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International Energy Agency IEA

Implementing Agreement for a Programme of Research and Development on Wind Energy Conversion Systems – Annex XI

24th Meeting of Experts – Wind Conditions for Wind Turbine Design

Risø, April 29/30, 1993

Organized by:
Project Management Organization Biology, Energy, Ecology BEO
Research Centre Jülich GmbH

On behalf of the
Federal Ministry for Research and Technology,
The Fluid Mechanics Department
of the Technical University of Denmark

Scientific Coordination:
M. Pedersen (Techn. Univ. of Denmark)
R. Windheim (BEO-KFA Jülich)

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Introductory Note

IEA Expert Meeting on:

Wind Conditions for Wind Turbine Design

RISØ, Denmark April 29-30 1993

Sten Frandsen

The International Electrotechnical Committee is at present preparing a standard for *Safety of Wind Turbine Generator Systems*, which will be subject to IEC approval procedures during 1993/94. The present IEC Committee Draft Document is the result of lengthy working group activities, and is supposed to reflect the contents of a number of national wind turbine design codes as well as the state-of-art in wind turbine design.

During drafting of the document, which deals with all aspects of wind turbine safety, it became apparent, that there is still some differences of opinion on what would be reasonable definitions of the wind conditions to be applied for design purposes.

The present expert meeting is arranged in order to bring forward the most recent experiences in the description of the natural wind, and to discuss the various viewpoints on the matter.

As it is, neither the IEC document nor the national standards have been employed much because they have been in existence for a very short time. Therefore, the consequences of the various explicit and implicit choices of nominal values, combination of wind climate incidents and methods regarding the "design wind conditions" are not well - if at all - known. Also, the value (in terms of saved materials without lowering the safety level) of employing highly refined and complicated design methods instead of simplified design criteria has not been analyzed to any significant extent.

The IEC document operates with two wind conditions, "normal" and "extreme" condition, with definition of a number of sub-conditions, summarized in the table next page.

Selected from these main wind parameters, the draft document operates with a total of 20 load cases. In 5 of these - basically the most frequently occurring - fatigue analysis shall be carried out, whereas in the rest of the cases ultimate stress analysis is to be performed. While under normal load conditions turbulence shall be represented in the calculations, the extreme load conditions are designed as deterministic load sequences, supposed to represent turbulence.

Regarding wind conditions, the following <u>models</u> are employed in the draft: Spectra (von Karman, Kaimal) with rotational sampling, model for turbulence level, coherence, vertical wind speed profile, horizontal wind speed profile, wind direction change, model for coherent gust.

Climate Parameter	Normal Conditions	Extreme Conditions
Wind Characteristics	Rayleigh distribution	ESW
Vertical Profile	NSW	EWS
Horizontal Profile	---	EWS
Wind Turbulence, σ_u	NTM	---
Wind Spectrum, S_u	NTM	---
Operating Gust	---	EOG
Direction Change	---	EDC
Coherent Gust	---	ECG
Coherent Gust & Dir.Ch.	---	ECD

The abbreviations are those used in the IEC committee draft.

The draft uses 5 wind turbine classes: 4 referring to specified wind climates with extreme wind speeds, average wind speed and turbulence intensity, and one class specified by the designer.

It is suggested to use the IEC document as a starting point. The participants are encouraged to prepare presentations describing experiences with use of national recommendations for normal wind conditions and for extreme wind conditions.

In particular recent information from measurements of turbulence parameters, and statistics on wind extremes would be welcome. Also reports on the sensitivity to the assumed wind conditions of final design parameters will be appreciated.

During the final round table discussion, the following points could be touched upon:

- In general, how does the IEC document relate to other (national) standards?
- Are the 4 wind turbine classes employed realistic, or will they systematically cause conservative designs?
- Are the 20 load cases together representative for real wind climates; conservative or non-conservative?
- Will the common user be able to carry out calculations involving rotational sampling, and is this complication necessary for accuracy (could the implications of it be taken into account otherwise)?
- What kind of extreme shear (vertical and horizontal) and wind direction changes are realistic?

- Will most wind turbines eventually be designed according to the "worst" common denominators (highest extreme wind speed, shear, wind direction change etc.) of the existing standards (IEC and national standards), to make the wind turbines sellable in all countries?

- How are the actual external conditions verified against the chosen wind turbine class?

SUMMARY OF IEA EXPERT MEETING prepared by Sten Frandsen

Risø National Laboratory, April 29-30 1993

A total of 11 formal presentations were made during the meeting, covering most aspects of wind conditions relevant for design of wind turbines. Naturally, much attention was drawn to whether the draft IEC standard wind load definitions are realistic and - at the end of the day - whether the standard is conservative or not.

The titles of the formal presentations were:

1. Sten Frandsen:	**Introductory Note.** *(Basically outlining the defined set of wind load cases in the IEC draft document)*
2. Frans Van Hulle:	**Comparison of wind turbine structural design according to the Dutch Standard and the draft IEC TC88 standard.** *(Compares the Dutch standard to the IEC draft, doing test calculations on 3 dutch machines with both standards, and evaluates the "safety reserve" in the respective standards)*
3. C. J. Christensen:	**Comparison of Danish Wind Turbine Design Code with the IEC-Code Draft.** *(The speaker is the chairman of the TC88 working groups which prepared the IEC draft: he presented the document philosophy and evaluated the safety reserve of the two documents)*
4. Massimo Falchetta:	**Extreme Wind Conditions in Italy.** *(The wind load cases in the IEC document was compared to Italian wind engineering standard (no wt-standard), finding that the ratio of maximum wind speeds and annual average wind speeds is higher in Italy than prescibed in the IEC document)*
5. Jørgen Højstrup:	**Models for Velocity Spectra.** *(Analysis of especially scales of turbulence outside and inside wind farms and evaluation of spectral models applied in the IEC standard)*
6. Christof Stork:	**The Turbulence Intensity in IEC WT Classification; Theoretical Considerations and Comparison with Italian Site Conditions.** *(Compared the turbulence intensities for the four wind turbine classes in the IEC document with those prescribed in the Italian wind engineering code for civil engineering structures; in a number of locations in Italy (reference) turbulence intensities were higher than the 17 % of the IEC document)*

7. William E. Holley: **Two Critical Parameters for Wind Turbine Design.**
(Described how the IEC values of the amplitudes of "maximum horizontal wind shear" and "maximum vertical wind" shear were derived)

8. Neil Kelley: **Defining the Normal Turbine Inflow within a Wind Park Environment.**
(Described and interpreted measurements of rare large loads of wind turbines in wind farms, analyzing the flow vorticity for coherent turbulent structures)

9. John Wills: **Wind Climate at a Windfarm Site.**
(Presented measurements of climatological parameters at a potential wind farm site in the UK)

10. David Quarton: **A Design Tool for Loading and Fatigue.**
(Presented a computer code, including verification, developed under the EC joule programme for calculation of structural loads in wind farms)

11. Hans Ganander: **Wind Description for Wind Turbine Design.**
(Described a method developed to gather and reduce wind data of relevance for fatigue loading of wind turbines)

The formal presentations led to discussions on a variety of topics such as
- whether to apply a pure probabilistic approach in defining load cases or deterministic load cases (the IEC document employs a mixture of the two),
- are rotational sampling really applicable for wind turbine designers?,
- are the scale(s) of turbulence prescribed too small?,
- is it low frequency, high amplitude loads or high frequency, load amplitude loads that are predominant in fatigue loading and are there special flow conditions - not fully described by probabilistic means - of importance for fatigue?,
- is there a need for further comparison of national codes for wind turbine design and the proposed IEC standard?,
- are the 4 wind turbine classes defined in the IEC document logical and/or relevant?,
- do the IEC load cases (and load definitions) properly cover wind turbines located in wind farms, and
- is it necessary with as much as 20 load cases as applied in the IEC standard draft?

Amongst all these interesting and important issues discussed at the meeting I have tried to condense the discussion in the following comments.

Comparisons with national standards. Two presentations dealt with the consistency, or lack of such, between national standards and the proposed international standard. The conclusion of both presentations were that in broad terms the loads calculated from the Danish, the Dutch standards and the IEC proposed standard in the end were deviating only up to 10-20

% although the results were reached employing rather different load cases. Thus, it seems that the remaining questions are if all three codes are conservative, and whether special load conditions would make the standards divert more than observed in these cases. In the discussion following the presentations it was put forward that the proposed IEC standard by default fits the American standard since at present there is "only" a AWEA recommendation in the US.

It was proposed and agreed that it would be useful to continue and to further broaden the comparison of national codes to the IEC standard, and to apply for JOULE-II funding to do so. Mr. Quarton will organize the relevant group for such application.

Scale of turbulence and spectral shape. The scale of turbulence was discussed in some details. It is widely assumed that the scale of the longitudinal wind component is of the order a "few hundred meters". Concerning fatigue, an uncertainty of the scale of, say, a factor of 2 will not be of major consequences. However, in flat homogeneous terrain there is some evidence that the scale could be of the order 2-3000 m, i.e. nearly a factor of 10 larger than usually anticipated. Therefore, if the scale of turbulence inside the wind farm is of the order of the rotor diameter, then the difference in scale inside and outside the wind farm may be approaching a factor of 10. With unchanged turbulence intensity, such large increase in the frequency may be significant for fatigue loading.

Low cycle fatigue and coherent turbulent structures. One presentation dealt with large rotor loads occurring a few times a day, which loads apparently determined the fatigue life of the blades. According to the speaker, Neil Kelley, presenting the Californian wind farm measurements, the loads could possibly be generated by large coherent turbulent structures, which in turn may be the result of the special flow conditions inside wind farms. If the observations (coherent turbulent structures with non-zero vorticity causing significant low cycle loading) are correct they may alter the present view on the nature of the wind load on wind turbines. I think most participants found the presentation interesting, though there was a certain amount of scepticism.

Design for wind farm conditions. Whereas the IEC proposal includes expected increased loads in wind farms by proposing a conservative (constant) 17 % reference turbulence intensity, solid scientific evidence is still missing to support this approach. On the other hand it seems that for wind farms with machine separations of more than 5-6 diameters the effect of the wind farm itself on the turbulence levels are not comprehensive, though it is not clear whether the turbulence scale is changed enough to have some impact on the design calculations. For smaller separations (< 5-6 D) there are indications that loads may seriously increase.

Employment of probabilistic methods. The use of probabilistic methods in design of large structures exposed to the wind has become increasingly more accepted - also in design of wind turbines. The IEC proposal employs a combination of probabilistic and deterministic load cases/situations, and there were at the meeting some discussion on whether the proposal should/could have been based on a pure probabilistic model of the wind conditions to which a wind turbine is exposed throughout its lifetime. 2-3 of the participants in the present meeting helped fathering the IEC proposal and explained that deterministic load cases were employed to reflect actual observed load situations and to take into account interaction between the wind turbine's control system and the wind itself.

There was no general agreement between the participants on what is the "right" way to do things.

Comparison of wind turbine structural design according to Dutch Standard and draft IEC TC88 Standard

Frans Van Hulle (ECN)
Helma Wiersma (INTRON)
Danny Winkelaar (ECN)

IEA Topical Expert Meeting 24
Wind conditions for wind turbine design
Risø, Denmark April 29-30 1993

INTRODUCTION

A comparative study of the draft IEC Standard [1] and the Dutch Standard [2] has been carried out in order to check the consequences of imposing the draft IEC TC88 standard for the structural design of wind turbines designed according to the Dutch Standard. The comparison has been made on the level of required cross sectional area of structural members and has been made for three types of (commercial) wind turbines, from different Dutch manufacturers.
The study deals with wind modelling and structural design (chapter 3 resp. 4 of the draft IEC standard). The present paper gives the most important findings of this study.
The paper also contains some ideas about requirements with respect to stochastic wind simulation.

PART 1. COMPARATIVE STUDY

1.METHODOLOGY OF THE COMPARATIVE STUDY

1.1 Wind turbines

For the analyses three wind turbines of different sizes and typology where used, all products of Dutch manufacturers.

The institutes involved with the analyses were the Netherlands Energy Research Foundation (ECN), Stork Product Engineering (SPE), Technical University of Delft (TUD) and Stentec. The coordination and collection of information was done by the Intitute for Materials and Environmental Research (INTRON).

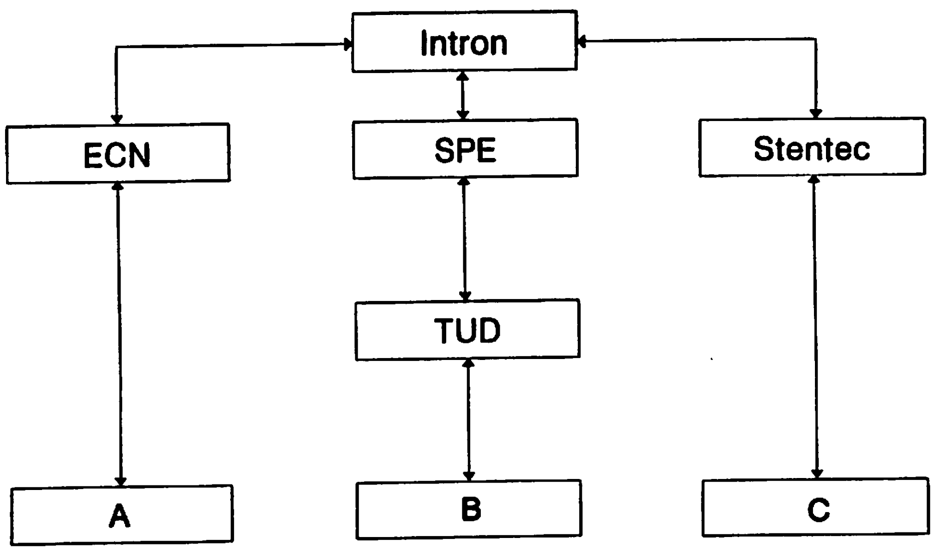


figure 1. Information Flow Chart

Some general specifications of the different wind turbines which were used are given in Table 1.

Table 1. Wind turbines used in the comparison

Wind turbine	Control	Rotor speed	Blade material
A	pitch (P)	variable	CFRP
B	stall	constant	GFRP
C	pitch (A)	constant	Wood epoxy

1.2 Analyzed cross-sections

For each of these wind turbines the loads on the gearbox and on three cross-sections were analyzed. The (near critical) cross-sections are:

* blade root
* main shaft
* tower foot

The load calculations were made for normal (fatigue) and extreme (ultimate) situations and were based on the Dutch Technical Criteria (DTC) and the draft IEC standard.

1.3 (Relative) stress reserve factors

For the purpose of comparison, relevant stress reserve factors can be determined as follows:

- After determining the loads, the stresses in the cross-sections have been calculated with the loads (ultimate and fatigue), and the related partial safety factors for loads. These factors are given in Table 2.

- The calculated stresses (taking into account the partial safety factors for material) were compared with the ultimate respectively fatigue strength (Table 3). The quotient between the limitative stress and the calculated stress is defined as the Stress Reserve Factor (SRF).

$$SRF = \frac{\text{limitative stress/material factor}}{\text{calculated stress} \cdot \text{load factor}}$$

For safe design, the SRF is required to be larger than one.
When the factor is used as measure for structural design calculations, the following applies:

low SRF => 'heavy' calculations
high SRF => 'light' calculations

Beside the SRF for the three mentioned cross-sections, the service factor for the gear box has been determined for each wind turbine. These calculations were based on the calculated torque loads.

To facilitate the comparison of both standards, the calculated SRF_{IEC} values were made relative with the SRF_{DTC}. The newly formed factor is called the Relative Stress Reserve Factor (RSRF):

$$RSRF = \frac{SRF_{DTC} - SRF_{IEC}}{SRF_{DTC}} \cdot 100\%$$

For the gearbox the Relative Service Factor is defined as follows:

$$RSF = \frac{SF_{DTC} - SF_{IEC}}{SF_{DTC}} \cdot 100\%$$

Based on the RSRF it can be concluded whether a wind turbine designed according to IEC will have more or less 'stress reserve' than according to the Dutch Criteria.
In order to meet IEC design requirements and to maintain the same stress reserve as resulting from the Dutch Criteria, material should be added or removed from a load carrying cross-section of the wind turbine:

positive RSRF => add material
negative RSRF => remove material

The various steps of the method followed to determine these RSRF's will now be explained.

1.4 Applied material and load factors

When following the Technical Criteria or the draft IEC standard, different material and load factors have to be used for determining the SRF's . The applied load factors for the fatigue and ultimate calculations (Table 2) are larger for the DTC than for the IEC:

Table 2. Applied load factors

	Technical Criteria		Draft IEC standard	
	fatigue	ultimate	fatigue	-ultimate
Blade	1.35	1.5	1.0	1.4
Hub	1.35	1.5	1.0	1.4
Tower	1.35	1.5	1.0	1.4

Table 3 shows that the material factors for fatigue of the IEC are higher than factors for fatigue of the DTC. For the ultimate analysis , the factors are equal.

Table 3. Applied material factors

	Technical Criteria		Draft IEC standard	
	fatigue	ultimate	fatigue	ultimate
Steel	1.00	1.0	1.25	1.0
Wood	1.10 - 1.40	--*	1.40 - 1.75	1.1 - 1.4
GFRP	1.48 - 1.78	1.2 - 2.0	1.90 - 2.25	1.8 - 3.0

* admissible stresses

1.5 Data flow of calculations

In the next two figures the data flow for ultimate and fatigue calculations are given for each cross-section. By following this path the occurring normal stresses, occurring Von Mises stresses and stress reserve factors were determined.

