be argued that this is not a power quality issue.

**Evaluation** It is not the purpose of this paper to evaluate the importance or consequences of the frequency deviations, but to propose measures for them to be quantifiable and comparable. Measure 1 would seem to be most relevant for appliances, computers, TV sets etc. Therefore the limits or criteria to be used for measure 1 should be specified by the manufacturers of the equipment. Measure 2 would seem to be most relevant for equipment connected to the grid through electric machinery. A wind turbine with induction generator will experience torque variations due to change of generator slip, in this case up to the order of 10% of rated torque.

**CONCLUSIONS AND RECOMMENDATIONS**

Measures for the frequency deviations of local, isolated electric power supply grids have been proposed. The measures are statistical of nature and includes also the rate of change of grid frequency.

The measures have been applied in a case study, using measurements from the Simple, Robust & Reliable Wind Diesel System at Risø National Laboratory. The measures are easy to apply and contain information of the type that is used in evaluation the power quality of remote power supply systems.

The modular dynamic simulation model JODYMOD was used in the case study to predict the measured results. JODYMOD was developed by a European project group with financial support from the JOULE II programme of the EU, and the model predicts the measured results with sufficient accuracy to be used as a tool in future assessments.

The measures are not fully developed in this paper. It is recommended that future work in this area should include more detailed investigation of the measures, the effects in real systems of the effects dealt with by the measures, and development of quantitative criteria to be used with the proposed measures.

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SUMMARY

A user-friendly software package to help engineers design wind diesel systems has been developed over the last three years with support from the CEC's JOULE programme. Such systems have an important role to play in the supply of electricity to rural, grid remote sites. The modelling and software development was undertaken cooperatively by several EEC and EFTA countries. Both logistic and dynamic aspects of system operation are included in the final package which has been written for implementation on a PC running under MS-DOS. This paper describes the modelling capabilities and validation of these engineering tools.

INTRODUCTION

A centrally supplied electricity grid is often not the appropriate or cost effective way to supply electricity to dispersed rural populations. This is true both to developed and developing countries. Decentralised electricity supply can be considered at a range of scales from the individual remote dwelling, to large village communities or even small towns. Conventionally, diesel generator sets of the appropriate size have been used to satisfy these needs. For small systems this has often resulted in inefficient use of the diesel due to its frequent operation at low load. In addition the cost of diesel fuel at remote locations can be high because of transportation costs. There is also often a national perspective in which the diesel oil, if imported, has an adverse impact on the national balance of payments.

More recently, environmental issues have demanded that attention be paid to the reduction of fossil fuel consumption. The difficulty for the developing countries is to increase the proportion of the population receiving an electricity supply as part of the legitimate aim of raising living standards, whilst at the same time not increasing unwanted emissions. It is here that renewable energy clearly has a major contribution to make. In this paper we will concentrate on how that renewable energy contribution can be made in the context of grid remote supply. This turns out to be far more technically challenging than the grid connected use of renewables.

Although there are a number of different renewable energy technologies with application potential, this paper, and the software package it describes, is concerned with wind energy. Since as already mentioned, diesels are the reliable conventional form of stand alone electricity generation, these form the natural backup supply to the wind power. Systems combining wind and diesel in this way have come to be known by the term "wind diesel".

For the reasons outlined above, the potential the market for wind diesel technology is very large. Effective exploitation of this market relies on the production of reliable and cost effective systems, possible only through the replication of proven design concepts, and also the ability of local engineers to select appropriate systems for a given application. The design process has been hampered, until now, by a lack of suitable design tools. This has meant that systems have been developed and installed without an reliable idea of their performance, which in some instances have turned out to be disappointing.

The Engineering Design Tools package has been developed, with support from the CEC JOULE programme, specifically to assist in the design and assessment of wind diesel systems. It has capabilities for overall performance prediction and dynamic and transient modelling. This paper places more emphasis on the logistic modelling which deals with overall performance in terms of fuel savings, diesel on/off cycling and so on. These are the factors which primarily effect the economics of an application, and hence are a key influence on system selection. Mention will also be made of the modular dynamic model which is part of the package. Its intended role is to assist the manufacturers design engineers assess the stability and dynamic control of a system under development.

BACKGROUND TO EUROPEAN PROJECT

Wind diesel has been an active research area in a number of European countries over an extended period. System models have developed in this context but usually with the aim of representing the particular hardware under experiment at a given research centre. Infield et al (1) provides a review of the research undertaken and the models developed. A wide range of different designs and system configurations have been developed.

