VERIFICATION OF EUROPEAN WIND TURBINE DESIGN CODES

J.G. Schepers and J. Heijdra
Netherlands Energy Research Foundation, ECN
P.O. Box 1, 1755 ZG Petten, Netherlands

K. Thomsen and J.T. Larsen
Risø National Laboratory, RISØ (DK)

D. Foussekis
Centre for Renewable Energy Sources, CRES (Gr)

R. Rawlinson Smith
Garrad Hassan and Partners, GH (UK)

I. Kraan and B. Visser, SPE
Stork Product Engineering, SPE (NL)

H. Ganander and I. Carlen
Teknikgruppen AB, TA (Sw)

S. Øye, DTU
Technical University of Denmark, Dept. of Energy Engineering, Fluid Mechanics Section, DTU (Dk)

M. Belessis
National Technical University of Athens, NTUA, Gr

L. Drost
Lagerwey, The WindMaster Netherlands, LW NL

JOR3-CT98-0267

Final publishable report

June 1 1998 to June 1 2001

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non-Nuclear Energy Programme
JOULE III

CONTENTS

SYMBOLS AND ABBREVIATIONS

Notation/Abbreviation	Description	unit
A	Coherence decay factor	-
$C_{D.ax}$	Axial force coefficient	-
D	Rotor diameter	m
dec	decay factor in coherence (Derived from measurements)	-
h	Heigth	m
h_{hub}	hub height	m
I(h)	Turbulence intensity	%
L	Turbulence length scale	m
M_{edge}	Blade edge moment	Nm
M_{flat}	Blade flat moment	Nm
M_{yaw}	Yawing moment	Nm
M_{roll}	Tower rolling moment	Nm
M_{pitch}	Tower pitching moment	Nm
P	Frequency of rotation	
P	Power	kW
R	Rotor radius	m
r	Radial distance from rotor center	m
TAS	True Air Speed (local wind speed at blade segment)	m/s
U,V,W	Axial, lateral and vertical wind speeds	m/s
winddir	Wind direction	deg
yawpos	Position of nacelle	deg
U_{hub}	Wind speed at hub height	m/s
α	Angle of attack	-
λ	Tip speed ratio	-
Ω	Rotor speed	[rad/s]
σ	Standard deviation (usually of wind speed)	[m/s]
θ	Pitch angle, or inclination	[deg]
APSD	Auto power spectral density	
rfc	Rainflow cycle counts	

Acknowledgement

This report has been prepared within the framework of the EU-JOULE project ’Verification of European Wind Turbine Design Codes, contract JOR3-CT98-0267.
ECN project number 74051
Additional funding was obtained from: Netherlands Organisation for Energy and the Environment, NOVEM contract number 224.750-9851
Danish Energy Agency contract number 51171/98-0015
Swedish National Energy Administration, contract numer P11573
The Greek General Secretariat for Research & Technology

Abstract

In this report, the results of the EU-JOULE project Verification of European Wind Turbine Design Codes, VEWTDC are described. In this project a verification is performed of eight wind turbine codes from five different European countries. Code predictions of mechanical loads (blade loads, rotor loads, tower loads) have been compared with measurements on three different turbines, obtained at different conditions (normal operating conditions and special events).

In this report, the working procedure is described, a global description of the different codes is given and the main results are reported.

Keywords

Verification of Wind Turbine Design Codes

1. PARTNERSHIP

- Coordinator:
  Energy Research Centre of the Netherlands, Westerduinweg 3, Petten, NL-1755 ZG, The Netherlands,
  Phone: +31 224 564894, Fax: +31 224 568214,
  Contact person: Gerard Schepers
- Partners:
  - RISØ National Laboratory, P.O. Box 49, DK-4000 Roskilde, Denmark,
    Phone: +454677 5071, Fax: +45 4677 5083,
    Contact person: Kenneth Thomsen;
  - Center for Renewable Energy Sources, CRES, 19th Km Marathon Avenue, Pikermi, Attiki, 19009 Greece,
    Phone: +30 1 6039900, fax +30 1 6039900,
    Contact person: Dimitri Foussekis;
  - Garrad Hassan and Partners Ltd, St. Vincent's Works, Silverthorne Lane, Bristol, BS20QD, United Kingdom,
    Phone: +44117 979900, Fax: +44117 979901,
    Contact person: Robert Rawlinson Smith;
  - Stork Product Engineering, SPE, P.O. Box 379, 1000 AJ Amsterdam, The Netherlands,
    Phone: +31205563452, Fax:+31205563556,
    Contact person: Bart Visser;
  - Danish Technical University, DTU, Building 403, DK-2800 Lyngby Denmark,
    Phone: +45 45 25 43 11, Fax: +45 45 930663;
    Contact person: Stig Øye
  - Teknikgruppen AB, P.O. Box 21, S-19121 Sollentuna, Sweden,
    Phone: +4684445120, Fax: +4684445129,
    Contact person: Hans Ganander;
  - National Technical University of Athens, P.O. Box 64070, 15710 Zografou, Athens, Greece,
    Phone: +3017721096, Fax +301 7721057,
    Contact person: Michael Belessis;
  - Lagerwey Windturbine B.V., P.O. Box 279, NL-3770 AG Barneveld,
    Phone: +31 342 422724, Fax: +31 342 422861,
    Contact person: Laurens Drost

2. OBJECTIVES

The European wind industry uses wind turbine analysis codes for the calculation of dynamic loads and energy yield. The codes are based on detailed aeroelastic and structural models. A stochastic wind simulator is part of the code: It provides the turbulent wind over the rotor plane, using statistical properties of the wind (i.e. mean wind speeds, turbulence intensities, turbulent length scales etc) as a basis. The results of the design codes (i.e. loads, power, control variables etc. as function of time) are important for the design of wind turbine (components) and for certification purposes.

In Europe different codes are used which are developed by several organisations. In the past several projects have been performed, which aimed at the determination of the accuracy and reliability of such codes. However, usually the number of codes which were involved in these projects was limited and the attention was often focussed on particular submodels of the design codes, i.e. the modelling and verification of dynamic stall effects, dynamic inflow effects etc. Consequently, a general insight on the accuracy and reliability of the present most widely used codes is lacking in the industry and certification institutes.

The objectives of the project were thus defined as:

- The assessment of the accuracy and reliability of the most widely used European wind turbine design codes for improved support of wind turbine design and certification;
- The definition of recommendations for improvement of the present wind turbine design codes and the required supporting experiments.