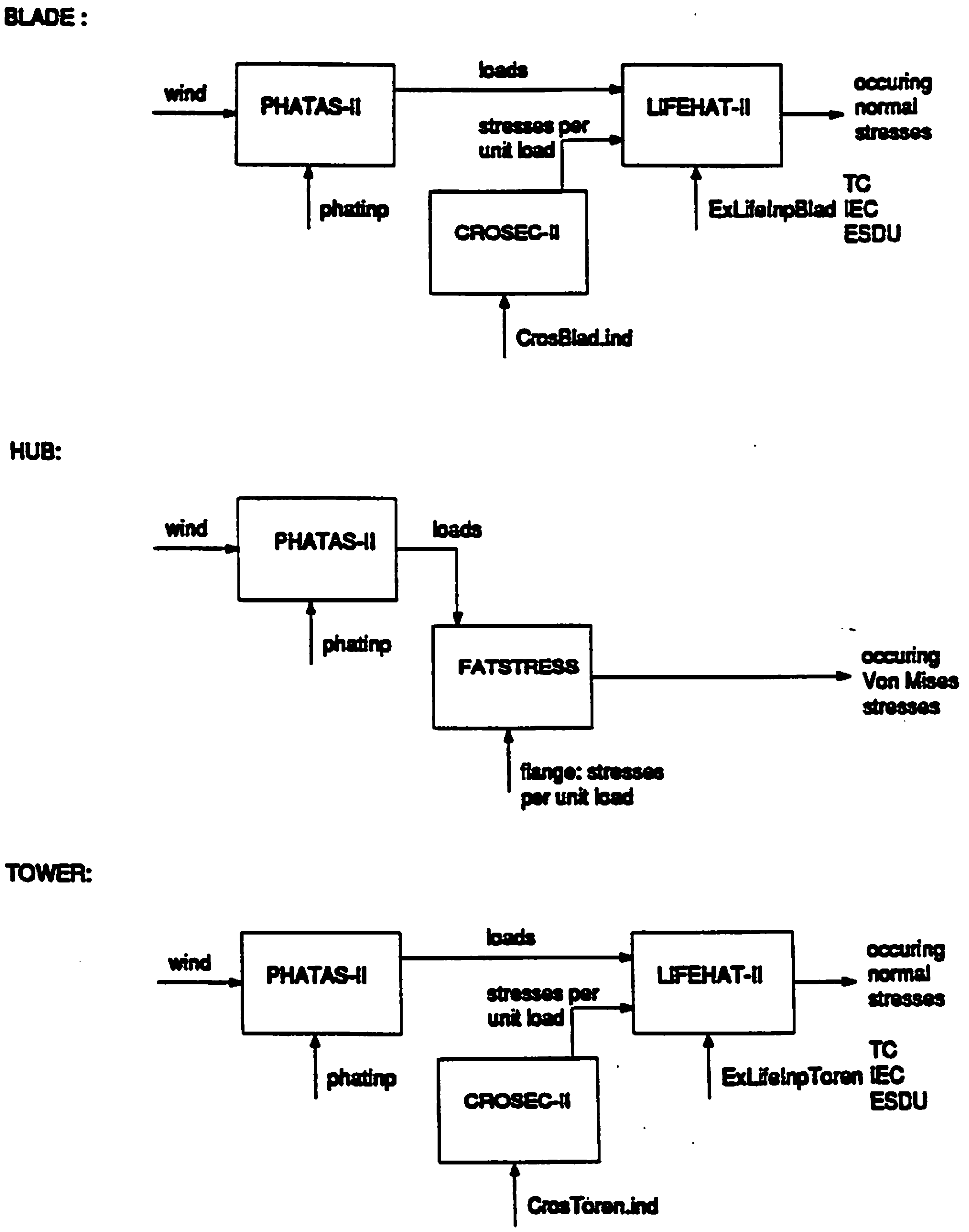


figure 2. Data flow ultimate calculations

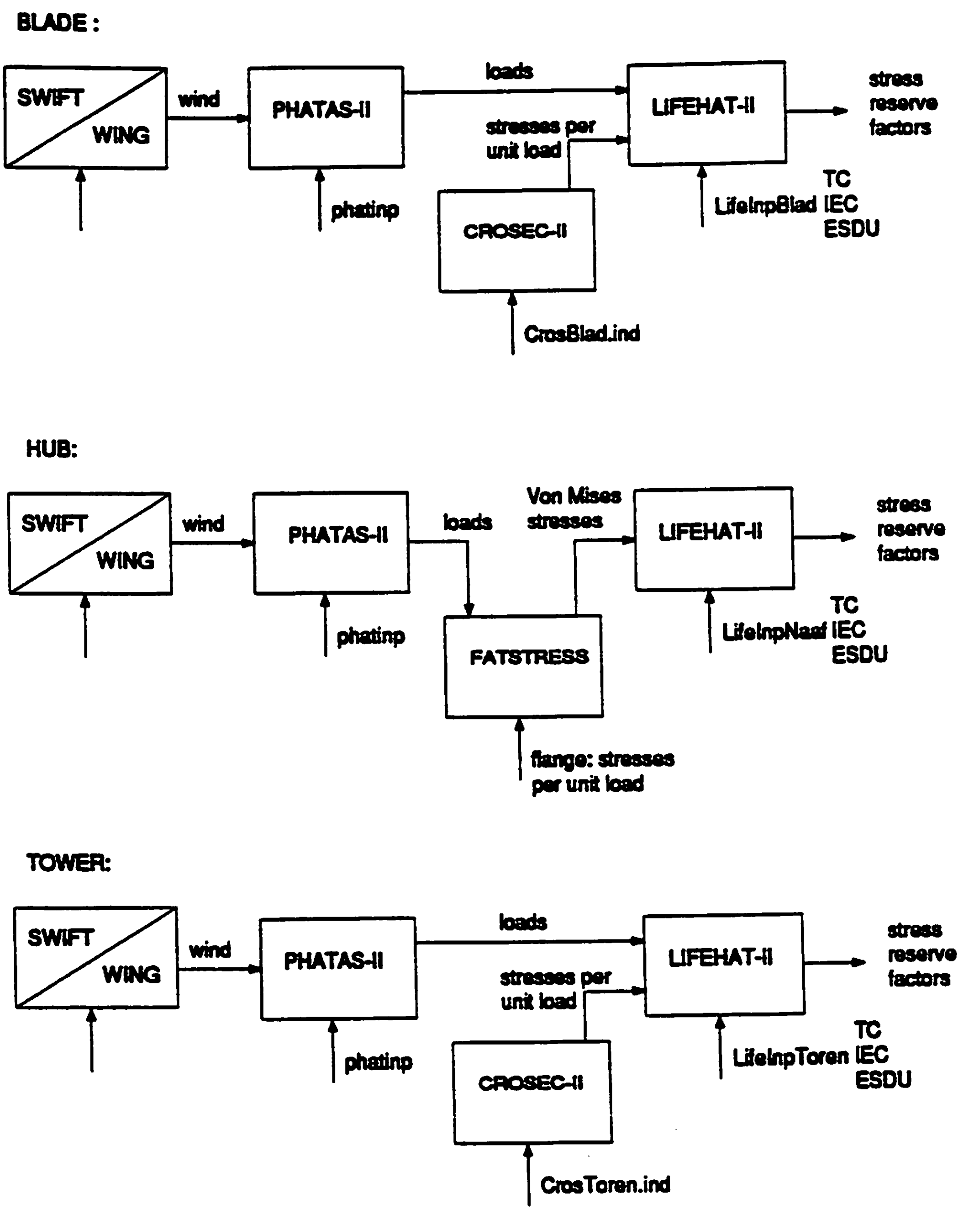


figure 3. Data flow fatigue calculations

1.6 Load cases

For illustration a list of load cases used for the calculations with the DTC for one of the three machines is given. In Table 4a the load cases with respect to the fatigue load spectrum can be found. The load cases with respect to the ultimate load spectrum are given in Table 4b.

Table 4a. Load cases with respect to the fatigue load spectrum (DTC)

loadcase number	load case description	wind speed V [m/s]	number of occurrences
1-72	normal production	V_m = 8.5	k = 2.3
73	imbalance due to ice	15	50
73	grid failure	15	100
75 76 77	start-stop cycles	5 15 19	40.000 400 4000
78	idling	3	1.370.000
79 80	activation of the first safety system	15 19	100 100
81	activation of the second safety system	15	60
82	failed yawing system	15	82.286

Table 4b. Load cases with respect to the ultimate load spectrum (DTC)

loadcase number	load case description	wind speed V [m/s]	remarks
100	idling	55	
101 102	activation first safety system (second system failed)	15 19	extreme amplitude gust
103 104	activation second safety system (first system failed)	15 19	extreme amplitude gust
105	failed parking; blades in working position	38	
106	blocked state: blades in vane position and blocked yaw system	55	

1.7 Wind speed distribution

In Figure 4 the wind speed distribution is given for both DTC and IEC. The Dutch Technical Criteria use the Weibull distribution function (k= 2.0 + 0.0084 (H-10), with H is the hub height) and the draft IEC standard the Raleigh distribution function. The different distributions lead to differences in occurrence of load cases, especially at wind speeds below 4 m/s and above 19 m/s.

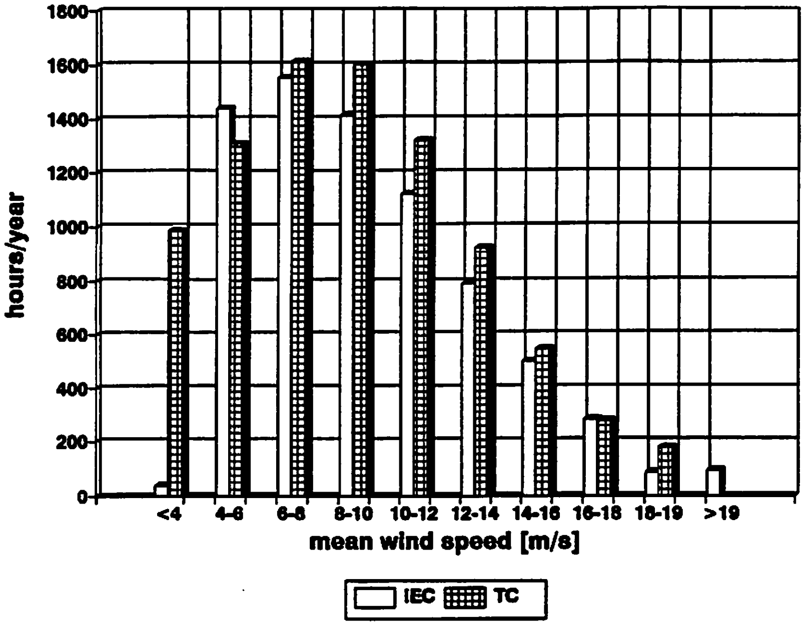


figure 4. Wind Speed Distribution

2. RESULTS

The resulting Relative Stress Reserve Factors of the comparison for the three wind turbines, and corresponding cross-sections are given in the table 5. Table 6 gives the Relative Service Factors for the gearboxes.

Table 5. Relative Stress Reserve Factors

Manufacturer	X		Y		Z	
Component	RSRF fatigue	RSRF ultimate	RSRF fatigue	RSRF ultimate	RSRF fatigue	RSRF ultimate
blade root	7%	21%	-25% (-22%)[1)]	-18%	4%[3)] -(5%)[2)]	55%
rotor shaft	6%	43%	-33% (-44%)[1)]	-5%	39%[3)] (10%)[2)]	56%
tower foot	12%	40%	-14% (10%)[1)]	-17%	29%[3)] (16%)[2)]	61%

1) Calculation with reduced yaw load
2) Calculation with ESDU-spectrum instead of IEC turbulence spectrum.
3) Calculated with IEC-spectrum but too low coherence, leading to very conservative rotational spectrum

Table 6. Relative Service Factor for gearbox

Manufacturer	X	Y	Z
RSF	-1%	-15%	3%

The differences in the stress reserve factors in the hub and tower section of one of the machines, calculated with the different methods, are illustrated in Figure 5 and 6.

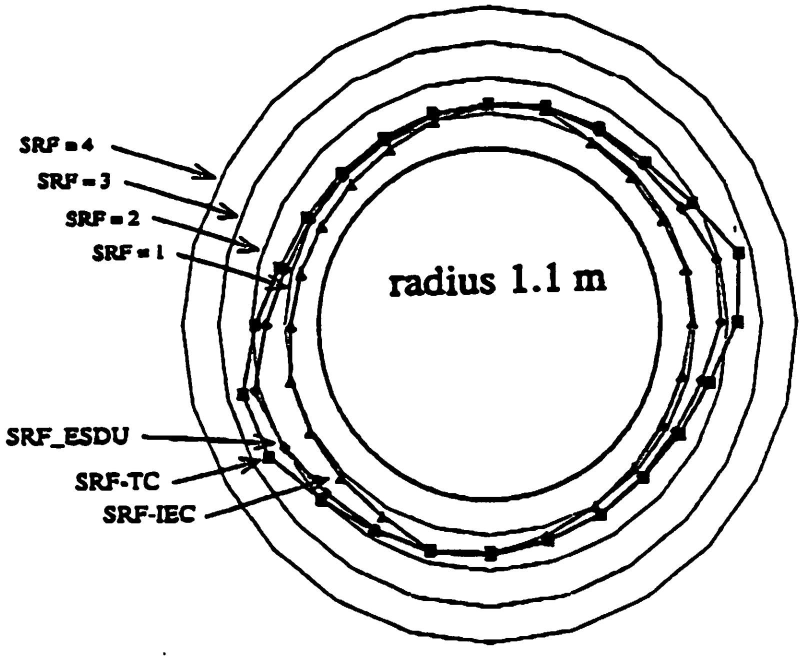


figure 5. Comparison of stress reserve factors in the hub at 0.5R, calculated with IEC wind, ESDU wind and wind according to Dutch Technical Criteria

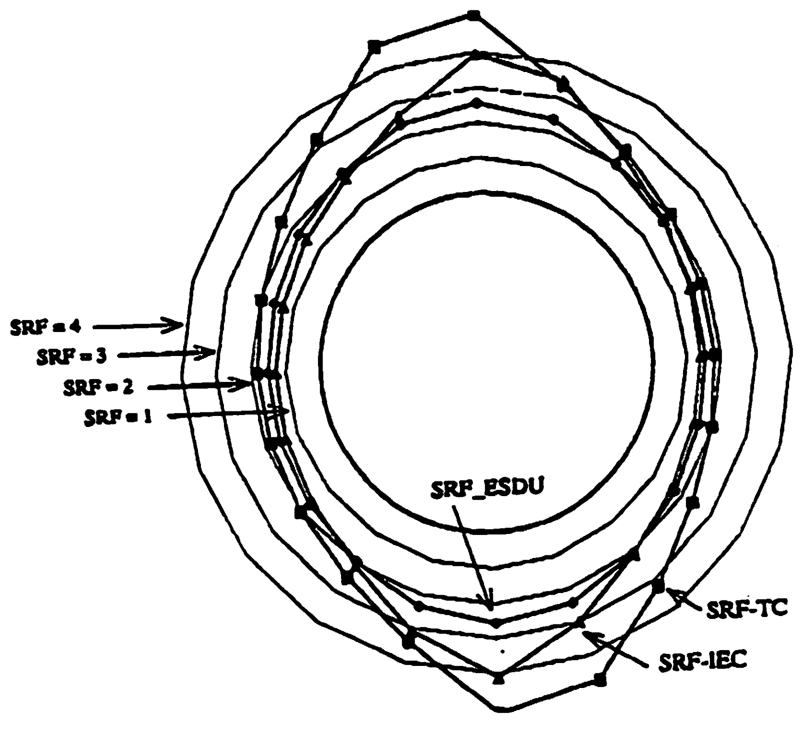


figure 6. Comparison of stress reserve factors in the tower, calculated with IEC wind, ESDU wind and wind according to Dutch Technical Criteria

3. DISCUSSION OF THE RESULTS

The analysis showed large differences in the Stress Reserve Factors and in the Relative Stress Reserve Factors for fatigue.
The results presented in Table 5, however, do not give a clear answer to the question whether the IEC standard is more severe, comparable, or less severe than the Dutch Technical Criteria (DTC). The IEC standard turned out to be more severe than the DTC for turbine X and Z, but less severe for turbine Y.

Why results differ so widely is still a matter of discussion and needs more investigation. Some comments however can be made:

- To a large extent the differences can be explained by the turbulence model and by the differences in partial safety factors.

- The differences can only partly be attributed to the different wind turbine structural dynamics codes employed. On one hand, all three participants used validated codes. On the other hand, the levels in which the structural dynamics have been taken into account, were not exactly the same.

- The IEC requirements are less restrictive on the loads than the DTC requirements. Various interpretations could lead to different contents of load cases and hence of different loads, stresses and SRF's. It was sometimes quite difficult to interpret the IEC draft. In some cases, e.g. the load and material factors, the help of the authors was needed to sort out which factors to choose and how to use them.

- The different characteristics (power control/ dynamic response etc.) of the turbines can probably cause different effects on the results.

PART II. STOCHASTIC WIND SIMULATION

4. REQUIREMENTS FOR STOCHASTIC WIND SIMULATION

An area where the IEC draft could be improved is the description of normal wind conditions (section 3.3.3 and the corresponding Annex A.1). Some ideas have already been discussed in a working paper presented by the Dutch delegation at a meeting of the IEC technical committee TC88 [4]. In this paper it is recommended to make more strict conditions on the (statistical) quality of the simulated wind field. It is proposed to assess the quality of the simulated wind field by comparing the spectrum of rotationally sampled wind speed (henceforth referred to as the rotational spectrum) with a theoretical rotational spectrum. The difference between the two spectra should be within some predefined limit. Also some comments have been made in [4] about the choice of coherence function, which seemed to differ considerably from other coherence functions, e.g. the one given by ESDU. A comparison of two rotational spectra, one based on the coherence function given by ESDU and the other based on the coherence function given by the IEC draft, showed large differences.

Unfortunately, the point about the necessity of some 'quality control' of the stochastic wind field was proofed not voluntary. Due to an error in the FORTRAN subroutine for the coherence function a faulty coherence was calculated and consequently a faulty rotational spectrum. This error was not yet discovered at the IEA meeting, so that there too a wrong comparison of rotational spectra was presented. It has also influenced the results presented in section two of this paper (see Table 5).