The much of the considerable European expertise was brought together in the JOULE project team. The aim was to make wind diesel design assessment effective through the provision of tried and tested, user friendly software. This has been achieved and the resulting software is now available: details of how to obtain a copy of the completed package are given towards the end of the paper.

LOGISTIC MODELLING TOOLS

It was decided that the logistic modelling package would be based on already existing models, but that a common user friendly interface would be constructed to facilitate access to them. Each of the participants in the JOULE project supports a logistic model as shown in Table 1. These models vary to a degree both in the kinds of systems they simulate and in the way they simulate those systems, reflecting the specific research inclinations of the respective institutions. Individually therefore none of the models constitute a comprehensive logistic simulation tool, however collectively they do account for most system scenarios currently considered.
TABLE 1 - Supported models

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![Diagram](image-url)

**Figure 1. Logistic model structure**

The Program Suite: A number of separate programs collectively constitute the integrated package, as shown in Figure 1. Overall control of the suite of programs is handled by the Executive, separate programs handle the pre and post simulation activity (Input and Output) and the six models are retained as individual codes. Communication between the separate program units is undertaken using standard files. (One file between the input code and the model; STDINP.DAT, and one file between the model and the Output code; STDOUT.DAT)

Input: A comprehensive range of pre-simulation functions are supported, including processing of data files and specification of component and system files.

Data: A number of functions for the processing of wind and load data files are catered for by the Shell. Three data types are identified: 'real', actual collected time series data; 'pseudo': time series data synthesised within the Shell, and 'stats': statistical parameters without time series data. Data processing functions are as follows:

Convert: Using this option the user may convert any wind or load data file (time series data only - of any format) to the standard Shell format specified above. Convert creates a new file in the 'wind' or 'load' directory devoted to Shell formatted data files.

Scale: All wind and load time series data files (Shell formatted) can be scaled with a new mean and standard deviation, using this function. The user may overwrite the existing file or save the data to a new named file.

Create: This option enables the user to create new wind or load data files, of types 'stats' or 'pseudo' from within the shell. In the first case the user simply enters key statistical data, which is subsequently saved in the standard header file format; no calculation is undertaken. The Pseudo option enables the synthesis of both wind and load data from within the shell. Basic statistical information entered by the user is used to generate a time series data file of up to 100,000 data points.

Components: The shell incorporates a component data base. Seven component templates are specified:

- wind turbine
- diesel-generator set
- flywheel
- battery
- rectifier
- inverter
- dump load

The user has access to a number of functions for the creation and subsequent manipulation of named components. An on-screen checking facility indicates to the user which parameters are required by each model. To assist the user, internal routines can be used to create a realistic wind turbine or diesel generator component. Only the component rating needs to be specified if this option is chosen. This is a very useful facility when no appropriate manufacturers data are available and an initial design study is required. Additional functions enable the user to view/modify, print or delete existing components.

Systems: Having defined the individual system components, a system specification can be made. It consists of the following elements:

Configuration: Eight basic system configurations are available; simple wind diesel, wind diesel with asynchronous flywheel, wind diesel with battery, wind diesel with interconnecting DC link, wind diesel with interconnecting DC link and asynchronous flywheel, wind diesel with interconnecting DC link and battery, DC system and simple wind diesel with mechanically coupled flywheel.

Between them these cover most wind diesel systems currently being considered.

Control strategy: Five generic control strategies are available; continuous diesel, intermittent diesel - normal mode, intermittent diesel - cycle charge mode, diesel only - normal mode and diesel only - cycle charge mode.

Control parameters: Depending on the strategy chosen up to four control parameters must be specified; power hysteresis level, diesel minimum load, diesel minimum run time and exponential smoothing factor.

Components: The user selects named components via a component template list the content of which is determined by the chosen configuration.

Initiating a Simulation: With appropriate wind and load data files, component specifications and a system specification file, the user is able to initiate a simulation run. The process is straightforward. A sequence of menus enable the user to choose wind, load and system files, along with certain optional additional parameters (including: wind and load data scaling parameters and environmental data). Once again, at each stage in this process the on-screen checking facility indicates to the user which models will run with the selected option. Finally the user is presented with a list of the models which will run with the chosen simulation specification. Once the user has chosen the model to run he/she is able to start the simulation.

Output: Model output results are saved to file and can be viewed as tables or graphically. Comprehensive graphing facilities are supported to include binned data functions for key parameters such as diesel-generator power, fuel consumption and diesel starts. Interactive options include: re-scaling, gridding, cursor (for taking spot measurements), overlays, printing and plotting. Figure 2 shows an example graphics screen with examples of binned performance curves.