To this end an overall verification of the most widely used European wind turbine codes is performed. Eight wind turbine codes from five different countries were involved.

Code predictions (mainly loads: blade loads, rotor loads and tower loads but also accelerations and inflow velocities) have been compared with measurements which are obtained at different conditions (normal operating conditions and special events). The experimental data are collected on three different turbines:

- The Nordtank-500 (NTK-500): This is a three bladed stall controlled, 41 m diameter constant speed turbine. The turbine is located at RISØ's test field near Roskilde Denmark and the measurements are performed by RISØ;
- The Tacke-500 turbine: This is a three bladed stall controlled, 37 m diameter constant speed turbine. The turbine is located on Crete, Greece in complex terrain. The measurements are performed by CRES;
- The Lagerwey 750 turbine (LW750): This is a three bladed, active pitch, variable speed, direct drive turbine with a diameter of 50.5 meter. This turbine is located in Oude Tonge (The Netherlands) and the measurements are performed by ECN.

The project started in June 1998 and ended in June 2001.

3. TECHNICAL DESCRIPTION

3.1 PARTICIPANTS AND CODES

In the following table, the participants and the name of their aeroelastic codes are listed. Note that the wind simulators are not included in this survey:

Participant	Name of code
Netherlands Energy Research Foundation, ECN, NL (Coordinator)	PHATAS
Center for Renewable Energy Sources, CRES, Gr	Alcyone
RISØ, Dk	HAWC
Garrad Hassan and Partners, GH, UK	Bladed
Danish Technical University, DTU, Dk	Flex4
Stork Product Engineering, SPE, NL	Flexlast
Teknikgruppen AB, TA, S	Vidyn
National Technical University of Athens, NTUA, Gr	Alcyone(free wake)

The characteristics of the codes, in terms of modelling and calculational time, can be summarized as follows:

- Aerodynamic modelling: With the exception of NTUA, all participants apply the blade element momentum theory, using (semi-)empirical corrections for stall, dynamic inflow, yaw etc. The NTUA model is based on a free wake panel method;
- Structural modelling: Various differences are apparent in the degrees of freedom and the numerical solution methods. RISØ, CRES and NTUA apply a finite element description, where the other participants apply modal descriptions or combinations of modal descriptions and FE-like descriptions;
- Wind Modelling: RISØ uses the Mann model, where all other participants apply a 'Veers like' method;
- Calculational time: The calculational time of the modal based methods is in the order of 1 to 2 times real-time on 400 MHz PC's . The calculational time of FE methods is in the order of 5-15 times real time. The NTUA free wake method takes some 5 days for a 10 minute time simulations.

3.2 APPROACH

The main tasks which have been carried out in the project are:

- Performance of measurements on the three turbines;
- Simulation of the measurements using the various aeroelastic codes. Two rounds of calculations are performed per turbine;
- Comparison of calculations and measurements;
- Evaluation of differences between calculations and measurements and between calculations mutually.

It was attempted to produce results, which would give at least some measure for design inaccuracies. Thereto an approach was followed, which was as much as possible representative for an industrial design approach. However, in the sequel it will be explained that a large number of uncertainties exist, some of which are not present in design calculations, which make it difficult to translate the differences between calculations and measurements to design inaccuracies.

Two calculational rounds have been performed per turbine. In the sequel they will be referred to by 1st and 2nd round.

3.2.1 First round

The first round is (in principle) carried out in agreement with a design procedure, without a-priori knowledge of the measurements. However, it was allowed to tune the measured values of eigenfrequencies. Thereto it should be realised that the definition of an actual design procedure is rather arbitrary: It can range from a complete new design project to projects in which an existing design is adjusted/ adapted/upscaled using the experience and data of the existing turbine. In all of these cases, drawings and complete component information is available. Such information was partly lacking in the present project. For this reason knowledge on measured eigenfrequencies was supplied to compensate the lack of complete drawings and component data. The eigenfrequencies were also supplied, because the response near a natural frequency is extremely sensitive to the precise value of the eigenfrequency.

3.2.2 Second round

Although, as stated above, it was attempted to follow a procedure which is as much as possible representative for an industrial approach, it should be realised that the comparison between calculations and measurements is obscured by a large number of uncertainties, some of which are not present in design calculations. In particular the uncertainties in the turbine model description and the wind modelling, can play a large role in this respect. In the second round of calculations it was allowed to tune the input parameters to the measurements. In this way the uncertainties in input could, theoretically speaking, be eliminated. Obviously some basic parameters, i.e rotor diameter, tower height, mean wind speed, turbulence intensity etc. are prescribed and could not be tuned.

As a matter of fact, the second round can be considered as a sensitivity study to find the most sensitive design parameters and it helped understanding the cause of some discrepancies from the first round.

Obviously the second round of calculations also served as a ’second chance’, i.e. input errors and misunderstandings on the input, which were apparent in the 1st round have been corrected.

3.2.3 Selection of load cases

For every turbine the design driving load cases have been determined. This made it possible to select and define measurements, which are as much as possible comparable to the design driving load cases. In this way the comparison would yield the most practical design value.

3.2.4 Input for the load cases

The input for the different load cases, which have been simulated is based on measurements of the external conditions (i.e. mean wind speeds, turbulence intensity, turbulence length scales, coherence parameters etc) as well as an aero-elastic description of the turbine. Much effort was spent in order to make this model description of the turbines as complete as possible. Actually the gathering of data for the turbine modelling turned out to be a difficult, time consuming and floating process, which complicated the progress of the project considerably: Often, additional or corrected information became available after many calculations were already performed. As such the calculations of the 1st round are sometimes based on different turbine data than the 2nd round. The final turbine data, which have been used in the second round of calculations are given in confidential task reports, [1], [2], [3] and [4]. A very important, but also very uncertain part of the input data is apparent in the airfoil data. The airfoil data have been prescribed, but they are based on only a limited number of measurements: Measurements were only available for a few airfoil thicknesses and for a limited angle of attack range (say from -10 to + 20 degrees). Hence an uncertain inter- and extrapolation of airfoil data was inevatible.