If was done what was proposed in the earlier mentioned working paper, namely to assess the quality of the wind simulation by comparing rotational spectra with the theoretical ones, then it would immediately have been found that something was wrong.

Removing the bug results in a far less dramatic difference between the rotational spectrum based on the IEC formula and the rotational spectrum based on the ESDU formula, see Figure 8.

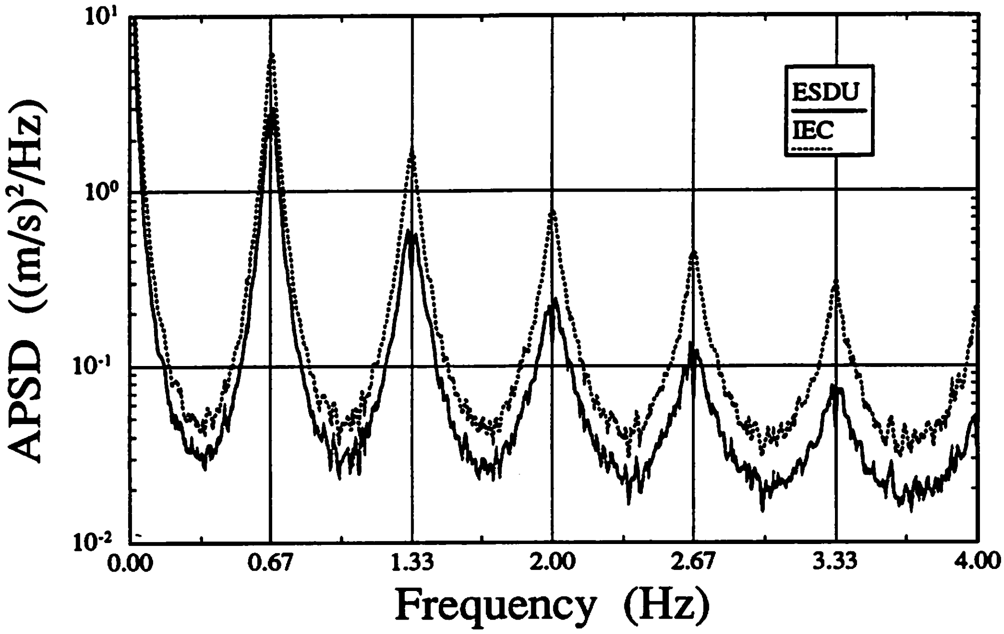


Figure 8. Comparison of rotational spectra using the turbulence model according to ESDU and according to the IEC document, using data of a PNL measurement.

The idea behind the first recommendation should be clear by now:

1) The standard should give criteria to assess the (statistical) quality of the simulated wind field. The easiest way to check whether rotational sampling has been incorporated properly, is to compare the spectrum of rotationally sampled wind speed with the theoretical rotational spectrum, e.g. the one given by Dragt [5,6]

$$\tilde{S}(f) = \sum_{-\infty}^{+\infty} k_n(f-nf_0)\ S(f-nf_0)$$

In which S(f) is the rotational spectrum, k_n are the coefficients of the Fourier expansion of the uniform and periodic coherence function, f_0 is the rotational frequency, and S(f) the homogeneous fixed point spectrum of the longitudinal wind speed.

If the theoretical rotational spectrum and the simulated rotational spectrum are close over a certain range of frequencies, then it can safely be assumed that the simulated wind field has the proper target spectrum and coherence function. Such an approach to assess the quality of the simulated wind field has the advantage that it is independent of the wind simulation model employed, that it checks on the spectrum that has the most influence on fatigue and that for example the effects of spatial and temporal interpolation can be taken into account. See as an example Figures 9 and 10 taken from Ref. [3]. The solid lines in these figures, labeled TURBU, are based on equation (1).

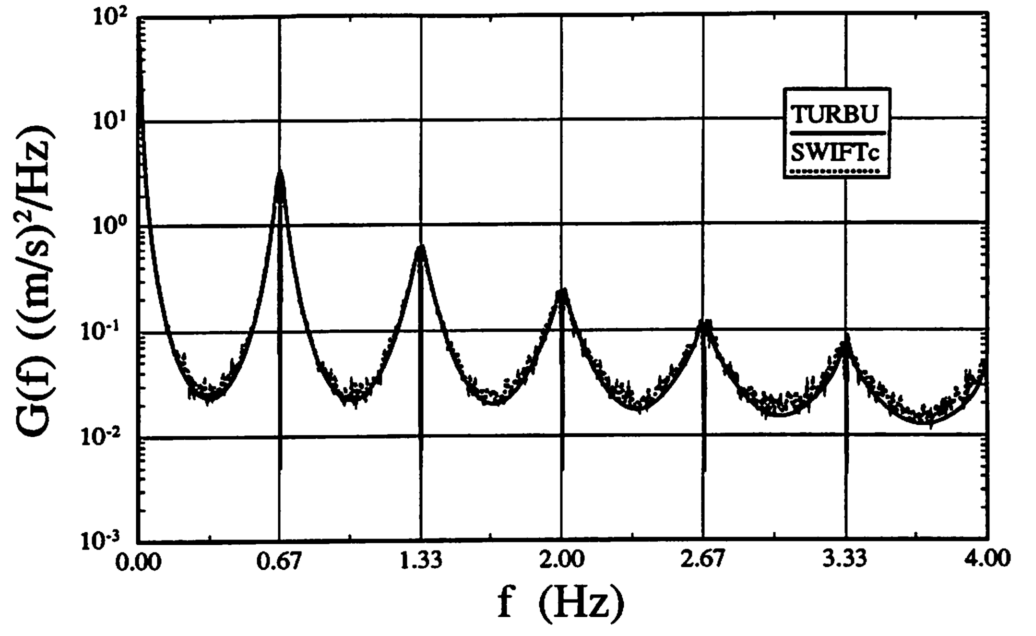


Figure 9. Comparison of the APSD of rotationally sampled wind speed; homogeneous SWIFT wind field.

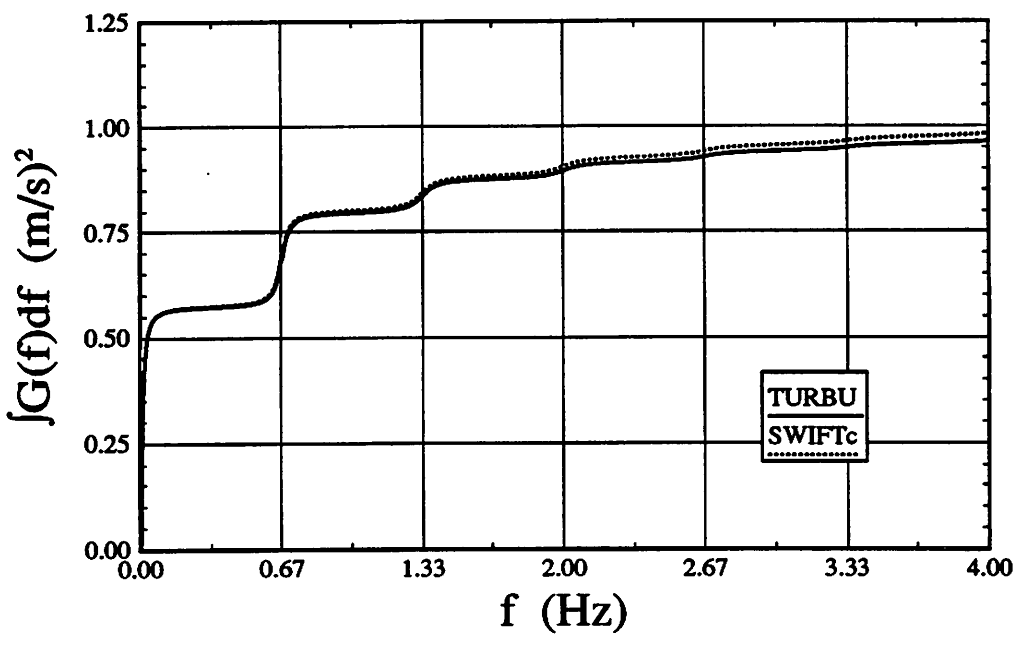


Figure 10. Comparison of the distribution of variance in the APSD of rotationally sampled wind speed; homogeous SWIFT wind field.

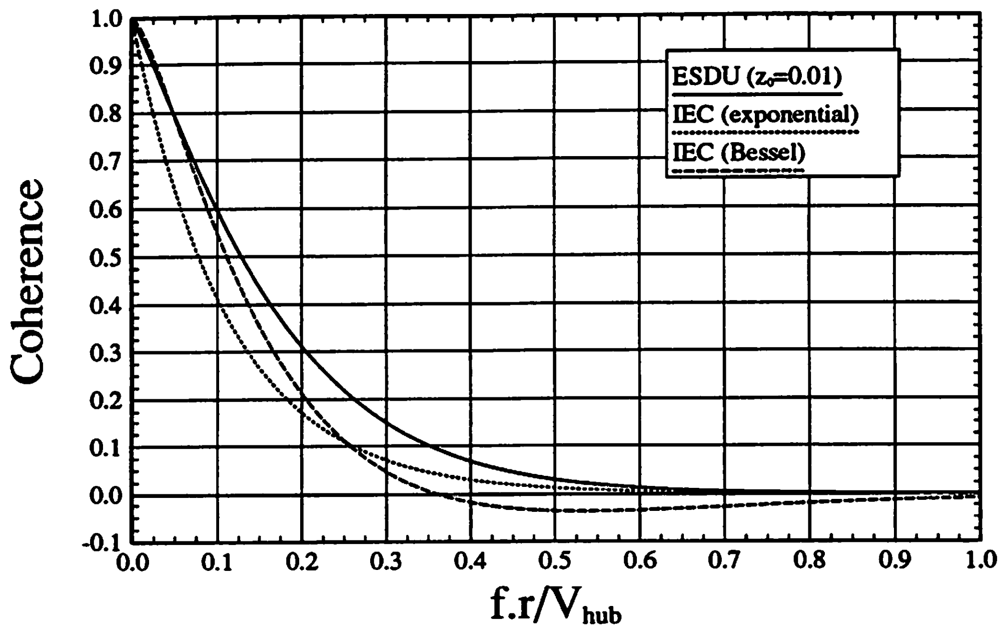


Figure 11. Comparison of coherence functions.

Figure 11 shows a comparison of the exponential coherence function according to ESDU, the exponential coherence function according to the IEC draft and the theoretical coherence function based on modified Bessel functions of fractional order, also given by the IEC. Combining Figures 8 and 11 it is easily concluded that the rotational spectrum based on the IEC exponential coherence will contain more variance (energy) at and above 1P than the rotational spectrum based on the theoretical coherence function. In other words more turbulent energy is shifted to the frequency region where blade dynamics play a role. Hence, fatigue loads will generally be higher using the exponential coherence function.
Combining the two spectra and the two coherence functions lead to four different rotational spectra, and consequently four different fatigue load spectra (everything else kept constant). It seems better to avoid discussion and confusion by including only the combination that in general will be the most conservative.

The second recommendation therefore is:

2) Avoid discussion and confusion by including only one model for the spectrum and coherence function. Preferably the combination that generally will give the highest (fatigue) loads.

The spectrum that is used as input for wind simulation is an average estimate. In reality the (measured) spectrum for a certain hourly mean wind speed will exhibit quite some variation, especially at the low frequency part of the spectrum. For a small part of the time this low frequency region can be much higher than average. At those instances large gusts with small probability of occurrence pass by. These gusts can contribute significantly to fatigue.

When stochastic wind simulation is properly applied these variations will occur in the simulations too. However, finding rarely occurring large gusts with some certainty requires an impractical large number of realizations of a wind field or long simulation time.

This leads to the third recommendation:

3) To increase the probability of producing large gusts in simulations, it is better to prescribe not just one average spectrum but also spectra which contain more variance and that will occur only a small part of the time. These spectra should then be used in proportion to the time that they occur.

Note that there is one pitfall. It is implicitly assumed that large gusts will automatically lead to large loads. That is only true for a linear system. A wind turbine is a strongly nonlinear system, hence the above stated assumption need not be true. In general we should not try to find low-probability events in the wind, but extreme responses of the wind turbine with a low probability of occurrence.

The IEC draft also includes spectra for the lateral and vertical turbulent components of the wind speed. No description of the spatial coherence function or cross correlation of these components is given, however. Trying to include all three velocity components we can only produce, at best, an isotropic model, which is not very realistic. Hence, the last recommendation is:

4) Include a more detailed description of the spectra and coherence function (and cross correlation with the u-component) of the v- and w-component.

5. CONCLUSIONS

Some general conclusions can be formulated, based on the results of the above described comparisons and evaluations.

1. The general method and approches for wind turbine design of the IEC standard and the Dutch Technical Criteria are comparable.
2. Large differences in results were encountered when calculating based on the IEC draft. Apparently it seemed possible to yield both heavy and light designs starting from the IEC document. This leads to the conclusion that the IEC leaves way to too many possible interpretations. These include the quantification of load cases (e.g. number of occurences), the freedom in choice of material properties, material factors (dependent on local codes), the various ways how to incorporate dynamics in the calculations and the lack of constraints in defining a basic turbulence spectrum.
3. Stochastic and deterministic approaches for turbulence modelling do not yield corresponding results. The input parameters for both ways are insufficiently specified in the IEC draft.
4. The IEC exponential coherence function leads to conservative rotational spectra (as compared with e.g. the valid ESDU spectra).

REFERENCES

[1] Safety of Wind Turbine Generator Systems; IEC TC 88 (sec) 21A

[2] Stam, W.; Regulations for the type Certification of Wind Turbines: Technical Criteria; NEN 6096/2; ECN-90-013; 1990

[3] Winkelaar, D.; SWIFT Program for Three Dimensional Wind Simulation, Part 1: Model description and program verification; ECN-R-92-013; Petten, The Netherlands; December 1992

[4] Föllings, F.J.; Comparative Study on National Dutch and International Standard for Wind Turbines; Intron 93286; Houten, The Netherlands; February 1993

[5] Dragt, J.B.;'The Spectra of Wind Speed Fluctuations Met by a Rotating Blade and Resulting Load Fluctuations'; Proc. European Wind Energy Conference; pages 453-458; October 1984; Hamburg Germany.

[6] Dragt, J.B.; 'Load Fluctuations and Response of Rotor Systems in Turbulent Wind Fields'; ECN--172; Petten, The Netherlands; October 1985

[7] Powell, D.C. and Connell, J.R. and R.L. George;'Verification of Theoretically Computed Spectra for a Point Rotating in a Vertical Plane'; PNL-5440 ; Battelle Pacific Northwest Laboratory; Richland, WA; March 1985

[8] Powell, D.C. and J.R. Connell;'Review of Wind Simulation Methods for Horizontal-Axis Wind Turbine Analysis'; PNL-5903; Battelle Pacific Northwest Laboratory; Richland, WA; June 1986

[9] Engineering Sciences Data Unit;'Characteristics of Atmospheric Turbulence Near the Ground. {Part III}: Variations in space and time for strong winds (neutral atmosphere)'; ESDU; 75001; London, UK; October 1976

THE DANISH CODE OF PRACTICE for LOADS AND RELIABILITY of WIND TURBINES.

C. J. Christensen and P. Hjuler Jensen,
Risø, Denmark

DS-472, The Danish code of practice for wind turbines,

International Electrotechnical Commission (IEC/TC88).

- **The Danish code is described.**

- **The Danish code is compared to the newest IEC draft.**

THE DANISH CODE, DS-472.

basis:

- **method of limit state design**
- **partial coefficients method.**
  (NKB-55) and DS-409

covers:

- **Denmark itself**
- **loads and mechanical safety (rotor diameter > 5m).**

IEC code

basis

- **as the Danish**
  ISO-2394

covers:

- **as the Danish PLUS**
- **All climates**
- **electrical safety in general**
- **safety on turbine sites.**

A limit state:

- **a state of structure and loads, beyond which the structure no longer satisfies the design requirements.**

The purpose of design calculations:

- **keep the probability of a limit state from being reached below the value prescribed**

  in short: keep failure probability below limit

The design requirement (partial coefficient method):

$$R_k/\gamma_R \geq L_k\gamma_L \qquad (1)$$

$$r = R_k/(\gamma_R L_k \gamma_L) \geq 1 \qquad (2)$$

r is here called 'safety reserve'

Types of limit state:

DS-472

- ultimate ⎤
- fatigue ⎦ IEC: ultimate
- accidental
- serviceability

Control and Safety Systems.

The control system shall
- watch essential function parameters
- take care of normal operations of the system.
- keep turbine within operational region.

The safety system shall
- detect fault in turbine or control system.
- keep turbine within extreme operational region.

Regulation of the safety system:
- precedence over the control system.
- tolerant to any single fault in the turbine
- double brake system, one brake aerodynamic.

IEC code: not too different, but no Danish brake request

Operational region:

- max 10 min wind speed (V_{max}) for operation
- a max power on the defined power curve
- a max 10min Power for wind speeds up to V_{max}.
- a max speed of rotation for normal operation.
- a wind speed, under which turbine can be stopped

Extreme operational region:

- an extreme speed of rotation
- a max transient speed of rotation.