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Riso-R-797
Help Facility: The modelling software package supports a fairly comprehensive context sensitive, on-line help facility. This function operates at three levels:

Option checking prompt: Uses of this function depend on the context. The specific applications are described elsewhere in the text.

Menu information: A hot key opens a window containing information on the overall function of the current menu.

Option information: A hot key opens a window containing information on the specific menu option currently highlighted.

LOGISTIC MODEL VALIDATION

Validation plays two important roles with regard to the modelling package. First, it gives a level of confidence to the design engineer in its application. Second, it should highlight the strengths and weaknesses of the individual models available through the Shell.

As already mentioned, the models have generally been developed with particular systems in mind and will not all be equally accurate when modelling a given configuration and control strategy. The user will need to know which models perform best for which applications. Unfortunately, detailed validation is a demanding and time consuming activity and limitations of resource precluded study of more than two systems. Previous model validation work has demonstrated that the modelling of systems in which the diesel runs continuously is not problematic; reliable predictions can be obtained from even simple models. Difficulties arise when the diesel engine is operated intermittently, accurate modelling of the functioning of energy storage combined with the operation of system controls is the main challenge.

For these reasons two systems allowing intermittent diesel operation, but with radically different approaches to energy storage were selected. One system, based at RAL, utilises short term flywheel energy storage mechanically coupled to the diesel engine via a clutch. The other, operated by EFI on the Norwegian Island of Froya, includes longer term battery storage and a power electronic interface.

Detailed data sets were collected from the systems. Data provided by EFI covered 392 hours of uninterrupted system operation, collected at ten minute intervals. For the RAL system, data was collected at 30 second intervals for 144 hours. The differences in data collection rates reflect the nature of these two very different systems. Input load and wind turbine output were dealt with by setting the wind speed to zero during these 'off' periods; this resulted in a reduction of the mean wind speed for the data set from 6.2 to 5.6 m/s. The additional system losses were compensated by adding a constant 0.838 kW to the load.

Table 2 compares predictions from the different models, using the modified input data, with the measured results. Percentage errors are indicated in brackets.

All models were run against the EFi data despite difficulties of representation in some cases. TKKMOD was developed for Ni-Cd batteries rather than the lead-acid ones used. In addition the control strategies available were not really appropriate. Similar considerations applied in the way diesel engine control is represented by E_WISDA. Finally, RALMOD was not developed for long term storage and consequently no meaningful calculation of diesel starts is provided in this instance.

Results of validation against RAL data

Initially the supplied wind turbine characteristic was based on historic data. After the collection of the validation data set this was recognised to be no longer appropriate; significant changes had occurred to the performance of the passive pitching mechanism in the interim. A revised power curve was supplied based on the validation data. A key difficulty created by this was that the control strategy implemented was based on the previous understanding of the wind turbine performance. With the revised performance curve, the criteria for switching off the diesel would never, in an averaged sense, be satisfied. This is because the rated power of the wind turbine was less than the applied constant load plus standing losses. In practice the diesel does cycle on and off, reflecting the inability of the passive pitch mechanism to control effectively short-term variations in power.

Difficulties were experienced with the fuel flow measurement. As a result emphasis has been put on prediction of the diesel load. Past experience has shown that, if this has been modelled accurately, calculating the correct diesel fuel consumption follows straightforwardly. Not all models were considered suitable for running on this data set. Table 3 summarises the validation results.

The model validation exercises, presented in this report, show that energy production, and in particular fuel consumption, can be predicted very well (within a few percent accuracy), depending of course on the accuracy of the model parameters. This is an important conclusion since it is the fuel consumption that normally forms the basis for later economic assessment.

Energy storage cycling, and the predicted number of diesel start/stops show a higher degree of uncertainty. The main reason for this is that the logistic control of the actual system is not always represented properly in a model. In particular, the strategy for start/stop of the diesel generators and for charging and discharging the energy storage, may vary a great deal from one model to another, and not exactly model the range of actual control strategies implemented on real systems.

MODULAR DYNAMIC MODEL

From the outset the intention was to develop a truly modular and fairly general electro-mechanical model suited to the needs of wind diesel systems. Modular electrical models had been available for some time, as had finite element models for mechanical analysis. A suitable model was not then available combining both these elements at a high enough level to allow a proper investigation of
stability and power quality issues for a wind diesel design. Oversimplified modelling could be misleading and the experience of the researchers had already indicated that more detailed aspects of electrical generator operation, such as saturation, are most important in a wind diesel context.