3.2.5 Processing and comparison of data

The aeroelastic codes produce results as time series. A comparison between calculations and measurements on basis of long time series is obviously not feasible. Therefore it was decided to make the comparison for the normal production cases on basis of 1P equivalent loads (for the variable speed LW750 turbine: 1Hz equivalent loads) and mean blade loads. These results were considered to be design driving and differences between calculations and measurements can be quantified straightforwardly. In order to understand the 1P equivalent loads, the rain flow cycle counts, the azimuthally binned averaged values and the auto power spectral densities have also been compared. These results are much more difficult to quantify and they are mainly compared on basis of line shapes, i.e. on a qualitative basis.

3.3 MEASUREMENTS AND LOAD CASE DEFINITION

3.3.1 Measurement campaigns

In order to select the campaigns to be simulated, an inventory was made of the design driving load cases of the different turbines. At the time the present project started, the measurement systems on the Tacke-500 and NTK-500 turbine were not operational anymore and therefore measurements from the existing databases had to be selected, which were taken at conditions as close as possible to the design driving load cases. The measurements on the LW 750 turbine could be performed within the project period.

Per turbine, at least a number of normal production measurements (10 minute time series) have been supplied. Normal production cases turned out to be design driving for several components. Usually a total of 9 normal production cases have been supplied per turbine, but for the LW750 turbine only 7 normal production cases were available. The nine normal production cases could, roughly speaking, be subdivided in three groups. Each group of measurements contains three realisations, which are taken at more or less similar conditions. The availability of more realisations per wind speed is expected to yield some indication on the spread in measured loads which are found at comparable conditions.

For the LW750 turbine, two special, design driving, load cases could be measured and simulated: An extreme yaw case of 60 degrees near rated wind speed, and a failed pitch case at idling conditions. The failed pitch case was measured at a wind speed of approximately 12 m/s. This obviously does not correspond to the wind speed of the failed pitch case in the design spectrum, which is much higher. However, it is assumed that differences between calculations and measurements are not influenced to a large extent by the wind speed.

The length of all campaigns is 10 minutes.

The definition of the load cases is described in more detail in the section 3.3.3, 3.3.4 and 3.3.5.

3.3.2 Available signals

For all turbines, measurements of blade root bending moments, tower top and tower bottom bending moments were available. For the LW750 turbine, measurements of nacelle accelerations have also been taken and the blade root bending moments are measured on all three blades. For the NTK-500 turbine, measurements of the flat moments are not only taken at the root, but also at 3 other radial positions. Furthermore shaft moments and inflow velocities have been recorded. In particular the measurement of the inflow velocities delivered a unique validation opportunity: A direct comparison could be made on basis of a very local blade property.

For all turbines some auxiliary signals (i.e. yaw position, electrical power, rotor speed, pitch angle and azimuth angle) are also measured.

The wind is measured at hub height, either with a sonic anemometer (Tacke-500, LW750) or by means of a cup anemometer and wind vane. For the LW750 and Tacke- 500 cases, the wind is measured at different heights using cup anemometers and wind vanes. From these wind measurements, the conditions of the cases to be simulated, were derived.

3.3.3 Definition of NTK-500 calculational cases

NTK-500 1st round

The mean external conditions for the NTK-500, 1st round are given in the table below (In this table the indicated wind speed gives the wind speed at h = 36 m, ’I’ = turbulence intensity at 36 m; ’yawpos’ is position of nacelle and ’winddir’ is wind direction at h =36 m):

Campaign name	Wind speed	I	yawpos	windir
	m/s	[-]	deg	deg
NTK Load case 1	7.86	0.12	259	269
NTK Load case 2	11.79	0.11	263	270
NTK Load case 3	15.40	0.10	299	300
NTK Load case 4	8.96	0.11	259	270
NTK Load case 5	11.38	0.10	263	271
NTK Load case 6	15.48	0.09	299	301
NTK Load case 7	8.60	0.10	259	269
NTK Load case 8	11.31	0.13	259	270
NTK Load case 9	15.14	0.09	301	300

Furthermore the following values have been adopted, which are derived by RISØ and rely on a large number of meteorological data taken at the site:

- Average roughness length = 0.06 m
- σ_v/σ_u = 0.84
- σ_w/σ_u = 0.62
- L_u = 600 m
- L_v = 180 m
- L_w = 60 m
- A_u = 12
- A_v = 6

- A_w = 6

The index u,v,w, denote the axial, lateral and vertical direction. S is the standard deviation. L is the length scale according to the Danish (DS) Code of practice. The ratio between the IEC1400 length scales (the IEC Kaimal formulation) and the DS length scale is a factor of 4:

$$L(IEC) = 0.25L(DS). \tag{3.1}$$

Thus if the IEC Kaimal formulation is used, the above mentioned length scales should be multiplied by a factor of 0.25.

A is the coherence decay factor. It should be interpreted as follows: An exponential coherence model to IEC 1400-1 is used but without the second (r/L1) term. Furthermore the factor 8.8, which is found in the IEC formulation, should be substituted by the A factors given above.

The NTK load cases 1, 2 and 3 have been simulated by the participants. The other campaigns are measured at comparable conditions, and they gave insight into differences which can occur at more or less comparable conditions. Thereto the measured values of the other campaigns have been added in the figures of the 1P equivalent loads and the rain flow cycle counts. The definition of the 1st round of calculations then follows from the conditions as given above, together with the aeroelastic model description from [1]. The following quantities have been calculated and compared with measurements:

- Flatwise moments at blade root, 25% span, 50% span and 75%;
- Edge moment at blade root;
- Inflow velocities at 75% span;
- Shaft torque;
- Shaft bending (in a rotating frame of reference);
- Tower top bending and tower top yawing moments;
- Tower bottom bending moments.

Note that because of the poor quality, the tower bottom moments have not been used in the analysis. The definition of these signals and their coordinate systems are described in [5].

The first round of NTK-500 calculations was followed by a second round.

NTK-500 2nd round

The definition of the 2nd round of calculations was very similar to the definition of the 1st round of calculations. However, the following differences were apparent:

- In the 2nd round of calculations, the participants were allowed to tune the input and model parameters to the measurement results, see section 3.2.2.
- In the 1st round of calculations, the measured yaw angle was supplied as input for the calculational cases. Although, no reasons could be found to suspect the measurement quality of the yaw angle, some doubt on the precise value of it arose at a later stage due to the fact that a sensitivity study performed by RISØ showed a remarkable improvement in results, after adding 7 degrees to the measured yaw angle. This improvement in calculational results was considered very convincing and for this reason 7 degrees of yaw angle was added to the measured values in the definition of the second round, even though the measurements itself did not yield any suspicion on the yaw angle.
- Information of some measured NTK-500 eigenfrequencies became more complete after the 1st round.