DS-472 defines groups of load cases

Load Case	Design Situation	External Conditions
Normal	Normal	Normal
Extraord	Normal	Extreme
	Fault *	Normal
Acci-dental	Multiple Faults	Normal

* one fault or common mode failures

DS-472 Load Cases.
Turbine operational modes (Design situations):

Normal:
- Normal production
- Start / generator change
- Stop / To Idling
- Parked / Idling

Extraordinary
- Extreme Wind
- Transport etc
- Function test
- Emergencies
- Fault situations

Accidental
- Severe (multiple) Fault

External Conditions and Load Calculations

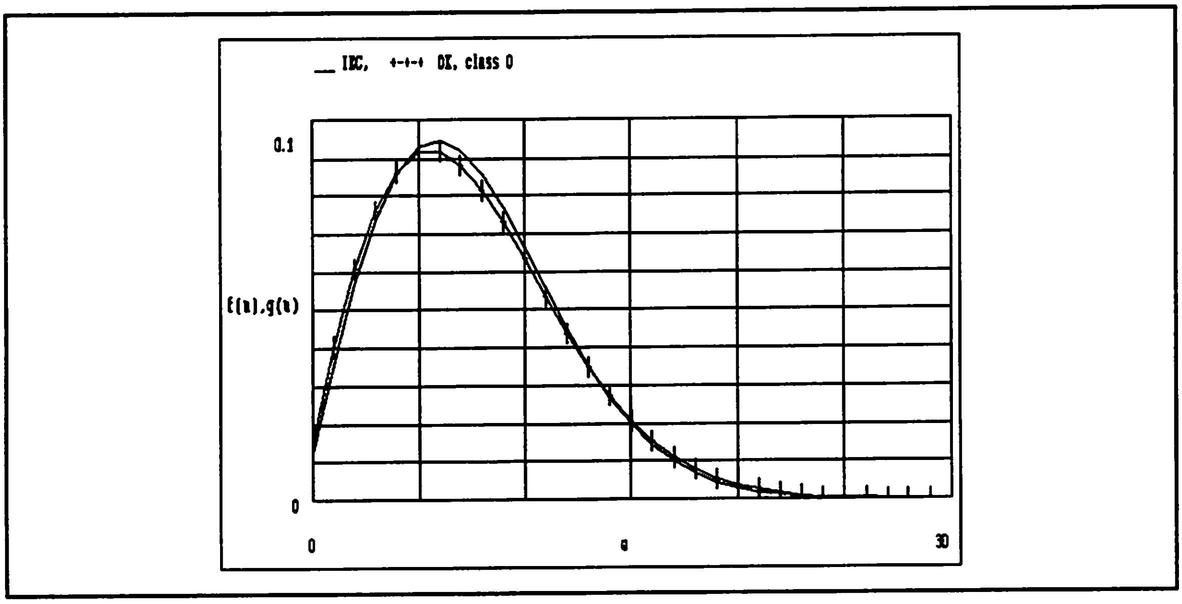
DK Characteristics of wind conditions:

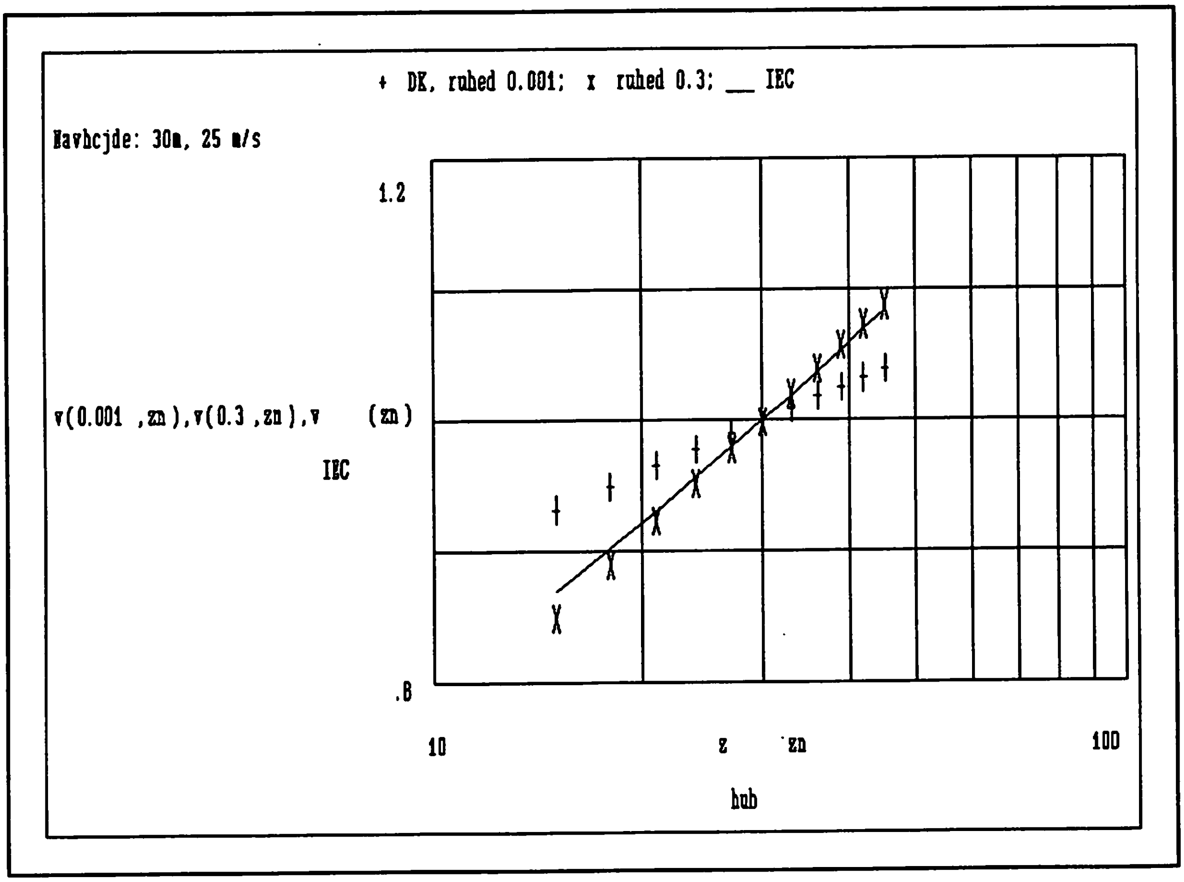
- a Weibull distribution
- 4 roughness classes
- a logarithmic wind speed profile
- a Kaimal turbulence model spectrum
- stochastic approach.

Extreme loads use amplification factors

$$p(r) = 0.5\rho v^2 c(r) \cdot \phi \qquad (3)$$

for dynamics.


__ IEC, +-+-+ DK, class 0
0.1
f(u),g(u)
0
0
30

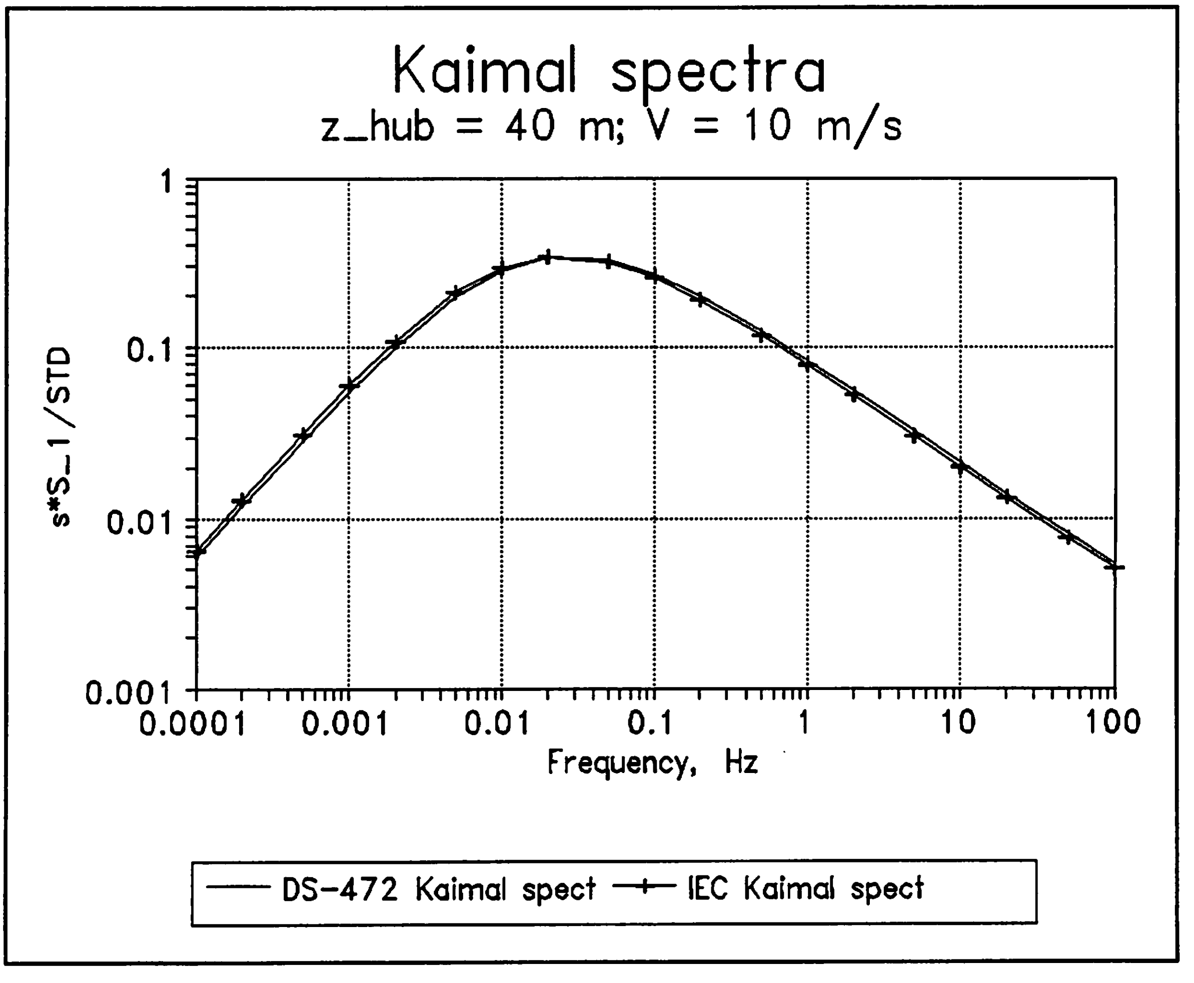

+ DK, ruhed 0.001; x ruhed 0.3; __ IEC
Havhcjde: 30m, 25 m/s
1.2
v(0.001 ,zn),v(0.3 ,zn),v (zn)
IEC
.8
10
100
hub

Both use Kaimal spectrum as possible Turbulens model

$$\text{DS} : \quad \frac{nS_1(n)}{(I_1 V_{10\text{min}})^2} = \frac{nl_1/V_{10\text{min}}}{(1+1.5nl_1/V_{10\text{min}})^{5/3}}$$

$$\text{IEC} : \quad \frac{fS_1(f)}{(\sigma_1)^2} = \frac{4fL_1/V_{hub}}{(1+6fL_1/V_{hub})^{5/3}}$$

$$\text{if} : \quad l_1 = 600m \leftrightarrow 4 \cdot 8.1 \cdot 20.3 = 660m$$



The IEC code:

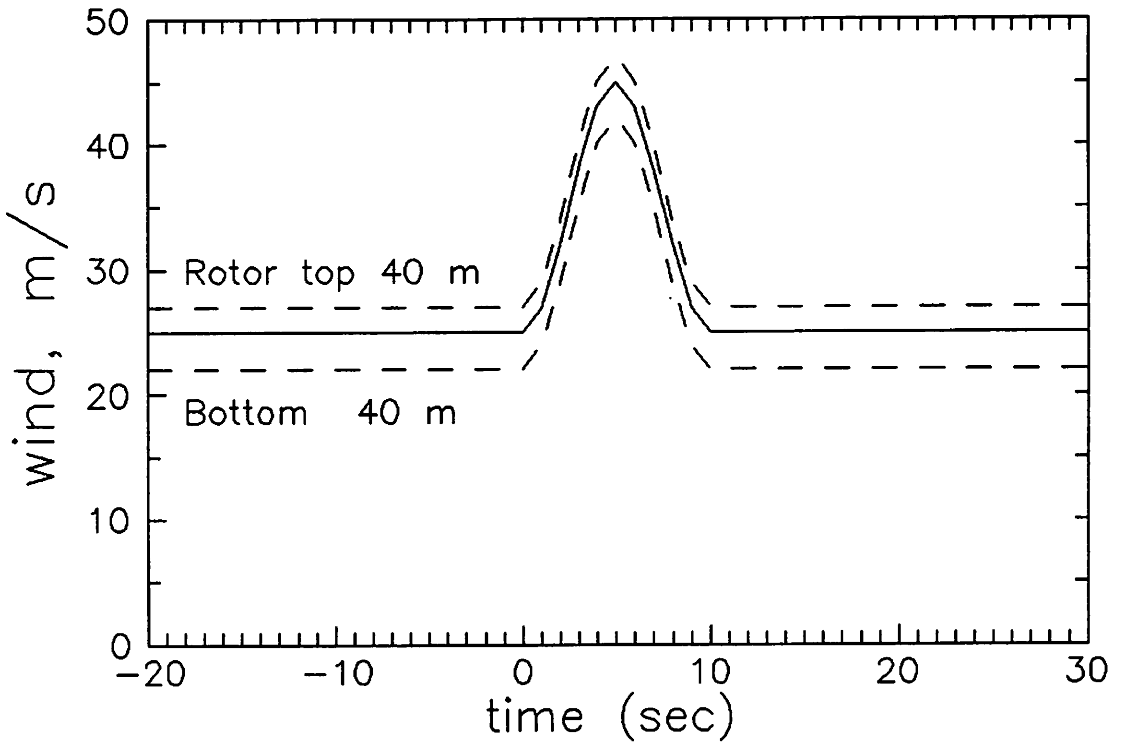
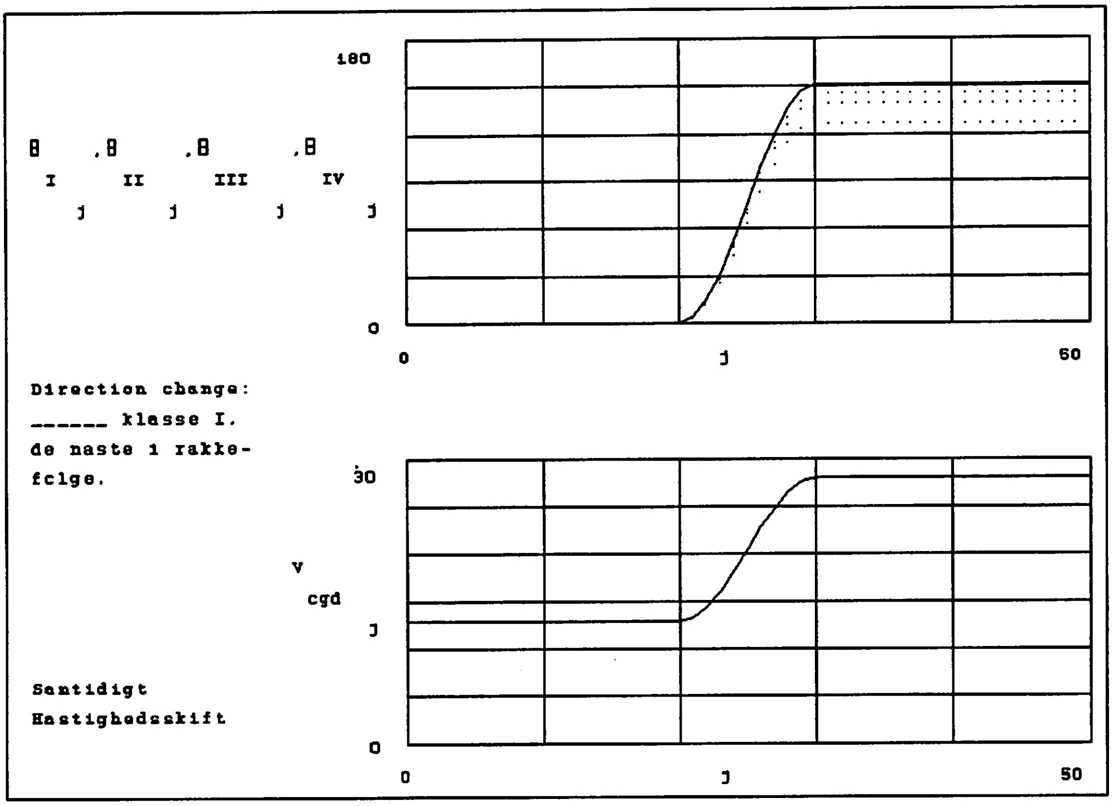


Figure 4. Extreme Operating Gust

extensive use of cosine-bell deterministic gusts (Example Figure 4).

The shape rise times of 5-10 sec - direct excitation weak.

but - influence via the control system.



Extreme Wind Direction AND Speed Change.

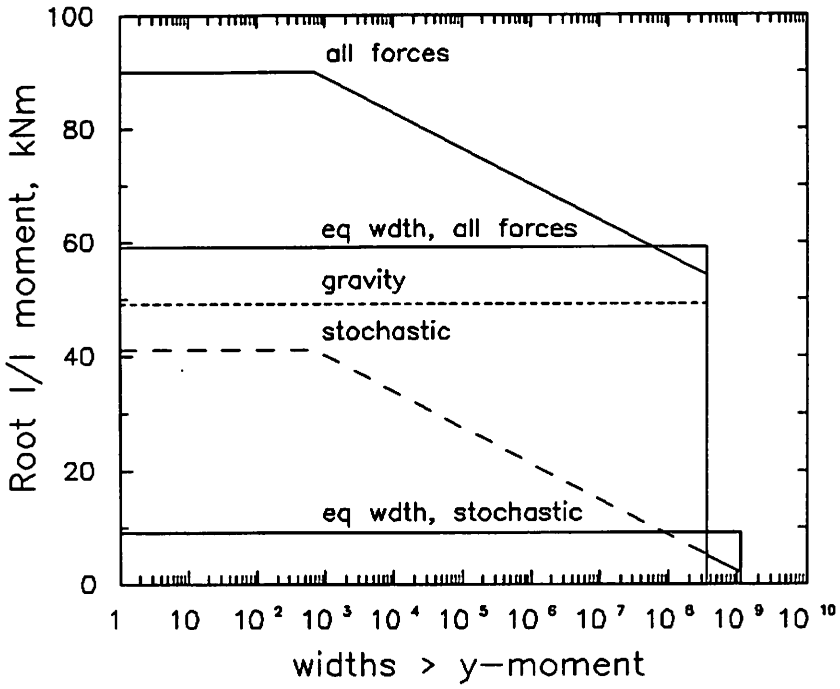
Danish Code - only 90 deg direction change

Table II: IEC turbine classes and equivalent values for DS class 0. 40m hub height.