The dynamic model JODYMOD (Joule DYnamic MODular Model) is based on a concept similar to the finite element method (FEM) in structural mechanics, where the equations of a model are built by the program according to the user's system specification. The proprietary simulation program Cypros/ESIM has been chosen as the environment for the model. The model is modular in that it gives the user the opportunity to build a system model by combining a set of available component models. The component model library includes mechanical models and electrical machine models. Each component has inputs and outputs, and a connectivity vector is used to connect the outputs to the inputs in order to build the system equations.

The electrical machine models allow the machine equations to be solved in a matrix form which lends itself to automatic equation assembly. Synchronous and induction machines are represented, and saturation of the electrical machines is dealt with by an iterative process operating on the entire system equations. Mechanical components such as wind turbine drive trains, diesel generator assemblies etc. are represented by FEM type equations. Mechanical components are linked to the electrical machines through the air gap torque. A routine is included that allows the user to define models of rotational systems with gears, with an option to represent a suspended gearbox and a synchronous flywheel. The user may also input the structural matrices directly.

The model provides a number of data handling and time history processing capabilities in addition to a quite powerful graphics package. The Project has negotiated licensing and application agreements with the proprietors of Cypros.

Modularity: The function of the model is to combine the components of a given system into a total system. The core of this problem is to combine the equations for each of the components into a total system of equations for the entire physical system in question. This feature is expressed by the term "modular". Each module or element within the available range of components may be combined with other modules of the same or other types to form a total system. JODYMOD is not a program that needs to be recompiled every time a new model is formulated, and neither is it restricted to a limited number of "precooked" models coded into the program once and for all.

In summary: the fully modular model, JODYMOD has been developed representing both the electrical, mechanical and control aspects of general systems at a sufficiently high level to make a powerful tool for wind diesel system analysis.

A user interface with pull-down menus facilitates access to the model. A typical screen dump is shown in Figure 3. Interactive graphics facilities supported by the Cypros ESIM environment are directly available to the user of JODYMOD. Figure 4 shows the simulation screen which is continuously updated through the simulation, for an example run.

Just as for the logistic models, validation is of central importance if users are to have confidence in the model predictions. A detailed and successful validation exercise has been undertaken for JODYMOD and full details are included in the reports available from the project. These details are also included in the comprehensive documentation that has been written and which is available with the software (see below).
Table 2: Validation results with EFI data

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>SOMET</th>
<th>VINDEO</th>
<th>E WISDA</th>
<th>WDLOG</th>
<th>RALMOD</th>
<th>TECMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine output</td>
<td>4901</td>
<td>4991</td>
<td>4934</td>
<td>4991</td>
<td>4934</td>
<td>4897</td>
<td>4934</td>
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<tr>
<td>(kWh)</td>
<td></td>
<td>(+3)</td>
<td>(+4)</td>
<td>(+3)</td>
<td>(+4)</td>
<td>(+2)</td>
<td>(+3)</td>
</tr>
<tr>
<td>Diesel set output</td>
<td>4615</td>
<td>4324</td>
<td>4304</td>
<td>4709</td>
<td>4751</td>
<td>4723</td>
<td>5099</td>
</tr>
<tr>
<td>(kWh)</td>
<td></td>
<td>(-3)</td>
<td>(-3)</td>
<td>(+1)</td>
<td>(+2)</td>
<td>(+3)</td>
<td>(+10)</td>
</tr>
<tr>
<td>Diesel run time</td>
<td>284</td>
<td>-</td>
<td>-</td>
<td>273</td>
<td>-</td>
<td>290</td>
<td>273</td>
</tr>
<tr>
<td>(hours)</td>
<td></td>
<td></td>
<td></td>
<td>(-4)</td>
<td></td>
<td>(+2)</td>
<td>(-3)</td>
</tr>
<tr>
<td>Dumped energy</td>
<td>1261</td>
<td>1160</td>
<td>1219</td>
<td>1339</td>
<td>1412</td>
<td>1690</td>
<td>1209</td>
</tr>
<tr>
<td>(kWh)</td>
<td></td>
<td>(-3)</td>
<td>(-3)</td>
<td>(+6)</td>
<td>(+12)</td>
<td>(+34)</td>
<td>(+4)</td>
</tr>
<tr>
<td>Number of diesel starts</td>
<td>29</td>
<td>20</td>
<td>23</td>
<td>17</td>
<td>45</td>
<td>2684</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(21)</td>
<td>(21)</td>
<td>(-1)</td>
<td>(+55)</td>
<td>(+38)</td>
<td>(+8)</td>
</tr>
<tr>
<td>Storage - energy in</td>
<td>144</td>
<td>365</td>
<td>279</td>
<td>364</td>
<td>151</td>
<td>-</td>
<td>238</td>
</tr>
<tr>
<td>(kWh)</td>
<td></td>
<td>(+32)</td>
<td>(+68)</td>
<td>(+119)</td>
<td>(+9)</td>
<td></td>
<td>(+33)</td>
</tr>
<tr>
<td>Storage - energy out</td>
<td>129</td>
<td>308</td>
<td>192</td>
<td>222</td>
<td>107</td>
<td>-</td>
<td>201</td>
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<td>(kWh)</td>
<td></td>
<td>(+94)</td>
<td>(+24)</td>
<td>(+58)</td>
<td>(+3)</td>
<td></td>
<td>(+26)</td>
</tr>
<tr>
<td>Total fuel consumption (T)</td>
<td>1812</td>
<td>1707</td>
<td>1732</td>
<td>1810</td>
<td>1919</td>
<td>1836</td>
<td>1818</td>
</tr>
</tbody>
</table>