- The shaft moments have also been presented in a fixed frame of reference.

3.3.4 Definition of Tacke-500 calculational cases

Tacke-500: 1st Round

The mean external conditions for the Tacke-500 1st round of calculations are given in the table below (The indicated wind speed is the u-component measured by the sonic anemometer at h = 35 m in a refence system which yields V_{mean} = 0 and W_{mean} = 0; θ gives the inclination, i.e. the inclination of the U_{mean} vector w.r.t. the horizontal (positive is an upward inclination). The shear is according to a logarithmic profile as specified in the Benchmark report from the previous EU-project Mountturb, [6]. Furthermore ’yawpos ’is the position of the nacelle and ’windir’ is the wind direction from the cup anemometer at 35 m.

Campaing	Wind speed	θ	shear	yawpos	windir
	m/s	deg	[-]	deg	deg
Tacke Load case 1	10.41	-2.84	0.126	282.27	299.63
Tacke Load case 2	10.26	-0.29	0.165	292.85	307.00
Tacke Load case 3	9.44	-1.94	0.102	291.37	307.25
Tacke Load case 4	13.97	0.76	0.078	283.87	308.64
Tacke Load case 5	13.83	-0.66	0.113	277.12	304.13
Tacke Load case 6	13.57	-1.08	0.146	291.38	307.43
Tacke Load case 7	18.18	-2.32	0.030	274.47	302.79
Tacke Load case 8	17.66	-0.64	0.130	284.79	307.50
Tacke Load case 9	17.92	-0.37	0.118	283.46	306.94

In the table below, the 3 turbulence intensities (measured at hub height with the sonic anemometer) are listed (again: V_{mean} = 0 and W_{mean} = 0). Then, there are 3 decay factors calculated using the 3 cup anemometers (l:low, m:middle, h:high) of the meteo mast. The average of these three values have been taken, see [6]

Finally, the 3 length scales (again from the sonic anemometer at hub height) are given, calculated as in the "Benchmark Exercise" Mounturb report [6].

Case	Iu	Iv	Iw	Dec(lm)	Dec(lh)	Dec(mh)	Lu	Lv	Lw
	[%]	[%]	[%]	[-]	[-]	[-]	m	m	m
1	10.114	7.678	5.255	5.618	4.934	4.285	132.1	23.0	11.8
2	13.343	8.450	6.499	6.025	2.407	4.882	96.0	14.9	9.8
3	9.835	6.375	5.181	7.703	5.531	10.209	75.7	12.5	9.8
4	12.739	10.930	6.750	5.951	6.760	3.002	80.6	34.9	11.7
5	12.149	8.120	6.433	8.960	7.896	7.042	106.2	21.2	13.4
6	7.322	6.887	5.443	7.013	7.564	2.641	37.1	13.5	9.2
7	8.581	7.209	5.786	7.557	4.073	3.553	84.4	30.5	15.2
8	10.071	7.660	5.775	11.823	9.784	11.267	80.1	20.9	11.0
9	11.285	8.315	5.142	11.346	8.021	5.439	175.5	35.9	12.8

The Tacke load cases 1, 4 and 8 have been simulated by the participants. The other campaigns are measured at comparable conditions, and they gave insight into differences which can occur at more or less comparable conditions. Thereto the measured values of the other campaigns have been added in the figures of the 1P equivalent loads and the rain flow cycle counts. The definition of the 1st round of calculations then follows from the conditions as given above, together with the aeroelastic model description from [2]. The following quantities have been calculated and compared with measurements:

- Flatwise moments at blade root;

- Edge moment at blade root;
- Tower top bending and tower top yawing moments;
- Tower bottom bending moments.

The definition of these signals and their coordinate systems are described in [5].

The first round of calculations was followed by a second round.

Tacke-500 2nd round

The definition of the 2nd round of calculations was very similar to the definition of the 1st round of calculations, but some exceptions are apparent:

- As explained in section 3.2.2, it is allowed to tune the input and model parameters to the measurement results in the 2nd round;
- In the first round, the measured yaw angles were prescribed for the definition of the calculational cases, but some doubt arose on these values, due to the complex terrain topography for this turbine. The agreement between the measured and the real misalignment could only be determined through a site calibration procedure but this was beyond the project's scope and was not performed. For this reason, the yaw error was left free in the second round of Tacke calculations, i.e. the yaw error was considered as one of the uncertain input parameters, which were allowed to be tuned to the measurements;
- The azimuth angle was not measured directly. In the 2nd round, the azimuth angle has been determined from the measured edge moment.

3.3.5 Definition of LW750 calculational cases

For the LW750 turbine, 3 normal production cases are simulated, as well as a yawed case and a failed pitch case.

The yawed case is a measurement campaign which simulates the failed yaw situation. The yaw angle is 60 degrees. The wind speed is 10.1 m/s, i.e. below rated. Hence the pitch angles of the blades are fixed at working position (0 degrees);

The failed pitch case simulates a failed pitch situation of blade 1. The pitch angle of this blade is (artificially) fixed to 0 degrees. The other 2 blades are feathered (i.e. $\theta = 87$ degrees). The generator is disconnected and the turbine idles. The wind speed is 12.7 m/s. Note that the campaign is supposed to correspond to the design-driving failed pitch case from the design spectrum. However, the failed pitch case of the design spectrum is calculated at a much different wind speed, i.e. at a wind speed of 50 m/s, which obviously could not be measured within the measurement period. It is assumed that differences between calculations and measurements depend only slightly on the conditions;

The length of all campaigns is 10 minutes.

For the second round comparisons, some measured realisations have been added, which are taken at conditions comparable to those of campaign 4 and 5. These additional campaigns are denoted by the campaigns 7 to 10 and they gave insight into differences which can occur at more or less comparable conditions. Thereto the measured values of the other campaigns have been added in the figures of the 1P equivalent loads and the rain flow cycle counts.

LW-750, 1st round

The mean external conditions for the 1st round LW750 calculations are given in the table below (The indicated wind speed is the u-component measured by the sonic anemometer at h = 50 m in a refence system which yields V_{mean} = 0 and W_{mean} = 0; θ gives the inclination, i.e. the inclination of the U_{mean} vector w.r.t. the horizontal (positive is an upward inclination). An exponential wind shear is assumed. Furthermore 'yawpos 'is the position of the nacelle and 'windir' denotes the wind direction.