Class	V_{ref}	V_{ave}	I_{Ave}
I	50	10	.17
II	42.5	8.5	.17
III	37.5	7.5	.17
IV	30	6	.17
DK-0	39.8	8.2	0.11

	V_{e50}	V_{ave}	I_{ave}
IEC-II	59.5	8.50	.17
DK-0	52.8	8.17	.11

Fatigue Calculations - DS-472
- recommended - not compulsory

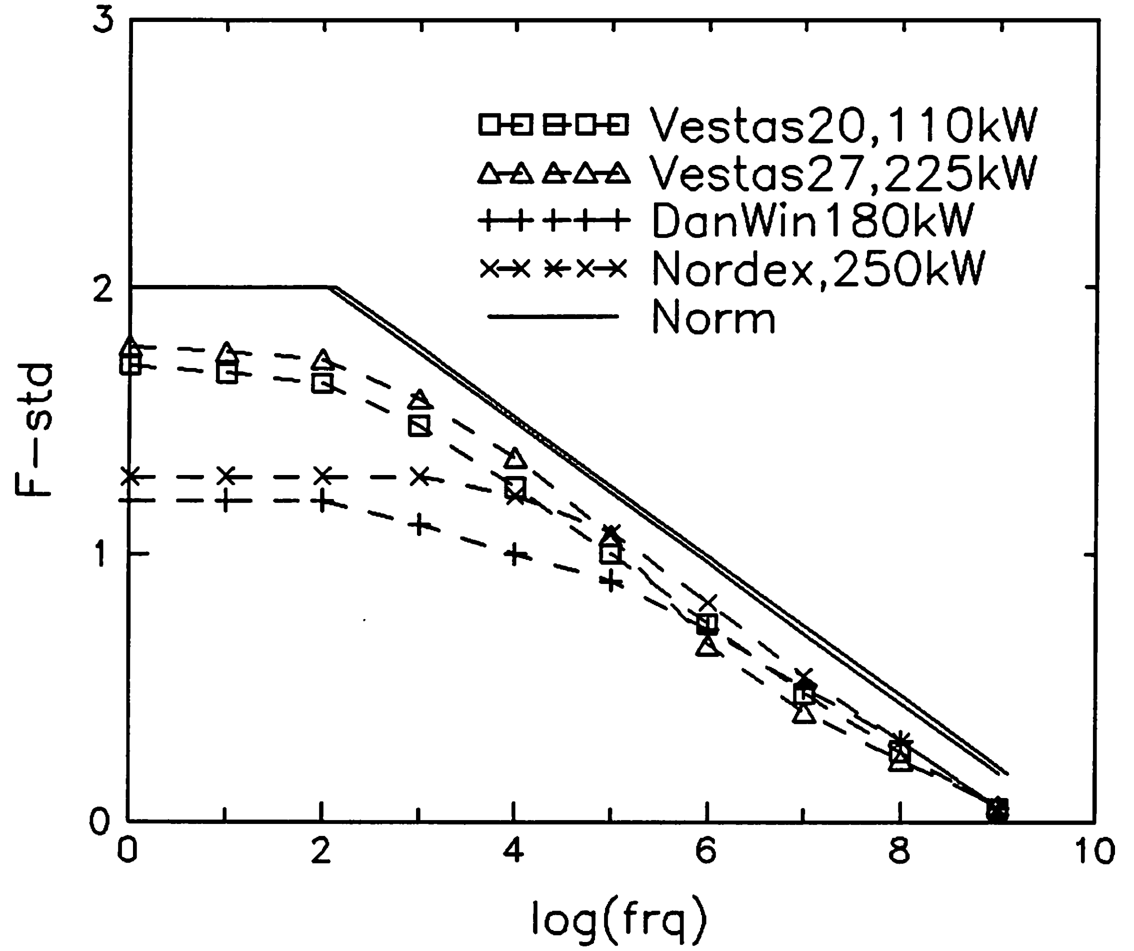


$$\hat{F}_{\Delta}(N_v) = \beta\ (\log(N_f) - \log(N_v)) + 0.18 \qquad (5)$$

$$\beta = 0.11\ (I + 0.1)\ (A + 4.4)$$

$$S_{\Delta}(N_v) = C_F F_{\Delta}(N_v) + C_G G_{\Delta}(N_V) \qquad (6)$$

IEC: Gives possible turbulence models, but no specified calculation method



3
2
1
0
F—std
0
2
4
6
8
10
log(frq)
Vestas20,110kW
Vestas27,225kW
DanWin180kW
Nordex,250kW
Norm

Comparing Safety levels of the two codes

Safety reserve:

$$r = R_k/(\gamma_R L_k \gamma_L) \geq 1 \qquad (7)$$

Comparing two codes - compare either of

- basic failure probability for the two codes

- all four factors of design requirement:

$$r_{IEC} = \frac{R_{k,IEC}}{R_k} \cdot \left(\frac{\gamma_R}{\gamma_{R,IEC}} \frac{L_k}{L_{k,IEC}} \frac{\gamma_L}{\gamma_{L,IEC}} \right)$$

If $r_{IEC} > 1$: IEC-Code mildest

measure of safety used for comparison:

- Factor 1.1 =
  ONE STEP Change of
  SAFETY CLASS

Extreme loads: 50 yr reccurrence.

Partial coefficients for ultimate loads, DS versus IEC

Load Type	DS 472	IEC
Aerodynamic	1.3	1.3
Functional	1.3	1.4
Gravitational	1.0	1.1
Inertial	1.0	1.2

Materials:

- National codes
- >95% survivability fractile
- Partial coefficient > 1.15

Change of Safety from DS-472

/

Resistance		Load		Total
R_k	γ_R	L_k	γ_L	r_{IEC}
1.02	1.1	0.85	1	0.95 [1]
1.02	1.25	1	0.9	1.15 [2]

1 short time average, extreme wind,steel

2 gravity, fatigue, steel

IEA TOPICAL EXPERT MEETING 24
Wind Conditions for Wind Turbine Design

RISØ National Laboratories, 28-30/4/93

Extreme Wind conditions in Italy

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Abstract

For the purpose of Wind power exploitation in Italy, existing wind data and civil engineering standards for Italy are analized. "Tornado" events, of great importance for possible damages to nuclear power plants, affecting mainly north-east adriatic coasts, the Padana Plane, and Tirrenian costs in the Lazio area, do not affect substantially areas with good wind resources.
The examination of existing long periods of wind data is not easy, because these data relate to airfield and meteo stations, generally not monitored for wind energy purposes.
The trend of a selected sub-set of stations and of a limited set of stations explictly monitored for wind energy purposes shows that extreme wind speeds that can be expected in Italy are higher than those prescribed by the IEC standard.
Existing italian regulations for buildings and civil structures is confronted with the proposed wind turbine classes, showing that the IEC standard is more conservative than the actual regulation.

1. Introduction

National plans set for Italy a goal of 300-600 Mw of Wind plants capacity installed at the year 2000. At the moment only few Mw of capacity are actually installed, therefore it can be said that most of the forecasted installations will have to comply with the new IEC standard.
A large part of these installations will be sited in mountaineous or in someway "complex orography" regions, at altitudes around 1000 mts. a.g.l., where a highly turbulent environment is present.
Moreover, as a general trend italian wind regimes depart quite substantially from the rayleigh statistics, having form factors of quite low value, generally of the order of 1.5.
The present work deals with the problem of evaluating some aspects of the proposed standard (namely the extreme windspeed values) in relation with the italian situation.

2. Existing studies on extreme wind conditions in Italy

No specific comprehensive actions for evaluating the extreme wind conditions applicable to Wind Turbine design in Italy have been reported up to now.
Two studies dealt with the "exceptional Wind events" [1], [2], comprising either tornadoes and other exceptional wind events whose damaging effects have been reported in the literature or in the

press.
About Tornadoes, it must be stated that italian tornadoes, although quite common, have not the same level of strength as in the U.S. and tropical regions. Yet severe damage can be expected.
The strongest tornado reported hit Venice in 1970, causing severe damages and some tens of deaths; the tornado path, 40 Km long, interested an area of around 8 Km^2.
The estimated maximum windspeed associated to such event is 80 m/sec, corresponding to a rotational speed of 62 m/s and a translational speed of 18 m/s [1].
On this basis a "design tornado" with a maximum tangential speed of 88 m/s and a pressure drop of 12450 N/m^2 in 5 seconds was proposed for the case of Nuclear Power Stations.
For the specific case of Wind Power plants, table I, taken from [1], shows the probability to be hit by a tornado for the italian regions, together with a rough classification with respect to the overall availability of interesting and exploitable wind resource.
It is clear that the risk is generally very limited in the most windy regions; indeed tornadoes do affect mainly the north-east coasts and Padana plane, and the Lazio coast, and do not propagate on mountainous region.

Region	Probability ($*10^{-4}$ / year) Source: [1]	Wind resource I = Interesting S = Scarce N = Negligible
Piemonte	5	N
Lombardia	5	N
Liguria	4	S
Veneto	3.6	N
Friuli	3.3	N
Emilia Romagna	2.4	S
Toscana	18	S
Lazio	24	S
Campania	9.4	I
Abruzzi-Molise	0.35	I
Marche	0.32	S/I
Puglia	1.2	I
Basilicata	1.8	I
Calabria	8.8	S/I
Sicilia	1.4	I
Sardegna	1.3	I

Table I: probability to be hit by a tornado in Italy

Regarding "exceptional wind" on more general terms (events with some damaging or outstanding effect, with either associated depressional effects or not) the events reported in the press for the period 1908 - 1983 are shown in fig. 1 (taken from [2]), where

the number of reported events is proportional to the area of each of the circles, located in the position of the administrative province to which the events belong.
The distribution confirms that southern and island areas and central and southern Appennini mountains are generally less affected. In this study a total number of 2364 events have been reported, of which 705 present a "tornado" behavior.
In fig. 2 , the distribution of the "Intensity" (calculated on the basis of an empirical classification of damages) of the events is shown.
An empirical scale of windspeed has been added to the original Intensity scale, assuming for the damage intensity/Windspeed a relation of the type:

$$I = K * V^2 - Io$$

and assuming V = 80 m/sec for I = 350 (the Intensity calculated for the Venice tornado), V = 18 m/sec for I = 0 (the lowest windspeed level of Fujita scale).
The associated windspeed calculated in this way is for most of the cases less than 54 m/s.

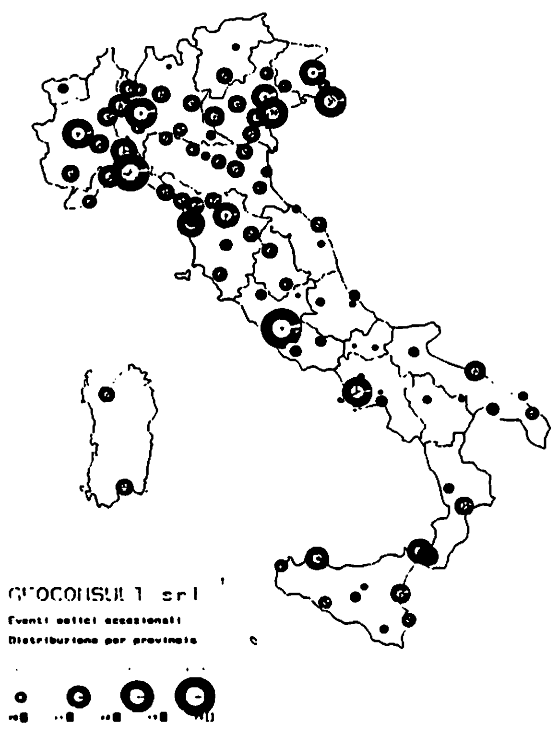

Fig. 1 Geographical Distribution of exceptional Wind events

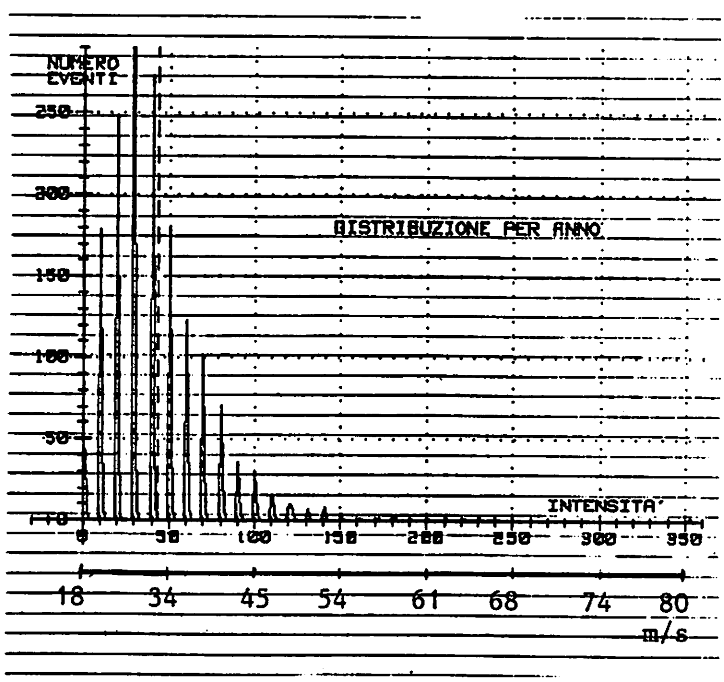

Fig. 2 Intensity distribution of Events

3. Statistics from meteo stations

Long term statistics (15-30 years) of Wind speeds are only available from the meteorological service of the Italian Air Force. The data refer to militar and civil airports and airfields, and to meteorological stations controlled by the air force and located on tops of mountains or on coastal capes.
Generally speaking such data are of limited value for Wind energy evaluations, given that the location of these stations is not correlated to the purpose of Wind Power evaluation; moreover the published information for the characterization of each station (heigth of the anemometer, roughness, obstacles) is quite limited.
The most comprehensive published data are basically reports of the "maximum windspeed" registered each year during the considered period [3], and the frequency of the windspeeds for each of 16 direction sectors [4].
The maximum Windspeed reported is the absolute istantaneous value (within the resolution of the anemometer).
From the windspeed frequency it is possible to evaluate the long term average windspeed.
It has been stated that the error on the true average value of long term series, taking into account only 6 readings/day, is limited to few percent [5]; but in the case of the data here considered the error is likely to be more pronounced, given that only two readings/day are considered and the final data are presented in a "bin form" with a very limited resolution (Vm < 1.66 m/s, 1.66 < Vm < 5, 5< Vm < 10, 10 < Vm < 15.3, Vm > 15.3 m/s).

A number of these stations among the whole set, located mainly in southern coasts, islands and central Appennini has aniway been selected taking into account their possible representativeness for Wind Energy evaluations.
The maximum windspeed Vmax and the ratio Vmax/Vave of these stations are shown in figs. 3 and 4 ; the data are referred to 10 mts. of heigth, using the values of the power exponent assumed in the standard.
The ratio Vmax/Vave is on general terms higher than 7 (the ratio prescribed by IEC standard draft in the case of the 50 years return time extreme is Ve-50/Vave = 7) and there is a clear tendency to higher values of this ratio as the average windspeed decreases.
The dispersion of data is high; the difference in measurement times has a clear influence, as expected, leading to higher values of the ratio as measurement periods increase, but even if only the main sub-set of stations with measurement periods in the range 20-24 years is selected the dispersion remains high.
The real reason for that can be the different orograhic characteristics, the difference in observation periods or intrinsic limitations of the way the averages have been calculated.
A more comprehensive study will be needed to clarify these aspects.

Another set of 5 sites monitored in the Sicily island under ENEA contract is shown in figs. 5 and 6.
These sites have been explicitily monitored due to their possible

use for Wind Energy purposes; the stations are positioned at heigths ranging from 15 to 1200 mts. and standard 10 min. averages are logged. Form factors from 1.5 to 1.64 have been measured during the first year of measurements.
A ratio Vmax/Vave sligthly higher than 5.25 (corresponding to the ratio Vel/Vave in the IEC standard) was registered in these stations; also in this case there is a tendency to increase the ratio as Vave decreases.