Table 3: Validation results for RAL data

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>SOMET</th>
<th>VINDEO</th>
<th>E WISDA</th>
<th>WDLOG</th>
<th>RALMOD</th>
<th>TECMOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine output</td>
<td>165</td>
<td>152</td>
<td>215</td>
<td>162</td>
<td>157</td>
<td>223</td>
<td>168</td>
</tr>
<tr>
<td>(kWh)</td>
<td></td>
<td>(-8)</td>
<td>(+30)</td>
<td>(-2)</td>
<td>(-3)</td>
<td>(+36)</td>
<td>(+36)</td>
</tr>
<tr>
<td>Diesel set output</td>
<td>414</td>
<td>432</td>
<td>393</td>
<td>420</td>
<td>380</td>
<td>404</td>
<td>404</td>
</tr>
<tr>
<td>(kWh)</td>
<td></td>
<td>(-5)</td>
<td>(-3)</td>
<td>(+1)</td>
<td>(+1)</td>
<td>(-2)</td>
<td>(-2)</td>
</tr>
<tr>
<td>Diesel run time</td>
<td>132</td>
<td>-</td>
<td>-</td>
<td>144</td>
<td>134</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>(hours)</td>
<td></td>
<td></td>
<td></td>
<td>(+9)</td>
<td>(+2)</td>
<td>(+9)</td>
<td>(+9)</td>
</tr>
<tr>
<td>Dumped energy</td>
<td>103</td>
<td>7</td>
<td>140</td>
<td>118</td>
<td>69</td>
<td>199</td>
<td>199</td>
</tr>
<tr>
<td>(kWh)</td>
<td></td>
<td>(-93)</td>
<td>(+36)</td>
<td>(+15)</td>
<td>(+3)</td>
<td>(+54)</td>
<td>(+54)</td>
</tr>
<tr>
<td>Number of diesel starts</td>
<td>66</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>63</td>
<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td></td>
<td>(-98)</td>
<td>(-98)</td>
<td>(-100)</td>
<td>(-3)</td>
<td>(-100)</td>
<td>(-100)</td>
</tr>
<tr>
<td>Total fuel consumption (T)</td>
<td>-</td>
<td>229</td>
<td>214</td>
<td>220</td>
<td>211</td>
<td>216</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Interactive Graphics Screen Dump
Figure 3: Simulation Data Dialog Box

Figure 4: Run Time Simulation Screen
REPLACEMENT OF OLDER WIND TURBINES - PERSPECTIVES AND MEASURES IN DENMARK

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Danish Energy Agency, DENMARK

INTRODUCTION

Denmark and California are pioneer markets, in which early generations of wind turbines were installed in the 1980's. In both places replacement of older wind turbines has been put on the agenda, Danish Energy Agency [1], Gipe [2].

In February 1993 the Danish Energy Agency was requested to investigate the possibilities of promoting replacement of old or misplaced wind turbines. The work was carried out by the Danish Energy Agency, supervised by a steering group with representatives from counties' and municipalities' organizations, planning and zoning authorities, Ministry of Environment and Planning, Energy Agency, utilities, wind turbine manufacturers and wind turbines owners. Test Station for Wind Turbines assisted the investigation.

The investigation showed that a good potential for better use of the sites of many old turbines existed and an administrative change in the use of the existing funds for development of renewable energies has been made to give possibilities for supporting replacement of old turbines. Danish Energy Agency [3].