Campaign	Wind speed	θ	shear	yawpos	windir
	m/s	deg	[-]	deg	deg
LW Load case 1(yaw_plus)	10.1	0.	0.143	240	180.1
LW Load case 3(pitch_fail)	12.7	0.	0.066	186	180.2
LW Load case 4	9.17	0.	0.137	178	171.4
LW Load case 5	12.8	0.	0.108	170	167.4
LW Load case 6	15.9	0.	0.042	255	252.8

In the table below, the 3 standard deviations (measured at hub height with the sonic anemometer) are listed (again: V_{mean} = 0 and W_{mean} = 0). Then, there are 3 decay factors which have been derived from the the 3 cup anemometers of the meteo mast, according to the procedure reported in the MOUNTURB "Benchmark Exercise" [6].

Finally, the 3 von Karman length scales (again from the sonic anemometer at hub height) are given.

Case	σ_u	σ_v	σ_w	Dec(u)	Dec(v)	Dec(w)	Lu	Lv	Lw
	[m/s]	[m/s]	[m/s]	[-]	[-]	[-]	m	m	m
1	0.68	0.58	0.39	8	5.8	6.9	54.2	16.5	6.9
3	1.18	0.85	0.61	8	7.1	7.6	89.8	29.1	7.6
4	0.52	0.48	0.32	8	4.9	6.5	34.2	11.7	6.5
5	0.94	0.79	0.56	8	5.6	6.8	64.2	19.9	6.8
6	1.09	0.94	0.65	8	5.3	6.7	122.8	43.4	6.7

The definition of the LW750 calculational cases then follows from these external conditions, the aeroelastic model description ([3]) and the description of the control modelling ([4]).

The following quantities have been simulated and compared with measurements:

- Blade root bending moments (flat and edgewise on all three blades at r = 3.907 m from rotor center);
- Tower top bending moments and tower top torsion. Note that because of the poor quality, the measurements of the tower top torsion have not been used in the comparison with the calculations;
- Tower bottom bending moments;
- Nacelle accelerations.

The definition of these signals and their coordinate systems are described in [5].

LW-750, 2nd round

Generally speaking, the definition of the 2nd round is similar to the definition of the 1st round and the same cases have been simulated as for the 1st round, i.e. the cases 1, 3, 4, 5 and 6. The following differences are apparent:

- As explained in section 3.2.2, the main difference between the 1st and 2nd round is given by the fact that in the 2nd round, the participants were left free to tune their input parameters. This led to important differences in the treatment of cases. This holds in particular for case 3 (the failed pitch case): In the 1st round most participants did not predict the rotor to be rotating. In the 2nd round some participants forced the turbine to rotate. Thereto some participants simply prescribed the measured rotor speed but other participants tuned the pitch angle or the yaw angle.
- Between the 1st and 2nd round, some small errors became apparent in the specifications of the calculational cases:
  - The yaw position of loadcase 1 should be 239 degrees instead of 240 degrees;
  - The wind direction for loadcase 6 should be 250.8 degrees instead of 252.8 degrees.

  Some, but not all participants corrected these errors.
- It should also be noted that the measurements on which the comparisons are based, are different for some cases in the 2nd round. This is due to the fact that the 2nd round calculations of the cases 4 and 5 are compared with three measured realisations, where only 1 measured realisation was available in the 1st round. These additional measurements are denoted by the cases 7, 8, 9 and 10. The cases 7 and 8 are taken at conditions more or less comparable to case 4 and the cases 9 and 10 have been taken at conditions more or less comparable to case 5. The campaigns have been added because they are expected to give insight into differences which can occur at more or less comparable conditions. The conditions (i.e. the mean wind speed, turbulence intensity and yaw misalignment) of the additional campaigns 7 to 10 are compared with the conditions of the corresponding 'basic' cases 4 and 5 in the following table:

Campaign	Wind speed	yawpos	windir	I
	m/s	deg	deg	%
LW Load case 4	9.17	178	171.4	5.7
LW Load case 7	9.41	184.4	178.0	5.6
LW Load case 8	8.99	184.3	177.0	6.3
LW Load case 5	12.8	170	167.4	7.4
LW Load case 9	11.46	197.5	192.7	7.3
LW Load case 10	11.37	169.4	173.8	6.9

3.3.6 Measurement quality

The uncertainties in the load measurements depend on the sensor. Items like calibration uncertainties, temperature effects, sensor positions and orientations, and cross-talks play an important role. For the measurements on the NTK-500 and Tacke-500 a 'sensor quality indicator' has been determined. This was a subjective measure based on the experience of the particular measurement group. The indicator ranges from 'very poor', to 'rather poor', 'rather good' and 'very good'. If the quality indicator was assessed to be 'very poor', the measured results were not included in the comparisons. This turned out to be true for the mean edge moment and for the tower bottom moments on the NTK-500 turbine. The uncertainty in the Lagerwey load measurements has been estimated by means of an uncertainty analysis. The uncertainty is determined on basis of the known or estimated uncertainties of the measuring equipment. Furthermore the uncertainties of the parameters in the relations, which are used to calculate the physical quantities from the measured signals, play a role and needed to be estimated. The calculations are done using the @RISK risk analysis tool from Microsoft Excel. @RISK uses Monte Carlo simulations to determine the statistical parameters of output quantities. It is based on the statistical distribution of selected input quantities using mathematical relations between the output and input quantities. Obviously some subjectiveness becomes apparent in the selection of the input quantities and their distributions. For the LW750 blade loads, an additional check on the accuracy has been carried out by comparing the statistics of the loads from the three different blades. The resulting uncertainties in LW750 blade and most tower fatigue 1Hz equivalent loads turned out to be be approximately +/-5%. The uncertainty analysis led to the conclusion that the quality of the tower top yawing measurements and the mean edge moment measurements was too poor to be included in the comparison.

3.4 COMPARISON AND EVALUATION

All participants sent their results to ECN in the form of time series. ECN then processed the results to 1P(1Hz) equivalent loads, rain flow cycle counts, APSD's, and azimuthally binned averaged values. These results are presented in graphs and tables.