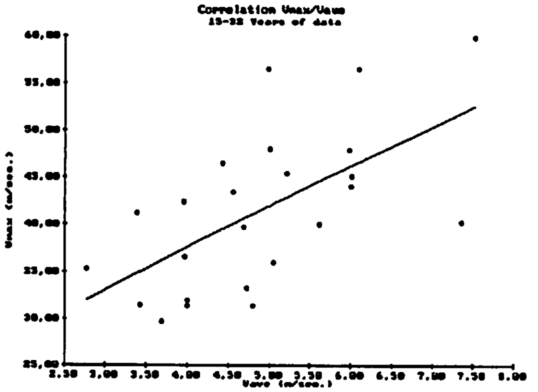

Fig. 3 Maximum Windspeed Air Force data

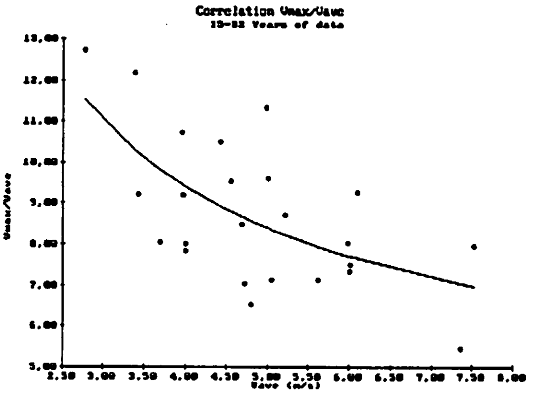

Fig. 4 Vmax/Vave ratio, Air Force data

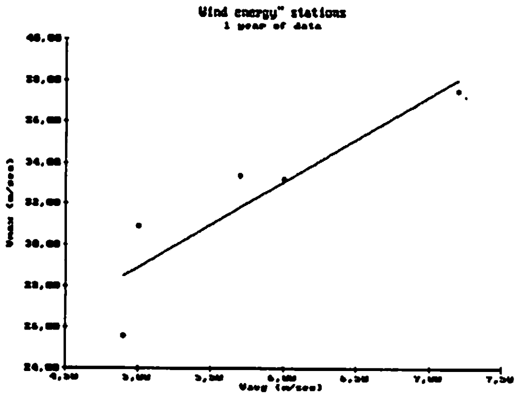

Fig. 5 Maximum Windspeeds, Wind Energy stations

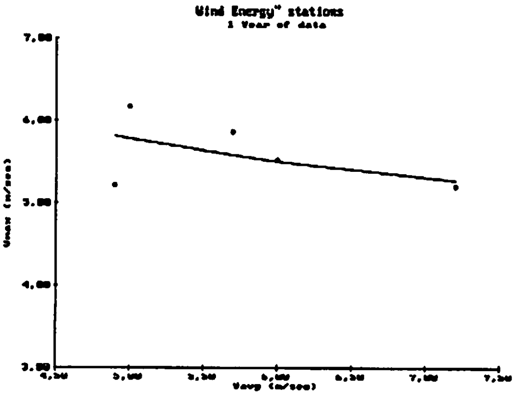

Fig. 6 VmaX/Vave, Wind Energy stations

4. Existing standards

In Italy does not exist at the moment any explicit standard for Wind turbines design.
As a general rule, the Wind turbines must fulfill the standards applicable to steel constructions (CNR-UNI 10011, june 1988), that do not prescribe specific rules for calculating wind loading, and the civil enginering standards applicable to buildings.
In the regulation of Ministry of Public Works n. 18591, 9 nov. 1978, the "design loads" due to the wind force acting on the structure are fixed.

The corresponding wind speed for standard air conditions can be calculated as follows:

Design Windspeed in (m/sec), Circ. n. 18591, 9 nov. 1978

Zone	1	2	3	4
H = 30 mt. a.g.l.	32	37	41	45
H = 60 mt.	36	41	44	48
H = 90 mt.	40	44	48	51

The zones (1 - 4) relate to a classification of the italian territory, taking into account altitude, proximity to the sea and geographical position.
It must be stressed that the standard applies to buildings, normally not sited in exposed sites.
It is responsibility of the designers to apply more conservative rules in the case of structures particularly exposed to the wind action (like telecommunication towers).
The all normative will be probably revised in the frame of EuroCode.

In the case of Electric Lines another standard applies (Decree of the president of Republic of 21 june 1968, n. 1062), stating that the design Wind speed is 36 m/sec (for Central and South Italy and Islands, with altitudes less than 800 mts. a.g.l.) or 18 m/sec (Northern Italy and all sites at altitudes over 800 mts a.g.l.): in this second case the calculation must be performed taking into accound a 12 mm. thick ice stratum on the conductors.

The situation of the regulation of the Ministry of Public Works referring to the proposed IEC standard is represented in figs. 7 through 10; the 50 years and 1 year return time extreme windspeeds prescribed by the IEC standard are plotted for the four classes in the two cases of 30 mts. hub heigth (typical medium size machine with 300-400 rated capacity) and 65 mts. (typical large size machine, as GAMMA60) together with the actual prescriptions at two heigths in the four "zones"; the IEC standard is evidently more conservative than the actual regulation.

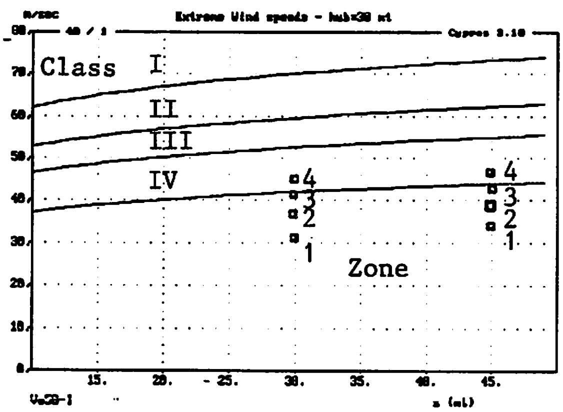

Fig. 7 Ve-50 vs. buildings regulation, 30 mts. hub

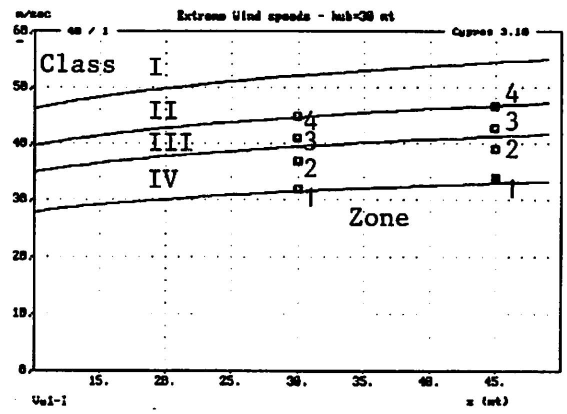

Fig. 8 Ve-1 vs. buildings regulation, 30 mts. hub

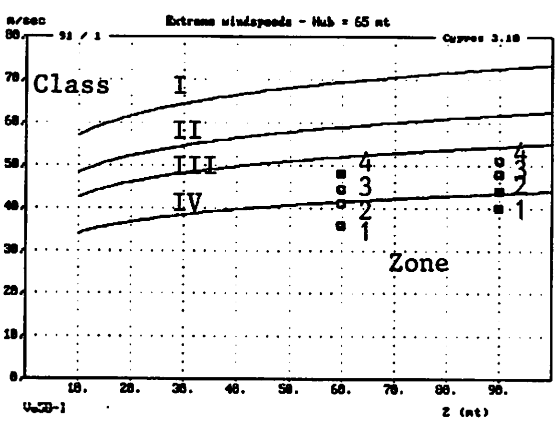

Fig. 9 Ve-50 vs. buildings regulation, 65 mts. hub

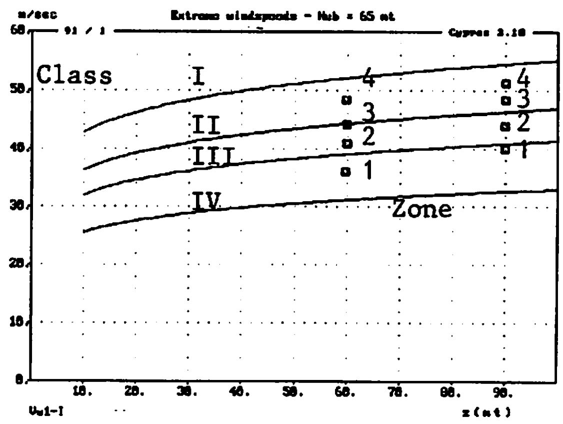

Fig. 10 Ve-1 vs. buildings regulation, 65 mts. hub

5. Conclusions

While catastrophic events (like tornadoes) are not likely to represent a design or economic constraint on the development of Wind Energy utilization in Italy, from the point of view of "extreme values" the proposed IEC standard, while being conservative with respect to actual civil engineering regulations, is likely to be not conservative if the choice of Wind turbine classes will be performed only on the basis of the "Annual average windspeed" of the site.
This fact, together with the high dispersion present on the available data, asks for a further investigation on the characteristics of italian wind regimes and the adoption of proper assumptions when actual users will be in the position to choose the "class" of the Wind Turbine to be adopted in specific sites in Italy.

REFERENCES

[1] S. Palmieri, A. Pulcini - Trombe d' Aria sull' Italia (Tornadoes over Italy), Rivista di Metorologia Aeronautica - V. XXXIX - N. 3/4, 1979.
[2] Eventi Eolici Eccezionali in Italia, 1908 - 1983, Geoconsult Roma, 1983, under ENEA contract.
[3] Valori estremi di alcuni parametri meteorologici nel periodo 1951-1978, Vol. I (1983) and Vol. II (1987) - C.D.U.551.582.2 - Aeronautica Militare, Centro Nazionale di Meteorologia e Climatologia Aeronautica
[4] Frequenze e medie delle osservazioni meteorologiche in superficie, Vol. I (1983) and Vol. II (1986) - C.D.U.551.582.2 - Aeronautica Militare, Centro Nazionale di Meteorologia e Climatologia Aeronautica
[5] A. Lavagnini, A. M. Sempreviva, G. Tosato Studio dell' errore introdotto dalla incompletezza dei dati nel calcolo dell' energia eolica - Energie alternative HTE n° 35, mag-giu 1985.
[6] Circolare del Ministero dei Lavori Pubblici, n. 18591, 9 novembre 1978 - "Istruzioni relative ai carichi, ai sovraccarichi e ai criteri generali per la verifica di sicurezza delle costruzioni".

IEA annex XI
workshop on IEC-standard for *Safety of Wind Turbine Generator Systems*
Risø, April 29-30 1993

VELOCITY SPECTRA

Jørgen Højstrup

INTRODUCTION

In this context realistic models for atmospheric velocity spectra are necessary for predictions of gusts and as input for models for the generation of timeseries. A number of different models for these purposes have been in use, some of these have very nice analytical properties, making it easy to derive a description of the whole turbulent field with specified cross-correlations, while others show a more realistic description of the velocity fluctuations actually found in nature. We will here focus on the two models proposed in the IEC draft standard and compare them with other well-known models.

IEC-MODELS FOR VELOCITY SPECTRA

The two models included in appendix A2 are the Kaimal model (eq. 1) and the Von Karman isotropic model (eq. 2).

$$\frac{fS_i(f)}{\sigma_i^2}=\frac{4fL_i/V_{hub}}{(1+6fL_i/V_{hub})^{5/3}} \tag{1}$$

where

- f: frequency in Hz
- i: index referring to the velocity component direction (i.e. 1=longitudinal, 2=lateral and 3=vertical)
- S_i: the single sided velocity component spectrum
- σ_i: velocity component standard deviation
- L_i: velocity component integral scale parameter

Velocity comp.	1	2	3
Standard dev.	σ_1	$0.8\ \sigma_1$	$0.5\ \sigma_1$
Integral scale	$8.1\ \Lambda_1$	$2.7\ \Lambda_1$	$0.66\ \Lambda_1$

$\Lambda_1 = 0.678\ z_{hub}$ for $z_{hub} < 30$m
$\Lambda_1 = 20.3$m for $z_{hub} \geq 30$m

$$\frac{fS_1(f)}{\sigma_1^2}=\frac{4fL_1/V_{hub}}{(1+70.78(fL_1/V_{hub})^2)^{5/6}}$$

$$\frac{fS_2(f)}{\sigma_2^2}=\frac{fS_3(f)}{\sigma_3^2}=2fL_1/V_{hub}*\frac{1+188.8(fL_1/V_{hub})^2}{(1+70.78(fL_1/V_{hub})^2)^{11/6}} \tag{2}$$

where
$\sigma_1 = \sigma_2 = \sigma_3$

The 'Kaimal model' in the IEC standard is not really the Kaimal model as formulated by Kaimal (1972), the alongwind component is identical to the Kaimal formulation, but the lateral component has a slightly different magnitude and slightly different length scale, and the vertical component has a different shape than that used by Kaimal (1972). Generally only small differences compared to the original Kaimal model, but it is very important to bear in mind that the Kaimal model was developed on the basis of data close to neutral stability as approached from the stable side (a situation in which long wavelength fluctuations are strongly damped), and for moderate windspeeds. In fig. 1 is shown a comparison between the two IEC spectral models for the alongwind component (U-component), for which the IEC-Kaimal and the Kaimal model are identical. The models are shown normalised with u_* resulting in coinciding high frequency asymptotes.

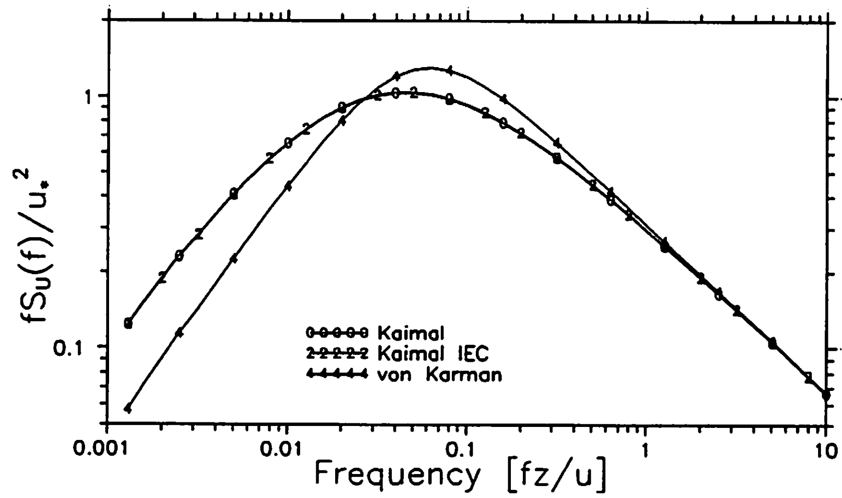

Figure 1 IEC velocity spectra, component 1, and original Kaimal formulation (for this component identical to IEC-Kaimal). z is the height above the ground, and u is the mean windspeed.

We see that the von Karman model has a more peaked appearance where the frequency of maximum energy content is some 50% higher than for the Kaimal formulation.

COMPARISON WITH DATA

In general we always see much more low frequency variance in the data than shown in the IEC models. One of the reasons for this phenomenon is that in real life we do not have homogeneous terrain, and terrain inhomogeneities in general do give rise to velocity fluctuations at scales comparable to the scales of the inhomogeneities (Panofsky et al, 1982), but even in homogeneous terrain it is well known that the velocity spectra do not look like the ones in fig.1, but contain more energy than expected at low frequencies (Eidsvik 1985, Iwatani 1985, Højstrup 1990, Wills 1992). As an example we can look at a high windspeed neutral case from the Nibe site, with the windprofile shown in fig. 2 showing a near perfect logarithmic profile, and the spectra of the alongwind component in five heights shown in fig 3 shows much more energy content at low frequencies than the Kaimal model.

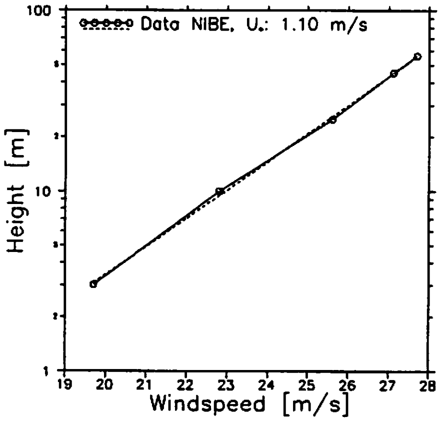

Figure 2 Windprofile from the Nibe site, the dashed line is a logarithmic fit to the measured profile.

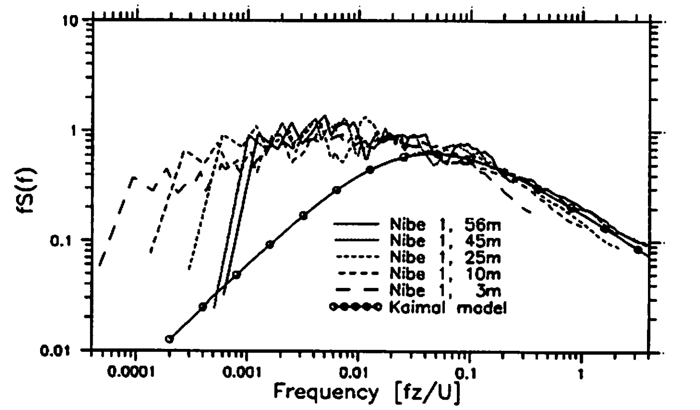

Figure 3 Velocity spectra corresponding to the profile in fig. 2. The Kaimal model spectrum is plotted for comparison.

A MORE REALISTIC MODEL

A more realistic model capable of describing the observed behaviour of the spectra in high windspeed neutral conditions has been described by Højstrup et al (1990). Basically the model consists of the Kaimal model (peak wavelength proportional with height) with an additional spectrum superimposed, where the peak wavelength is a constant (3000m) above 10m and decreasing at lower heights. The model has only been thoroughly tested for the alongwind component, the lateral component seems to be reasonably described by the Kaimal models, whereas the vertical component also contains more lowfrequency energy than does the Kaimal model. The models are presented together in a loglog plot on fig.4 (U-component).

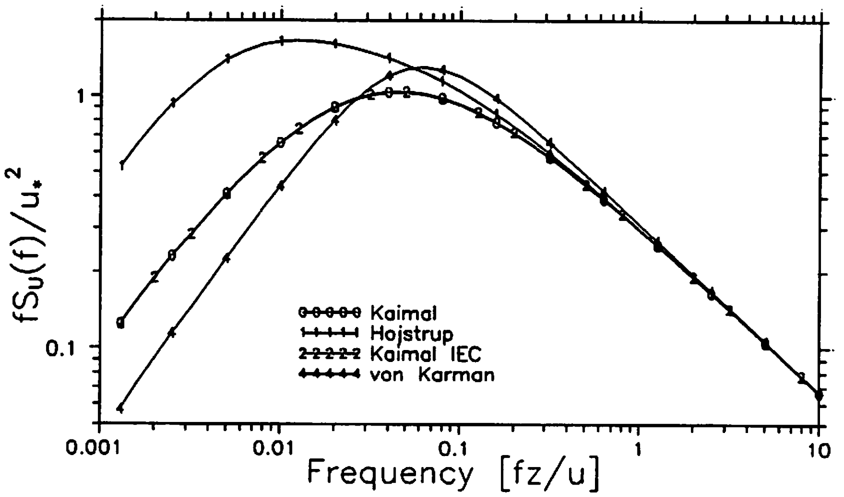

Figure 4 Models for the alongwind component, plottet for 30m height.