The main criteria for support have been decided in May 1994 and it is now possible to have up to 15% of the original investment cost of an existing turbine refunded if a new and bigger turbine is installed instead on the same site or near by. It is essential that the existing turbine is blocking for the new one and it will be the local municipality who decides whether this is the case.

PERSPECTIVES OF REPLACEMENT

Replacement of old and small wind turbines has several aims and spin-offs.

First, the earlier generations of wind turbines often were sited with no official planning and without any zoning restrictions. These turbines often were placed in areas, where deployment today is restricted or prohibited. For example in nature reservation areas or near living areas. In some areas with a very high wind power penetration, wind turbines are sited scattered in the open land, leaving an disorganized impression. In resent year the planning policy recommend that wind turbines are deployed in clusters of 2 to 5 machines or in wind parks. This leaves a more organized impression of the wind turbines and facilitates a better accommodation of wind turbines into the landscape / the open land.

Second, some older turbines are more noisy than modern ones. This combined with such a turbine’s closeness to neighbors in several cases have caused neighbor complains. Complains are often address to planning authorities or to political fora. By replacing such turbines with new ones on more suitable sites this problem can be mitigated.

Third, public disapproval of wind power often is related to few highly visible cases of misplaced turbines. A spin off effect of the above would mitigate the (small but increasing) public disapproval of wind power in Denmark.

* remove old turbines disorganizely sited in the open land
* mitigate neighbor complains
* mitigate increasing public disapproval
* enlarge total MW-potential
* stimulate market
* relieve pioneer wind turbine owners

Table 1. Aims and spin-offs of the replacement program.

Fourth, as a wind power pioneer nation, Denmark has achieved a certain saturation of wind turbines in the open land. It has become increasingly difficult to find good wind sites, which are not already occupied by existing turbines. Planning guidelines often demand that clusters or parks of turbines consist of identical machines. Consequently, one (old and small) machine placed on a good site can block further wind power utilization of this site. Replacement of existing old small turbines (typically 55 kW machines) with new large ones (typically 500 kW) would increase the total potential of wind power resources. An earlier investigation carried out for the Danish Energy Agency concluded that replacement of turbines up to a size of 75 kW would increase the resource potential with between
### Table 2. Overview of the stock of old turbines and the replacement potential. Potential I: replacement with one new turbine, Potential II: replacement with clusters of turbines.

<table>
<thead>
<tr>
<th>Size in kW</th>
<th>Total number</th>
<th>Ownership</th>
<th>Installation date</th>
<th>Potential I</th>
<th>Potential II</th>
</tr>
</thead>
<tbody>
<tr>
<td>15, 18, 22, 30, 37, 45</td>
<td>370</td>
<td>Almost 100% individually</td>
<td>Almost all before January 1986</td>
<td>146 MW</td>
<td>249 MW</td>
</tr>
<tr>
<td>55</td>
<td>476</td>
<td>Ca. 25% individually</td>
<td>Primarily before January 1986</td>
<td>+ 16 MW in parks</td>
<td>+ 16 MW in parks</td>
</tr>
<tr>
<td>65, 75</td>
<td>489</td>
<td>Ca. 25% individually</td>
<td>Primarily before January 1986</td>
<td>117 MW</td>
<td>117 MW</td>
</tr>
<tr>
<td>80, 90, 95, 99, 100, 130</td>
<td>740</td>
<td>Ca. 25% individually</td>
<td>Primarily before January 1986</td>
<td>117 MW</td>
<td>117 MW</td>
</tr>
<tr>
<td></td>
<td>2075/1890</td>
<td></td>
<td></td>
<td>279 MW</td>
<td>382 MW</td>
</tr>
</tbody>
</table>

150 MW and 250 MW. BTM-Consult [4]. If sizes up to 130 kW were included in a replacement program another 117 MW would be added to this potential.

Fifth, during the last years the installation rate of wind power (both private and utility) has dropped to 29 MW in 1993 - the lowest since 1985, DEF [5]. Major reasons for this are 1) the problems of finding suitable sites for the turbines and 2) decreasing benefits for private investors and developers, due to falling prices (excl. tax) on electricity. A replacement program could stimulate the market for wind turbines in Denmark.

Finally, in the late 1970'ies and early 1980'ies entrepreneurial individuals sat their private economy at stake by investing in premature wind power technology. Without these pioneers' effort in the early years Danish wind power technology supposedly not have been on the present level today. Some of these pioneers today possesses machines with very high maintenance cost and still carries a dept burden from their early wind power initiative. As a spin-off effect a replacement program could relieve pioneer wind turbine owners economically.