Note that the total number of figures is in the order 800. The figures are not included in the present report, but they can be found on the accompanying CD-ROM and on the Internet site: http://www.ecn.nl/unit_de/wind/project/vewtdc.html. The figures, which have been produced in the project have been evaluated and the main observations on every figure have been reported in task reports. It was attempted to perform the comparison of the design loads as much as possible in a quantitative way. Therefore the main comparison took place on basis of numbers which could be quantified straightforwardly, i.e. 1P/1Hz equivalent loads (including '1Hz equivalent'accelerations) and mean blade loads.

For every 1Hz/1P equivalent and mean load, the difference between calculated and measured values was determined as difference between the 'mean' of all calculations and the measured results:

$$\mathrm{difference} = (\overline{\mathrm{calc}} - \overline{\mathrm{meas}})/\overline{\mathrm{meas}} \tag{3.2}$$

The 'mean' value of the calculations is determined by:

$$\overline{\mathrm{calc}} = [\mathrm{calc}_{\mathrm{max}} + \mathrm{calc}_{\mathrm{min}}]/2. \tag{3.3}$$

with $\mathrm{calc}_{\mathrm{max}}$ the maximum calculated result and $\mathrm{calc}_{\mathrm{min}}$ the minimum calculated result. The bar, indicating the mean measured value refers to the mean value of the three blade measurements (for the LW750 cases) and/or the mean value of the different measured realisations.

In the determination of the differences according to equation 3.2 the very obvious outliers are ignored. These outliers have been reported in [7], [8], [9] and [10], but it should be realised that the exclusion of these results is always subjective.

A disadvantage from the presentation of differences according to equation 3.2, is the fact that they assess the whole group of all calculations. Hence no insight is gained into the question how the individual code results compare to the measurements. However this turned out to be the only practical way in which the evaluation could be performed: The results from the individual codes compare very randomly to the measurements and no clear trends can be distinguished in this comparison.

Another disadvantage from the definition given in equation 3.2 is the fact that misleading conclusions may be drawn. This is explained in figure 3.1. In this figure a hypothetical example is presented with 6 calculational points and 1 measurement point per wind speed. All calculational points differ substantially from the measured point, but nevertheless the 'mean' calculated value from equation 3.3 is very close to the measured value. Hence the misleading conclusion from equation 3.2 would be that the differences between calculations and measurement is small.

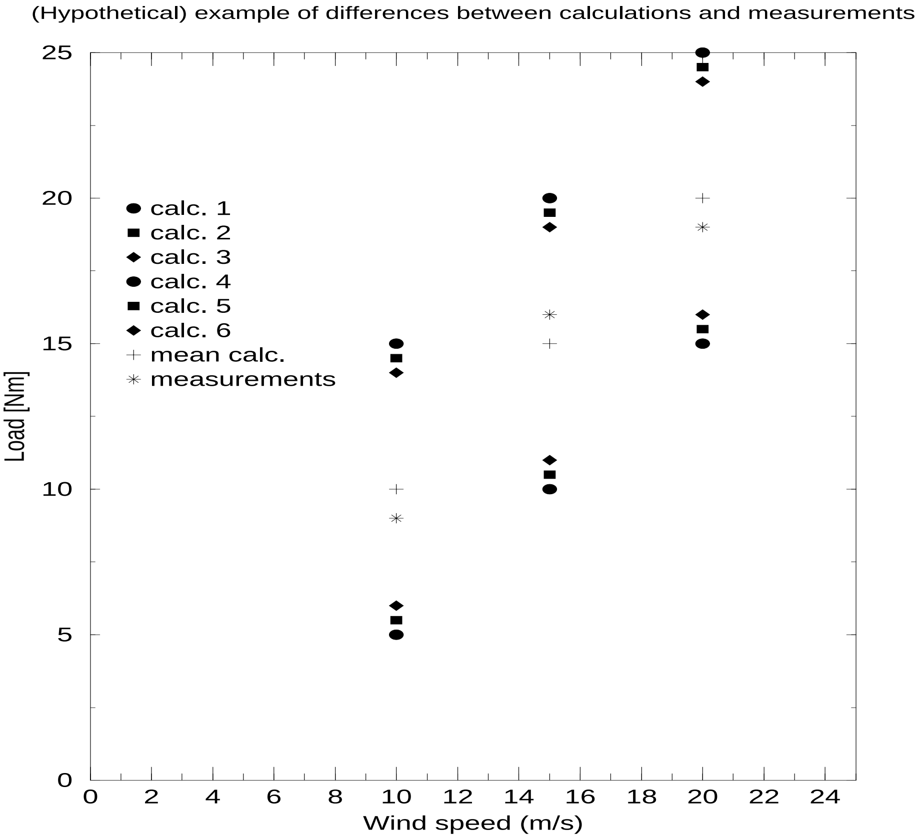

Figure 3.1 *Example of differences between calculations and measurements*

For this reason, the the spread in calculational results has also been determined.

The spread is defined as:

$$\mathbf{spread} = \pm[\mathbf{calc_{max}} - \mathbf{calc_{min}}]/[\overline{\mathbf{calc}}] \tag{3.4}$$

with $\mathbf{calc_{max}}$ and $\mathbf{calc_{min}}$ as defined above. It is emphasized that the spread, as defined in this way, is related to the max-min values and not to the standard deviation. Note that the spread in measurement results (from different realisations) usually turned out to be much smaller than the spread in calculations.

Although the main comparison took place on basis of 1Hz equivalent and mean loads, the comparison of rain flow cycle counts, azimuthally binned averaged values and APSD's was also carried out. This comparison is performed on a qualititave basis.

The comparison between calculated and measured results of the failed pitch cases of the LW750 turbine has been performed on basis of time series and statistics.

In the analysis of results it was found that there are many sources of differences between calculations and measurements. Since some of them are not present in practical design calculations, it should be realised that the translation of the difference between calculations and measurements to design inaccuracies is difficult to make.