The models for all three components are shown in figs. 5-7 plotted for 30m height in loglin plots, which have the well-known property that equal areas under the curves represent equal variances.

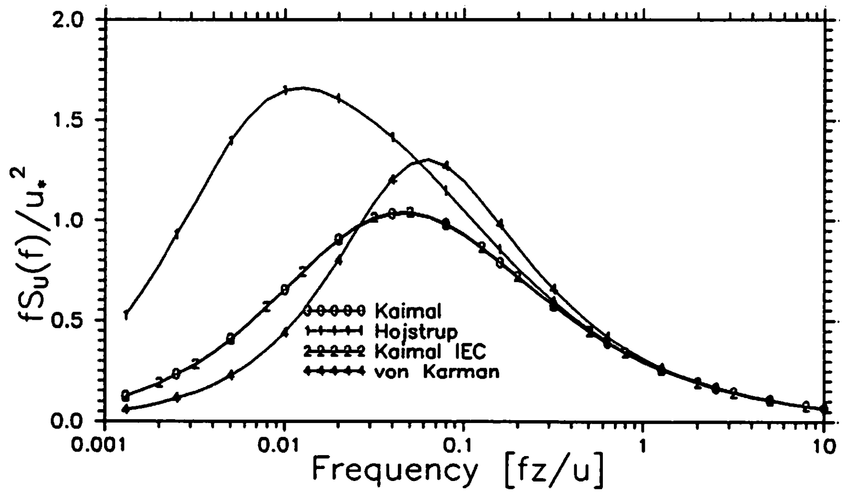

Figure 5 Alongwind component plottet for 30m height.

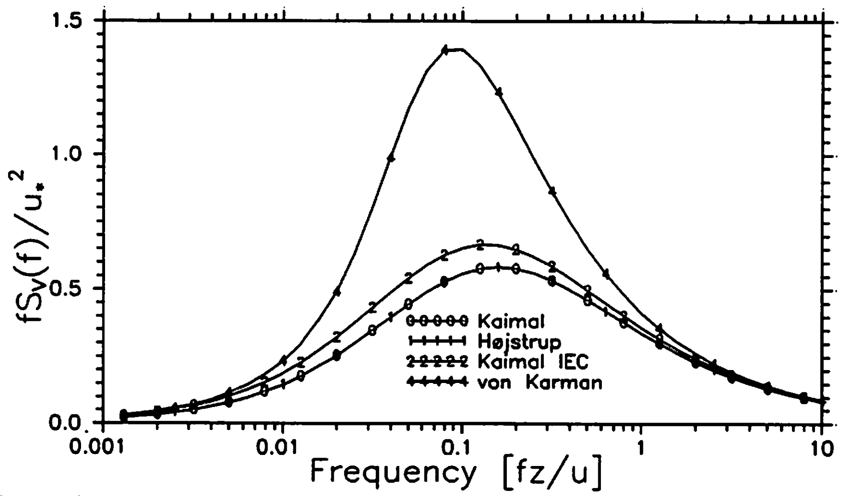

Figure 6 Lateral component models plottet for 30m height.

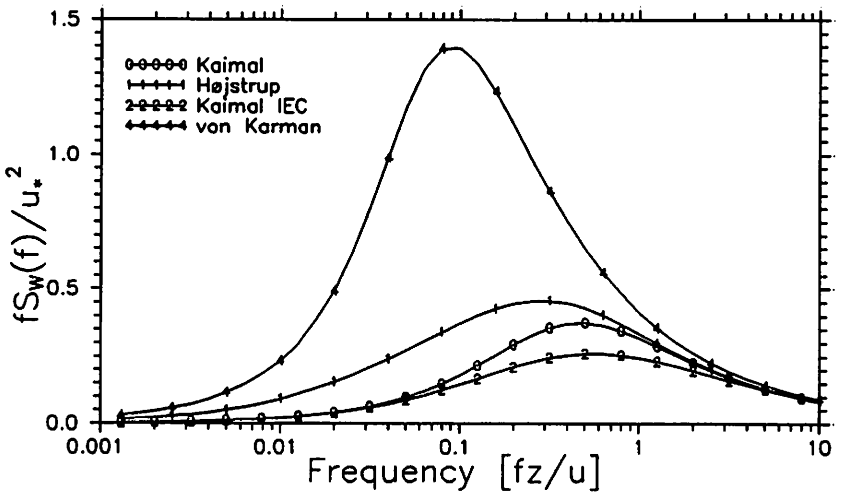

Figure 7 Vertical component plotted for 30 m height

It is quite obvious from these plots that:

- The IEC model U-spectra lack low frequency energy
- The von Karman V-spectrum overestimates the energy around the peak wavelength.
- Both the Kaimal IEC and the original Kaimal V-models underestimates energy content around peak wavelength, and the von Karman model severely overestimates the energy content around peak wavelength.

These comparisons are all based on the fact that all models have been normalised to coincide at high frequencies, in the socalled inertial subrange, to which there is very solid evidence that they should.

SPECTRA IN WINDFARMS

The turbulence in a windfarm is quite different from the turbulence experienced in the free undisturbed flow. The extraction of energy from the mean flow of the windturbines creates very large positive windshears above the wake of the turbine, and diminishes or changes the sign of the shear below the wake. The result of these processes (see Højstrup and Nørgård, 1990) is an increase in the production of turbulent kinetic energy, with the major increases occurring at length scales comparable to the scale of the wake. So the shape of the spectrum changes, and also the turbulence is no longer in equilibrium, it is in a state of constant change, such that modellers cannot with confidence use the usual wellknown (equilibrium, homogeneous terrain) assumptions about relations between variances, corellations and coherences.

The length scale in the Kaimal formulation is for the U-component about 20 times the height above the ground, now we have a typical wake whith dimensions 1-2 times the height, so we get energy input at scales a factor of 10 smaller than we would normally expect, the turbulence intensities are much higher, so a very rough way of describing the turbulence as experienced in a windfarm at hubheight would be to say that it looks roughly as if it were measured at ***one-tenth of hubheight in homogeneous terrain with a roughness length of 0.2-0.5m.***

One example of this behaviour is shown in figs. 8-9, which were taken from the Tændpibe windfarm (hubheight 23.5m, 35 75 kW VESTAS machines). In fig. 8 which shows velocity spectra measured by cupanemomenters at different heights upstream (full lines) and inside the farm (dashed lines), we can see that the main input of energy occurs in a fairly wide frequency range around 0.1-0.2 Hz which corresponds to a wavelength of approx. 2 rotor diameters. In fig. 9 which shows the results of measurements by fast response sonic anemometers inside the windfarm we can very clearly see that the cospectra S_{uw} below the wake have received some positive corellation in the frequency range in question, and above the wake there is a definite increase in that same frequency range (according to classical turbulence theory you would expect negative corellation over the whole frequency range, which indeed you also see in data taken over homogeneous terrain).

CONCLUSIONS

The deviations between the models for velocity spectra proposed in the IEC draft standard and more realistic models are considerable even for homogeneous terrain, and a quantitative evaluation of the effects of these differences on the resulting loads would be useful.

In windfarms and inhomogeneous terrain there are even more complications with turbulence generation on different scales than expected by classical theory. In the windfarm situation we see non-equilibrium turbulence making life difficult since most of the assumptions used in the homogeneous, equilibrium situation breaks down.

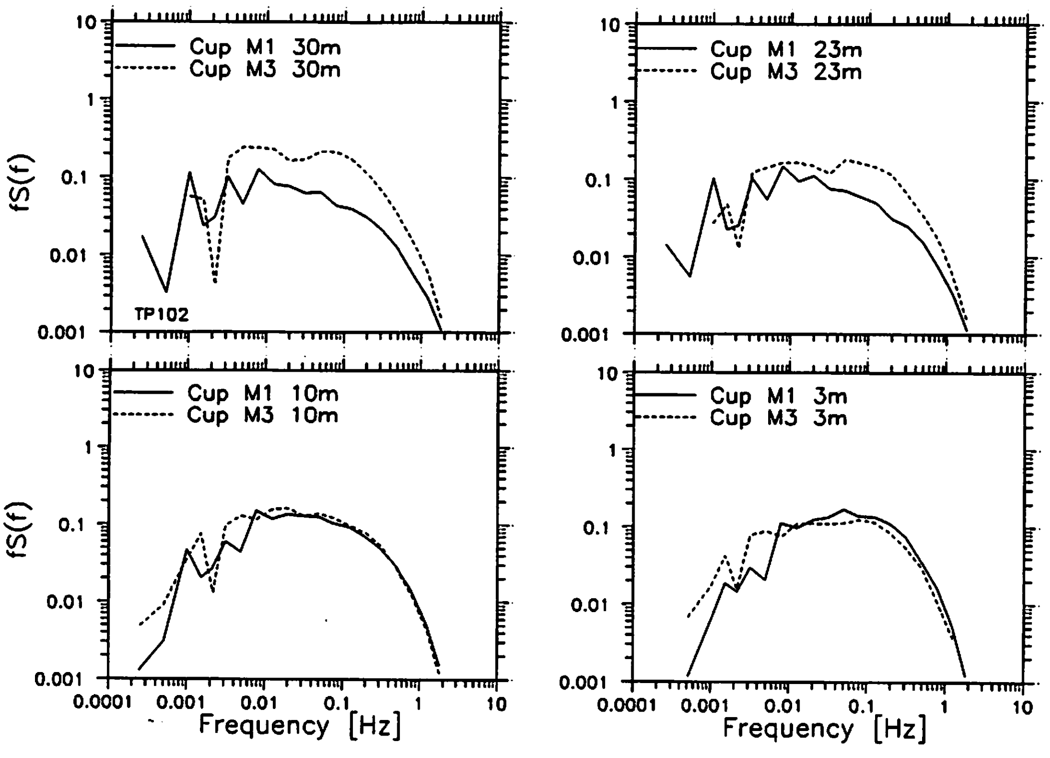

Figure 8 Cupanemometer measurements from the Tændpibe windfarm (hubheight 23.5m, rotor diameter 17m). Full lines: upstream, dashed lines: inside windfarm.

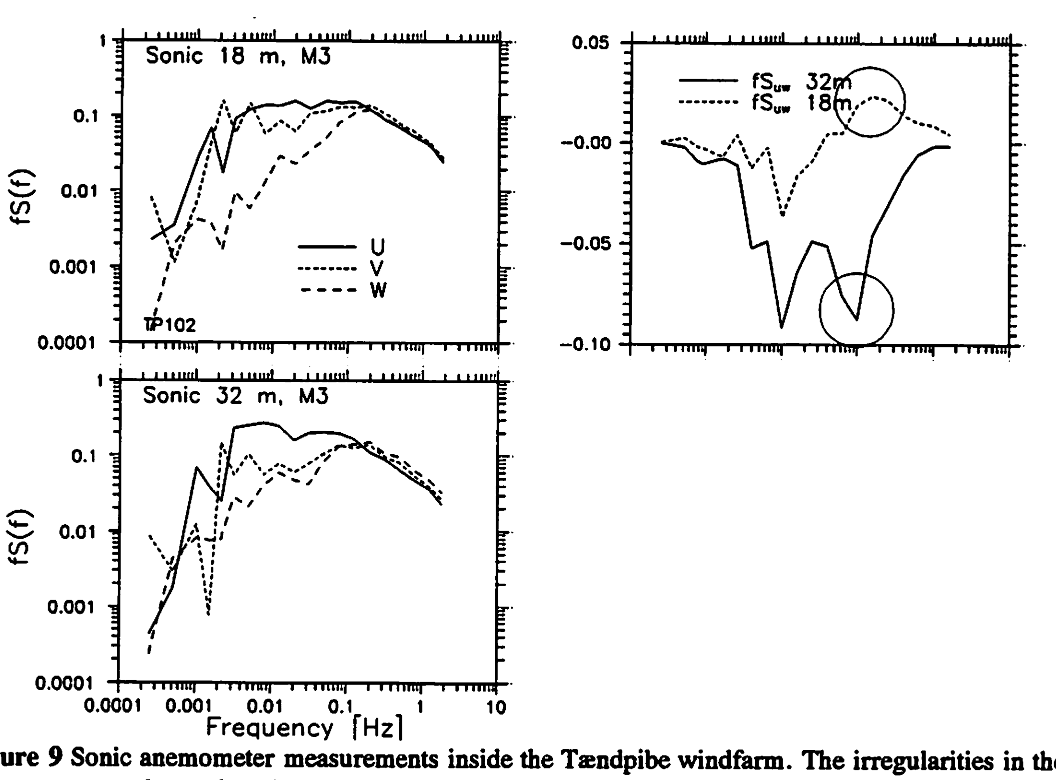

Figure 9 Sonic anemometer measurements inside the Tændpibe windfarm. The irregularities in the cospectra around wavelengths corresponding to wake dimensions are marked with circles.

Some suggestions for simplifications:

WINDFARMS: Spectra at hubheight look as if they were measured at a height 5-10 times lower than hubheight, and over terrain with a roughness length of 0.2-0.5m.

INHOMOGENEOUS TERRAIN: It is much more difficult to give recommendations here, since there are so many possible types of terrain inhomogeneities, but we do know that terrain inhomogeneities typically will produce more turbulent kinetic energy at long wavelengths.

REFERENCES

Eidsvik, K.J. (1985). Large-sample estimates of wind fluctuations over the ocean. *Bound. Layer Meteorol.*, vol. 32, 103-132.

Højstrup, J., Larsen, S.E., Madsen, P.H. (1990). Power spectra of horizontal wind components in the neutral atmospheric surface boundary layer. In proceedings from: *AMS ninth symposium on turbulence and diffusion, Roskilde, Denmark,*

Højstrup, J. and P. Nørgård (1990). Tændpibe windfarm measurements 1988. *Risø M-2894*, Risø, Roskilde, Denmark. 44 pp.

Iwatani, Y. (1985). Spectra and scales of the atmospheric turbulence in high winds ranging from 10 to 60 m/s. *Jour. Met. Soc. Japan*, vol. 63, 947-957.

Kaimal, J.C., Wyngaard, J.C., Izumi, Y. and Coté, O.R. (1972). Spectral characteristics of surface-layer turbulence. *Quart. J. Roy. Met. Soc.*, vol. 98, 563-589.

Panofsky, H.A., Larko, D., Lipschutz, R., Stone, G., Bradley, E.F., Bowen, A.J., Højstrup, J. (1982). Spectra of velocity components in complex terrain. *Quart. J. Roy. Met. Soc.*, vol. 108., 215-230.

Wills, J.A.B (1992). Offshore wind structure measurements at the West Sole gas platform. *Jour. Wind Eng. Ind. Aerodynamics*, vol. 41-44, 2465-2473.

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The Turbulence Intensity Definition in IEC WT Classification

Theoretical Considerations and Comparison with Italian Site Conditions

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ITEMS OF PRESENTATION

A) Turbulence Intensities of Italian Sites

B) Comparison with IEC TC88 Draft

C) Turbulence Effects on Fatigue Life

D) Conclusions

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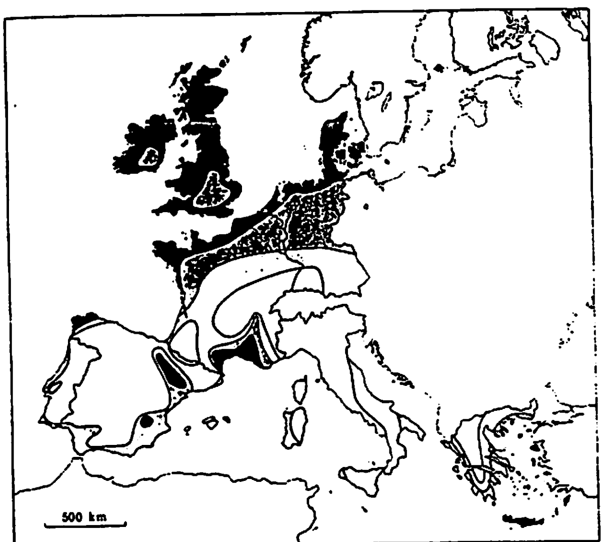

Wind resources at 50 metres above ground level for five different topographic conditions

	Sheltered terrain m s⁻¹	Sheltered terrain W m⁻²	Open plain m s⁻¹	Open plain W m⁻²	At a sea coast m s⁻¹	At a sea coast W m⁻²	Open sea m s⁻¹	Open sea W m⁻²	Hills and ridges m s⁻¹	Hills and ridges W m⁻²
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

European Wind Resource Map

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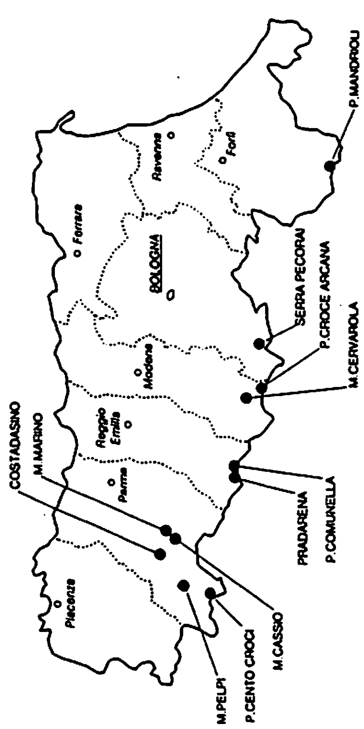

Suitable Sites for Wind Farm Installation in Emilia Romagna Region

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Wind Conditions for Wind Turbine Design

Wind Energy Dept.