### TECHNOLOGY STOCK AND REPLACEMENT POTENTIAL

By the end of 1993 Denmark had installed 3548 wind turbines with a total installed capacity of 491,7 MW, DEF [5]. During 1993 wind turbines produced 1051 GWh, or 3,3 % of the country's electricity consumption.

Approximately two thirds of these machines are rated less than 130 kW. 1635 machines are first generation turbines rated between 15 kW and 75 kW, and 740 machines is rated between 80 kW and 130 kW.

An investigation carried out in 1992 by BTM-Consult for the Energy & Environment Ministries' special Committee for Wind Turbine Siting analyzed the MW-potential for a replacement program. The investigation found that replacement of machines smaller that 75 kW would add 162 MW of wind power if existing, replaceable turbines were replaced by one new large turbine. If existing replaceable turbines smaller that 75 kW were replaced by clusters of turbines (2 to 5 pcs) 165 MW would be added. Se table 2.

If existing replaceable machines between 80 kW and 130 kW were replaced by one new machine additional 117 MW would be added to the potential.

Most of the machines are installed before January 1986. This is important because this data marks the introduction of a governmental regulation on wind turbine ownership.

The investigation revealed, that the biggest impediment for replacement of old turbines is the owners disapproval, primarily rooted in lack of economical benefits following a replacement.

### RESTRAINTS FOR REPLACEMENT OF OLD TURBINES

Replacement of turbines is in principle restrained by the same regulation as installation of new turbines. And a number of regulations are to be considered.

**Planning procedures**

All of Denmark's 14 counties have prepared guidelines for a regional planning, which regulates the wind
power deployment with respect to the overall interest connected to "the open land". The municipalities then carry out the local planning and define areas for wind turbine deployment following these guidelines.

In January 1994 the Ministry of Environment has issued a Circular to the municipalities obliging them to present their proposals for wind turbine planning before the end of June 1995. Meanwhile or if not local planning has defined areas reserved for wind turbines an individual zoning approval by the county are required. This to some extend has raised problems of finding suitable sites for new turbines.

In connection with the Circular there has been started an intensified information effort which has spelled out to the municipalities the wishes of the Government to reserve suitable sites. Together with the Circular a publication with examples of good siting and description of the regulations for the open land has been issued and the Danish Energy Agency has supported the publication of a newspaper explaining present situation and the possibilities of wind power together with the positions and views of all the parties with interest in wind energy.

Furthermore, partners in partnerships can maximum own a part of a turbine corresponding to his annual consumption + 50% or 9000 kWh. This restriction on the right to establish private wind energy facilities is based on the wish that, as long as considerable grants are available through the subsidy to the purchasing price, a private commercial possibility of speculation in the expansion of wind energy facilities should be avoided. At present the subsidy per kWh is 27 øre (0.036 ECU).

The majority of replaceable turbines were installed before 1986 and the new regulation will not allow a part of these owners to replace their turbines. Either because of the old turbine is placed outside the owner's municipality or because a new larger machine will exceed the owners consumption limit.

Other regulations

Deployment of wind turbines must follow the regulation on noise emission as spelled out in the Environmental Laws. Also Law on Nature Protection, international nature preservation obligations (Ramsar-areas, etc.), and building authorities are to be taken into account when planning and siting turbines.

THE GOVERNMENTS REPLACEMENT PROGRAM

The Danish wind power program is aiming at 1500 MW of wind power within 2005 as a part of the policy of reducing the CO₂ emission in the Government's energy plan. Today (end 1993) Denmark has an installed wind power capacity of 591.7 MW. However, during the last years the rate of wind power installation (both private and utility) have decreased to 29 MW in 1993 - the lowest since 1985.

The Danish Government has acknowledged that the present installation rate is unacceptably weak. Therefore, the Government has taken a number of initiatives to revitalize the wind power program: 1) municipal wind turbine planning, 2) updating economy survey of privately owned wind turbines, 3) in-depth survey of the social value (external costs) of wind power, 4) chart of conditions for installing off-shore wind turbines, 5) promotion of small wind (household) turbines, and finally 6) a program for replacement of old or misplaced wind turbines.

The aim of the replacement program is to increase the wind power capacity in areas, where old and small turbine are misplaced or blocking installation of further capacity. Also the aim is to improve the visual impact of the turbine.
on the landscape and to reduce the nuisance for the neighbors.

The replacement program uses subsidies to encourage owners of old and/or misplaced turbines to replace these with new ones. The Government has designated annually 10,000,000 DKK (1,300,000 ECU) in 1994, 1994 and 1996 for subsidies to replaced wind turbines. Danish Energy Agency [6]. Subsidies are given on the following terms:

* A declaration from the local planning authority stating that the existing wind turbine is misplaced.