3.4.1 Sources of discrepancies between calculations and measurements

The following sources of discrepancies can be distinguished:

- Discrepancies due to errors in postprocessing and coordinate systems: It should be realised that many apparent differences between calculations and measurements, simply could be attributed to misunderstandings or errors on file formats, coordinate systems etc. Many, but not all, of these errors were eliminated in the second round of calculations;
- Uncertainties in machine description: In the description of the turbines some parameters were unknown or had to be estimated. The importance of some of these uncertainities have been quantified by means of sensitivity studies. Significant effect of among others the structural damping and the unknown aerodynamic and mass unbalances between the blades have been found. A change from 1 to 2% structural damping decreased some loads with approximately 15%;
- Uncertainties in the prescribed external conditions: Uncertainties in the external conditions are extremely important. This holds in particular for the wind input. The wind input is fed to the aeroelastic codes in the form of spatially distributed wind fields as function of time. These wind fields are generated by stochastic wind simulators which use the statistics of the wind as input (Mean wind speed at hub height, turbulence intensity, wind shear, turbulent length scales, coherence parameters). In the present calculations these statistics are derived from a limited number of measurements on meteorological masts, which are placed some distance away from the turbine. In this way it cannot be guaranteed that the real wind is captured. As such the present calculations are principally different from design calculations: In design calculations the external conditions are prescribed by the regulations and hence they play no role when assessing inaccuracies in calculated loads.
  Even if the statistics of the wind measured at the mast would be fully representative for the location of the wind turbine, one should bear in mind the statistical variability of the wind: For the same mean wind speed, turbulence intensity, turbulence length scale and coherence function, the wind simulators generate different windfields when applying different random seeds. Sensitivity studies showed a very large effect of these different random seeds (in the order of +/-10%). Similar numbers have been found by analysing the summary data of

the measurements: The spread in measured 1P equivalent loads turned out to be in the order of +/- 10%, even if the conditions at which the measurements are taken are almost similar. In addition it should be realised that, even for a time period of 10 minutes, the three different blades are exposed to a different statistical realisations of the wind. The differences in 1Hz equivalent loads between the three blades could be up to 2-4%.
Hence it should be borne in mind that the observed differences between calculations and measurements are somewhat arbitrary: The numbers depend on the chosen random seed and on the blade.
Finally it should also be mentioned that some doubt existed on the precise value of the measured yaw error, to be used as input in the calculations. This holds in particular for the Tacke-500 turbine (due to the complex terrain topography) and for the NTK-500 turbine, where a change of 7 degrees in yaw error led to a remarkable better agreement between calculated and measured loads, see the sections 3.3.4 and 3.3.3. A large sensitivity to the yaw error was found: A change in the order of 7 to 10 degrees could lead to differences in loads which are in the order of 15 to 20%;

- <u>Uncertainties in the load measurements</u>: As explained above, doubt exists on the quality of some measurement signals;
- <u>Uncertainties due to different implementation and interpretation of the input description</u>: Although a complete input description of the load cases and the turbines is made, these descriptions always leave some freedom for the analyst, i.e. the number of time steps, elements etc. (in both the aeroelastic code as well as the wind simulator) are code dependant and cannot be prescribed. As a result, one should realise that the observed differences between calculations and measurements depend on the analyst and his/her experience: Different results can be delivered even if the same code and the same input description is used. In order to distinguish the effects from different implementations, all participants were asked to summarize their assumptions;
- <u>Differences caused by fundamental model effects</u>: The codes which are used by the participants are based on different models (i.e different wind model, aeroelastic modelling, numerical solutions etc). In order to interpret the results, all participants were asked to summarize their model descriptions.

Note that in principle many of the above listed uncertainties could be eliminated in the second round, since it was allowed to tune the uncertain input parameters to the measurements. Nevertheless the large number of uncertainties and the large number of output data made such tuning practically impossible.

4. RESULTS AND CONCLUSIONS

The graphs and tables in which the calculations and measurements have been compared have been evaluated extensively. Among others, the differences and spread has been determined for every figure, according to the definitions given in section 3.4. Obvious outliers are excluded when determining the differences and the spread. The evaluations are reported in task report see [7], [8], [9] and [10]. The evaluations led to the following results and conclusions:

- When assessing the results it should be realised that very obvious outlying results, usually could be explained by input errors or misunderstandings on the input;
- As explained in section 3.4.1, verification projects suffer from the fact that a straightforward determination of differences between calculations and measurement is not sufficient for the determination of design uncertainties. Many sources of differences can be distinguished, some of which are not present in design calculations. This holds among others for the uncertainties in the specified input (both machine input as well as wind input) and the measurement uncertainties;
  - With regard to the uncertainties:
    - In the 1st round, the uncertainties in input description are mainly believed to be apparent in:
      - The yaw error;
      - The pitch control algorithm of the LW750 turbine, which was misunderstood by some participants;
      - The statistical variability: The variation in statistical realisations at comparable mean conditions was expected to yield a ± 10% uncertainty on the 1Hz/1P equivalent loads. Even differences in the statistical realisations of the different blades could lead to arbitrary results which are in the order of ± 2 % to ± 4%;
      - The airfoil data. The airfoil data have been prescribed, but they are based on only a limited number of measurements. Inter- and extrapolation of airfoil data was inevatible.
    - The practicul tuning of these uncertainties, which was allowed in the 2nd round, turned out to be very difficult due to the large number of degrees of freedom;
    - Although an uncertainty analysis has been performed on the measurement accuracy it should be stressed that these uncertainties have an uncertainty by themselves.
- With regard to the power curve calculations:
  - At wind speeds (far) below rated wind speed, the agreement between the measured and the calculated powers is good (difference $< 10\%$).
  - For the stall controlled turbines, the differences between calculated and measured power become more than 15% near V_{rated};
  - For the pitch controlled turbine, differences in power are (obviously) very small at above rated conditions. This is due to the power control keeps the power at its known value;
- With regard to spread in calculated results:

  - The spread in fatigue blade loads is often limited to ± 15%, where the spread in mean blade loads is often limited to ± 5% to ± 10% The lower spread in mean loads, compared to the spread in fatigue loads, is due to the fact that these quantities donot suffer from uncertainties in statistical variation;
  - The spread in calculated loads on the other components is usually larger (in the order of ± 20% to ± 30%). Generally speaking the spread increased slightly in the second round. This is mainly due to the fact that the definition of the second round was less confined (more freedom in input parameters).

- With regard to differences between calculations and measurements:
  - The differences between calculated and measured mean blade loads were often in the order of 5 to 10%; The differences between calculated and measured 1Hz(1P) equivalent blade loads were often in the order of approximately 5 to 20%;
  - Very roughly speaking the differences between calculated and measured 1Hz(1P) equivalent loads on the remaining components (shaft, tower, nacelle accelerations) were often between 10%-40%. In particular the differences in tower rolling moments turned out to be large (>50%);
  - For the special load cases, differences between calculations and measurements are usually larger than for the normal production load cases (differences of 50% have been found in the extreme loads).

  It is important to emphasize that the above mentioned differences are very crude: Many exceptions have been found. Furthermore some subjectivity is apparent in the evaluations, in particular because of the inevatible subjective selection of outliers, which were ignored in the assessment.
- With regard to differences between 1st and 2nd round:
  - Generally speaking the differences between calculations and measurements in the 2nd round, are comparable to those of the 1st round, despite the fact that it was allowed to tune the 2nd round calculations on the measurements. As stated above, the practical tuning is very difficult due to the large number of degrees of freedom. Some exceptions exist, where the 2nd round led to significantly better results:
    - ∗ Many individual improvements can be observed in the 2nd round. This is incidentally caused by calculations being tuned to the measurements, but the improvements are usually a result of corrected input errors;
    - ∗ In the LW750 second round some participants took an aerodynamic unbalance into account, which, together with some changes in the tower eigenfrequency led to dramatic lower differences between calculated and measured 1Hz equivalent tower rolling moments. The difference between calculated and measured 1Hz equivalent tower rolling moment reduced from approximately 70% to approximately 10%;
    - ∗ In the second round calculations on the NTK-500 turbine, a different yaw error (i.e. different from the measured value) led to considerably better inflow velocities ands shaft moments: The differences between calculated and measured 1P loads reduced from 60% in the first round to 10% in the second round.

- With regard to the general trends
  - The differences between calculated and measured blade loads tend to be less than the differences between calculated and measured tower loads and nacelle accelerations. Again many exceptions exist, but this observation can

  be explained by the fact that many nacelle and tower loads are induced by relatively small differences of large blade loads, which implies that small differences in blade loads may yield large differences in tower loads;
  - For the special cases, the differences between calculations and measurements and the spread in the calculational result is usually larger than for the normal production cases;
  - When assessing the individual codes, it turns out that the accuracies from the different codes show a very random behaviour and it is not possible to discover common trends.
    In addition it is not possible to detect a clear improvement from the NTUA model (with the more advanced free wake model) compared to the other models. It must be noted however that it is the first time that such model is used for practical design calculations;

- When assessing the results on the variable speed, pitch controlled LW750 turbine in comparison with the results on the fixed speed, stall controlled NTK-500 and Tacke-500 turbines ([8]), the following observations can be made:
  - It should be realised that the variable speed operation is a source of discrepencies. Small, inevatible, differences in the power curve are reflected in a different rotor speed, which in turn, effects the loads. For the NTK-500 and Tacke-500 turbines, the rotor speed remains constant, and differences in power curve are not reflected in the rotational speed, although differences in power curve are obviously associated with different mechanical loads by itself;
  - It should be realised that the standard quasi-stationary BEM theory which is applied by almost all participants, is in principal not suited for the prediction of stall, nor for the prediction of instationary pitching actions. Thereto empirical corrections have been added for the modelling of stall and dynamic wake effects. These empirical relations suffer from inherent uncertainties. The uncertainties, which can be attributed to the stall modelling mainly play a role for the stall controlled NKT-500 and Tacke-500 turbines. On the other hand, the uncertainties which are due to pitching actions (i.e. dynamic wake effects) only effect the pitch controlled LW750 turbine. However, it is believed that these latter uncertainties are limited, see [11].
  - Despite the different modelling aspects between variable and constant speed turbines, the resulting differences between calculated and measured LW-750 loads tend to be in the same order as the differences between calculated and measured loads on the Tacke-500 and NTK-500 turbine. As such the often heard statement that stall controlled turbines are more difficult to model than pitch controlled turbines is not confirmed by the present results;

- Finally it can be concluded that the comparison between calculations and measurements was obscured by many misunderstanding or errors on the input. As such it should be concluded that quality assurance at design calculations is very important. The same holds for quality assurance during measurements, due to the sometimes large uncertainty in the measurements;
- A final recommendation is to perform verification projects on turbines, which are specifically developed for research purposes: For such turbines, the machine data can be obtained relatively easy, without the problem of machine data being restricted.

5. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

This project is a combined research and development project, containing the verification and application of aeroelastic design tools to wind turbine engineering. The main results are the insights into the accuracy and reliability of the major European design codes, and a database which contains a comparison between calculated and measured loads. The insights from the project will be used by the participants to improve the quality of the design support they offer to the industry. The importance of the database lies in the fact that design codes are regularly updated. The quality improvement of updated codes will be assessed by comparing the results from the updated codes with the results from the database.

REFERENCES

[1] T.J. Larsen, P. Fuglsang, K. Thomsen. “Aeroelastic description of Nordtank 500 turbine. RISØI- 1340(EN), RISØ, May 1999.

[2] D. Foussekis and H. Ganander. “Aeroelastic description of Tacke 500 turbine. Technical report, CRES, December 1999.

[3] T. van der Wekken, J. Heijdra, H.J. Kooijman and J.G. Schepers. “Description of Wind Turbine LW 50/750 turbine. , Lagerwey, January 23 2001.

[4] J. Heijdra. “Description of LW 50/750 pitch control. , ECN, February 12 2001.

[5] J.G. Schepers. Definitions for VEWTDC measurements. DOC- Form 01-01, ECN, June 2001.

[6] CRES, Mounturb participants. “Mounturb, Data Analysis Benchmark Test”. CRES.WE MNTRB.24, Centre for Renewable Energy Sources, July 1996.

[7] J.G. Schepers et. al. “Evaluation of first round results VEWTDC”. VEWTDC-DOC-EVA00-01, ECN, October 2000.

[8] J.G. Schepers et. al. “Evaluation of second round results VEWTDC”. VEWTDC-DOC-EVA01-02, ECN, February 2001.

[9] J.G. Schepers et. al. “VEWTDC: Final evaluation of calculations and measurements on NTK-500 and Tacke 500 wind turbines”. ECN-CX-01-071, ECN, June 2001.

[10] J.G. Schepers et. al. “VEWTDC: Final evaluation of calculations and measurements on Lagerwey 750 turbine”. ECN-CX-01-125, ECN, June 2001.

[11] H. Snel and J.G Schepers (ed.) . “JOULE1: Joint investigation of Dynamic Inflow Effects and Implementation of an Engineering Method”. ECN-C-94-107, December 1994.