* The subsidy is 15% of the costs of the old turbine, but not can exceed more than 15% of the original installation costs excluding previous subsidy if such has been given.

* The maximum subsidy is 200,000 DKK (27,000 ECU) for each old turbine.

* The capacity of the new turbine or turbines must be substantial higher than the capacity of the old ones.

Status for the replacement programme so far (April 1994 to September 1994) is the following:

* 16 turbines have been replaced by 14 new ones

* 1.6 MW has been replaced by 5.1 MW adding 3.5 MW of capacity

* Total subsidies granted are 1,300,000 DKK (173,000 ECU).

* Ownership of the 16 replaced turbines was distributed with eight turbines were individually owned, one was owned by a company, and seven turbines were by private cooperatives.

* Size of the new machines is: Six are rated 225 kW, one is 300 kW and seven are rated 500 kW.

Experiences of the program so far indicates a satisfying interest among relevant turbine owners for replacement.

**CONCLUSION**

A replacement program has been initiated in Denmark. The aims and spin-offs of this program are: removal of old and small wind turbines scattered sited in the open land, mitigation of neighbor complaints, mitigation of the small but increasing public disapproval of wind turbines, an enlarged total MW-potential, a stimulation of the wind turbine market, and an economical relieve of pioneer wind turbine owners.

The replacement program is based on subsidies to owners who are replacing their old or misplaced turbines. Five month into the program 16 turbines have been replaced, and 3.5 MW of wind power capacity has been added.

<table>
<thead>
<tr>
<th>Replaced turbines</th>
<th>New turbines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sizes in kW</td>
<td>No.</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>8</td>
</tr>
<tr>
<td>100-200</td>
<td>6</td>
</tr>
<tr>
<td>&gt; 200</td>
<td>2</td>
</tr>
<tr>
<td>Totals</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 4. Status for the replacement programmes first five month.

**LIST OF REFERENCES**

1. Danish Ministry of Energy
   ENERGY 2000 - Follow up.
   Copenhagen. November 1993


5. DEF (Association of Danish Utilities)
   Private communication, September 1994.

Contributions from the Department of Meteorology and Wind Energy to the EWEC'94 Conference in Thessaloniki, Greece

Edited by Gunner C. Larsen

The 5'th European Wind Energy Association Conference and Exhibition - EWEC'94 - was held in Thessaloniki, Greece during the period 10-14 October 1994. 461 delegates, mainly from Europe but also from other parts of the world, attended the conference. The conference contributions included 235 oral presentations and 143 posters.

The Department of Meteorology and Wind Energy contributed with 18 oral presentations and 3 posters with members of the department as authors or co-authors. The present report contains the full set of these papers, covering a wide spectrum of subjects including wind resources, reliability and load assessment, grid connection, wind–diesel systems, and marked aspects.

Descriptors INIS/EDB
AERODYNAMICS; DYNAMIC LOADS; MEETINGS; RISOE NATIONAL LABORATORY; STRUCTURAL MODELS; TURBULENCE; WIND; WIND LOADS; WIND POWER; WIND TURBINES

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Objective
The objective of Risø's research is to provide industry and society with new potential in three main areas:

- Energy technology and energy planning
- Environmental aspects of energy, industrial and plant production
- Materials and measuring techniques for industry

As a special obligation Risø maintains and extends the knowledge required to advise the authorities on nuclear matters.

Research Profile
Risø's research is long-term and knowledge-oriented and directed toward areas where there are recognised needs for new solutions in Danish society. The programme areas are:

- Combustion and gasification
- Wind energy
- Energy technologies for the future
- Energy planning
- Environmental aspects of energy and industrial production
- Environmental aspects of plant production
- Nuclear safety and radiation protection
- Materials with new physical and chemical properties
- Structural materials
- Optical measurement techniques and information processing

Transfer of Knowledge
The results of Risø's research are transferred to industry and authorities through:

- Research co-operation
- Co-operation in R&D consortia
- R&D clubs and exchange of researchers
- Centre for Advanced Technology
- Patenting and licencing activities

To the scientific world through:

- Publication activities
- Co-operation in national and international networks
- PhD- and Post Doc. education

Key Figures
Risø has a staff of just over 900, of which more than 300 are scientists and 80 are PhD and Post Doc. students. Risø's 1995 budget totals DKK 476m, of which 45% come from research programmes and commercial contracts, while the remainder is covered by government appropriations.