Item	Site	Altitude [m]	Measurement Period from	Measurement Period to	Vave [m/s]	Iave [%]
1	Monte Cassio	785	ago-91	dic-92	4.0	25.0
2	Monte Marino	950	ago-91	dic-92	4.8	25.7
3	Costadasino	810	ago-91	dic-92	4.2	22.1
4	Passo Centocroci	1100	ago-91	dic-92	5.1	20.7
5	Monte Pelpi	970	ago-91	dic-92	4.3	19.5
6	S. Pecorai	740	set-91	dic-92	4.1	27.5
7	P. Crocearcana	1700	set-91	dic-92	7.3	13.1
8	M. Cervarola	1600	set-91	dic-92	6.0	24.4
9	Passo Comunella	1600	set-91	dic-92	6.2	15.8
10	Pradarena	1580	lug-88	gen-92	5.5	20.0

Wind Conditions of Emilia Romagna Sites

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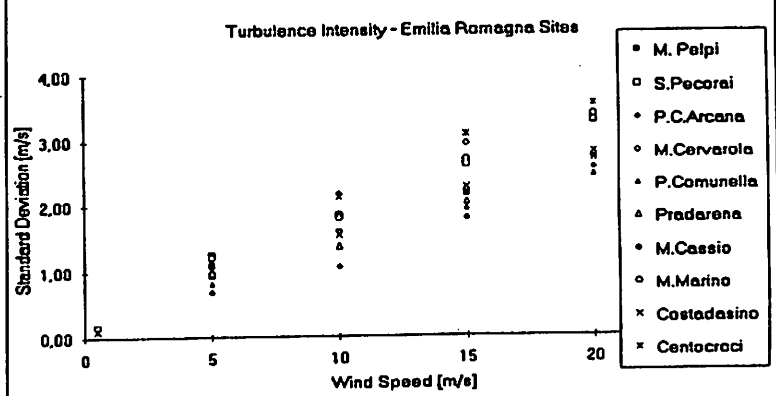

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Wind Conditions for Wind Turbine Design

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	Wind Turbine Class				
	I	II	III	IV	S
Reference extreme wind speed, V_{ref}(m/s)	50	42.5	37.5	30	Values to be stated by manufacturer
Annual average wind speed, V_{ave}(m/s)	10	8.5	7.5	6	
Annual average turbulence intensity, I_{ave}	0.17	0.17	0.17	0.17	

Basic Parameters for Wind Turbine Classes (Draft Secr. 21B)

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Wind Conditions for Wind Turbine Design

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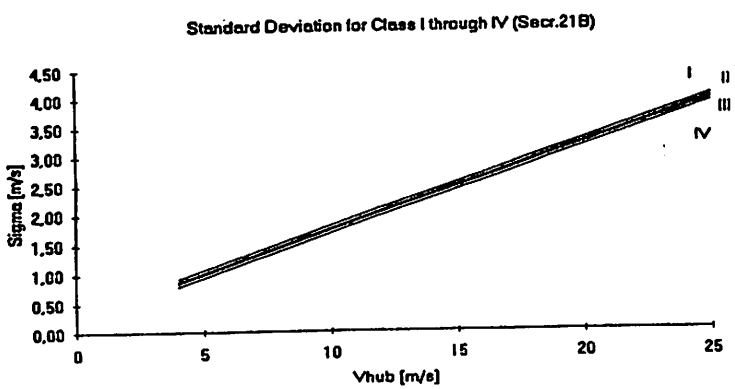

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Wind Conditions for Wind Turbine Design

Wind Energy Dept.

	Wind Turbine Class				
	I	II	III	IV	S
Reference extreme wind speed, V_{ref}(m/s)	40	35	30	25	Values to be stated by manufacturer
Annual average wind speed, V_{ave}(m/s)	8	7	6	5	
Annual average turbulence intensity, I_{ave}	0.21	0.18	0.15	0.12	

Basic Parameters for Wind Turbine Classes (Draft Secr. 21)

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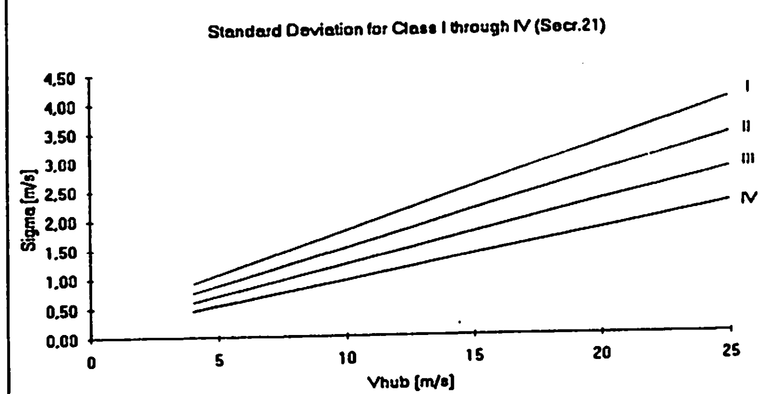

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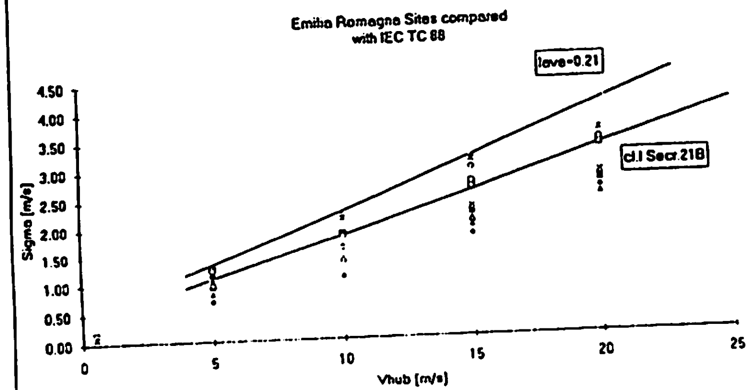

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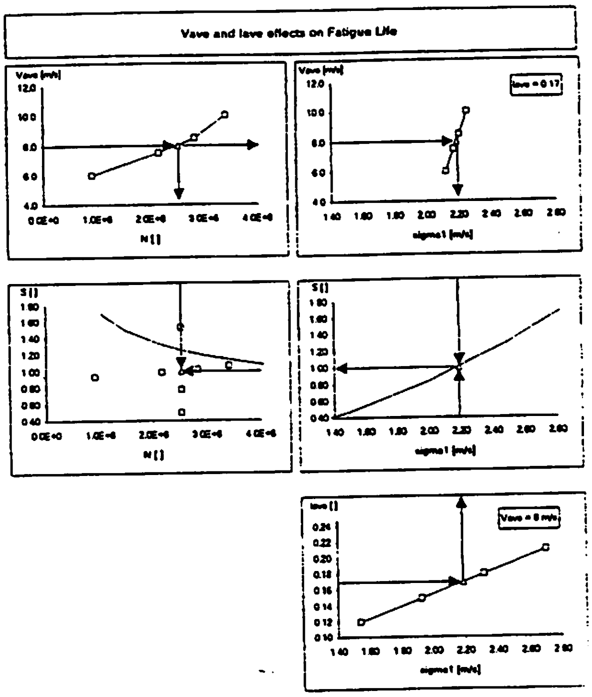

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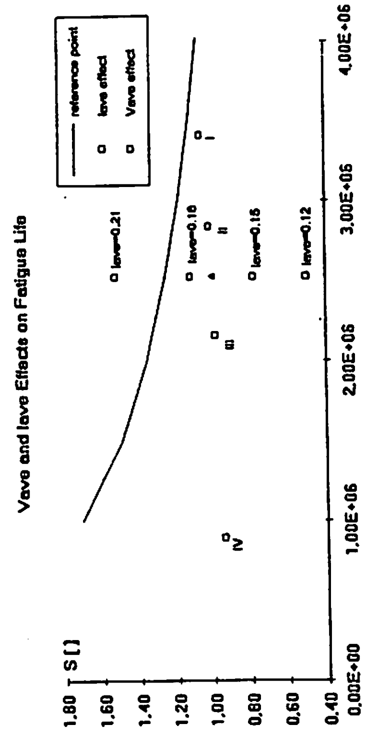

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CONCLUSIONS

- Turbulence intensity is one of the key parameters for fatigue life.

- Turbulence intensities specified by the IEC standard classes do not lead to a conservative approach.

DEFINING THE NORMAL TURBINE INFLOW WITHIN A WIND PARK ENVIRONMENT

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Introduction

This brief paper discusses factors that must be considered when defining the "normal" (as opposed to "extreme") loading conditions seen in wind turbines operating within a wind park environment. We define the "normal" conditions to include fatigue damage accumulation as a result of

- *start/stop cycles*
- *emergency shutdowns*
- *the turbulence environment associated with site and turbine location.*

We also interpret "extreme" loading conditions to include those events that can challenge the survivability of the turbine.

Loading Characteristics Responsible for Maximum Fatigue Damage Accumulation

Recent analyses of the loading events associated with turbine rotor blades constructed of composite materials have shown that the bulk of the fatigue damage is associated with infrequent (or low-cycle), high-amplitude (peak-to-peak load) events. This is particularly true of blade materials that are characterized by a high S-N exponent.

We recently analyzed two sets of extensive root flapwise bending moment measurements taken from two stall-controlled, rigid-hub Micon 65 turbines and an NPS-100 teetered-hub turbine. The blades of these rotors were of similar length and weight. We used rainflow counting to determine the alternating (p-p) stress cycle distributions seen by these three machines over record lengths of 67.5 and 70.1 hours, respectively, in wind park environments. Figure 1 compares the results for the rigid and teetered rotors. The maximum cyclic stress reduction for the teetered rotor occurs near 15 kNm but asymptotically approaches the rigid ones at both the high- and low-cycle extremes. Above a p-p value of 15 kNm, both hub designs exhibit a decaying exponential distribution, as is indicated in the figure.

The region of the curves of Figure 1 above p-p values of 15 kNm is the greatest concern from the viewpoint of fatigue damage accumulation. It is therefore very important, when defining the "normal" loading environment for a wind park, to identify such low-cycle events and include them in any dynamic simulations.

Impact of Coherent Turbulent Structures

The consequences of a turbine rotor blade encountering a coherent or organized patch of turbulence are demonstrated in Figures 2 and 3. Figure 2 plots the root edgewise bending moments from Blade No. 1 of two, side-by-side, Micon 65 turbines. One of the turbines had blades based on the NREL (SERI) thin airfoil family and the other with refurbished, original-equipment AeroStar blades. Also presented are the root flapwise bending moments of the three blades on the AeroStar-equipped turbine. The plots indicate that the AeroStar rotor reacted differently to an excitation that lasted approximately 3-4 seconds.

The corresponding hub-height turbulent inflow characteristics are presented in Figure 3. Figure 3a shows the strong correlation of the instantaneous $u'w'$ and $v'w'$ shear or Reynolds stresses within the period of enhanced blade response. The estimated hub-elevation vorticity components (ω_i) and helicity ($u_i\omega_i$) time series are plotted in Figure 3b. These parameters indicate the existence of a vortical structure that could be responsible for the shear stress pattern in Figure 3a. The evidence implies a one-to-one correspondence between the enhanced cyclic activity on Blade No.1 of the AeroStar rotor and the presence of a vortical structure in the inflow.

We examined the inflow conditions associated with the largest observed root flapwise tension peak and one of the larger compression (negative) ones. Figure 4a plots a five-second record of the flapwise loads from each of the three blades on the NREL rotor. The largest excursion occurs on Blade No. 3. The remaining two blades also are affected but to lesser degrees perhaps indicating that a coherent structure is convecting through the rotor disk. The enhanced loading extends to a period of about 2 seconds. The corresponding hub-height estimated vorticity/helicity record also lasts about the same amount of time. When the later is aligned with the Blade No. 3 peak of Figure 4a, the plot of Figure 4b results. Similarly, Figure 5a documents the peak compression load experienced by Blade No. 2. Again, the corresponding vorticity/helicity record is superimposed in Figure 5b, *but no time alignment has been performed.* The plots of Figures 4 and 5 do seem to support the hypothesis that organized, vortical structures are indeed connected with large induced blade stresses.

We looked more closely at the population of inflow conditions connected with the 25 largest flapwise stress cycles seen on either of the two Micon 65 rotors. In applying damage theory, it is assumed that the rotor materials have an *infinite memory.* This requires that all cycles must be closed to assess the corresponding damage. When the entire 67.5-hour record was rainflow counted as a single time series, a significant number of large-amplitude cycles were found that spanned the original ten-minute records. Figure 6 plots the largest maximum and minimum pairing found in the data set from the NREL-equipped rotor. The period between the minimum (compression) and positive (tension) peaks was 43 hours or almost three days. From a meteorological point of view, the conditions associated with each of the peaks can be considered *independent events.* Thus, we can look at the meteorological conditions associated with the population of the peak tension and compressional stress events independently also. We did that and found the following:

- *All of the tension peaks associated with the largest stress cycles occurred during slightly stable flows emerging from a deep canyon southwest of the wind park.*
- *The common time of occurrence was 22 h local standard time.*
- *The negative (compression) peaks of these cycles occurred during **slightly more stable** conditions centered near 04 h.*

The identification of these high-stress loading events, and the inflow conditions associated with them, has raised the following questions that will need to be answered in the near future:

- *How often can these large peaks be expected to occur?*
- *What are the appropriate statistical models to describe the distributions of such events?*
- *What are the turbulence conditions associated with them?*
- *Can such inflow conditions be simulated for use by dynamic simulation codes such as* ADAMS® *(Automated Dynamic Analysis of Mechanical Systems)?*

The Need for Stochastic 3-D Turbulence Simulation

Events such as those described above are impossible to simulate using only the longitudinal (*u*) component of the wind even if it is stochastic. A *full-vector* or three-dimensional simulation is required that includes not only spatial coherence but local cross-axis correlation as well. The latter is needed to simulate the dynamic shearing stress fields observed in actual flows. It is not clear which fluid dynamics parameter or parameters are the best indicators of the coherent turbulence that is responsible for the increased dynamic loading of wind turbines. We hope to answer this question in the near future with further analysis and field measurements.

We have used the computational kernel of the SNLWIND Code developed by Paul Veers of Sandia National Laboratories [1] as a basis for achieving a full-vector simulation. The objective of this work has been to develop the ability to simulate a *statistically relevant* ten-minute record of the three-dimensional wind field found in and near a large wind farm. This simulation also includes, at least statistically, the temporal and spatial variations of coherent structures embedded in the more random inflows found in these locations.

The modeling of the turbulent inflows upwind, downwind, and within a large wind farm was based on extensive measurements taken at a large wind farm in San Gorgonio Pass in southern California [2,3,4]. The methodology used to expand the SNLWIND Code to a full-vector simulation included:

- *Identifying suitable homogeneous terrain spectral models for each of the three wind components (u,v,w) for use as references*
- *Developing empirical "target" velocity spectral scaling based on the measurements taken in San Gorgonio*
- *Developing empirical relationships for the vertical coherence of the longitudinal (u) and crosswind (v) wind components*
- *Deriving empirical relationships between the normalized cross-axis correlations* (r_{ij}) *and boundary layer scaling parameters*

We used the homogeneous (smooth) terrain models of Olesen, Larsen, and Højstrup [5] as target spectra references. Local spectral scaling was accomplished by applying empirically derived ratios to the appropriate homogeneous terrain model. It was necessary to include up to three spectral peaks to describe the observed 10-minute spectral variation distributions. For example, to describe the crosswind (v) spectra downwind of the wind farm under *unstable* flows three peaks were required: $S_V(n) = S_L(n) + S_H(n) + S_{wake}(n)$. Here, the total spectrum is composed of low-frequency, high-frequency, and turbine wake contributions. The predicted crosswind (v) spectra for a mean hub-height wind speed of 12 ms^{-1} are plotted in Figure 7 for representative unstable, near-neutral, and stable conditions.

The spatial coherence was introduced using an exponential decay model using empirically derived coherence decrements based on the measurements upwind and downwind of the San Gorgonio wind farm. It was found that these decrements were monotonic functions of the hub-height mean wind speed. The observed decrements and corresponding linear regressions are plotted in Figure 8 for the horizontal wind components. Empirical normalized cross-axis covariances (r_{ij}) scaled with boundary layer parameters are used to crossfeed the wind components to simulate the observed shear stresses. For example, a reasonable facsimile of the shear stress means and distributions may be accomplished by crossfeeding the u component with only the v and w velocities per the relationship

$$u'(t) = u'(t) + \overline{r_{uv}}\, v'(t) + 2\overline{r_{uw}}\, w'(t).$$

When simulation locations are downwind and within the wind farm, all three wind components must be crossfed to achieve the reasonable replicas of the observed shear stress distributions.

Conclusions

There is strong evidence that coherent turbulent structures ingested by turbine rotors are responsible for the largest peak stresses seen in the flapwise and edgewise bending moments. These interactions produce a coherent (phase specific) response in the rotor and other structural components because of multiple structural modes being excited simultaneously. The most damaging tension stresses occur during boundary layer conditions most likely to support atmospheric wave motions and enhanced turbine wakes. The expanded version of the Veers SNLWIND Code (SNLWIND-3D) provides a much more realistic simulation of the turbulent inflow seen by turbines installed in various locations within a wind farm in complex terrain.

Acknowledgement

This work has been supported by the U.S. Department of Energy under contract DE-AC02-83CH10093.

References

1. Veers, P., "Three-Dimensional Wind Simulation," SAND88-0152, Sandia National Laboratories, March 1988.

2. Kelley, N.D., "An Initial Look at the Dynamics of the Microscale Flow Field within a Large Wind Farm in Response to Variations in the Natural Inflow," SERI TP-257-3591, Solar Energy Research Institute, October 1989.

3. Kelley, N.D. and A.D. Wright, "A Comparison of Predicted and Observed Turbulent Wind Fields Present in Natural and Internal Wind Park Environment," NREL TP-257-4508, National Renewable Energy Laboratory, October 1991.

4. Kelley, N.D., "Full Vector (3-D) Inflow Simulation in Natural and Wind Farm Environments Using an Expanded Version of the SNLWIND (Veers) Turbulence Code," NREL TP-442-5225, National Renewable Energy Laboratory, November 1992.

5. Olesen, H.R., S.E. Larsen, and J. Højstrup, "Modeling Velocity Spectra in the Lower Part of the Planetary Boundary Layer," *Boundary-Layer Meteorology*, Vol. 29, 1984.

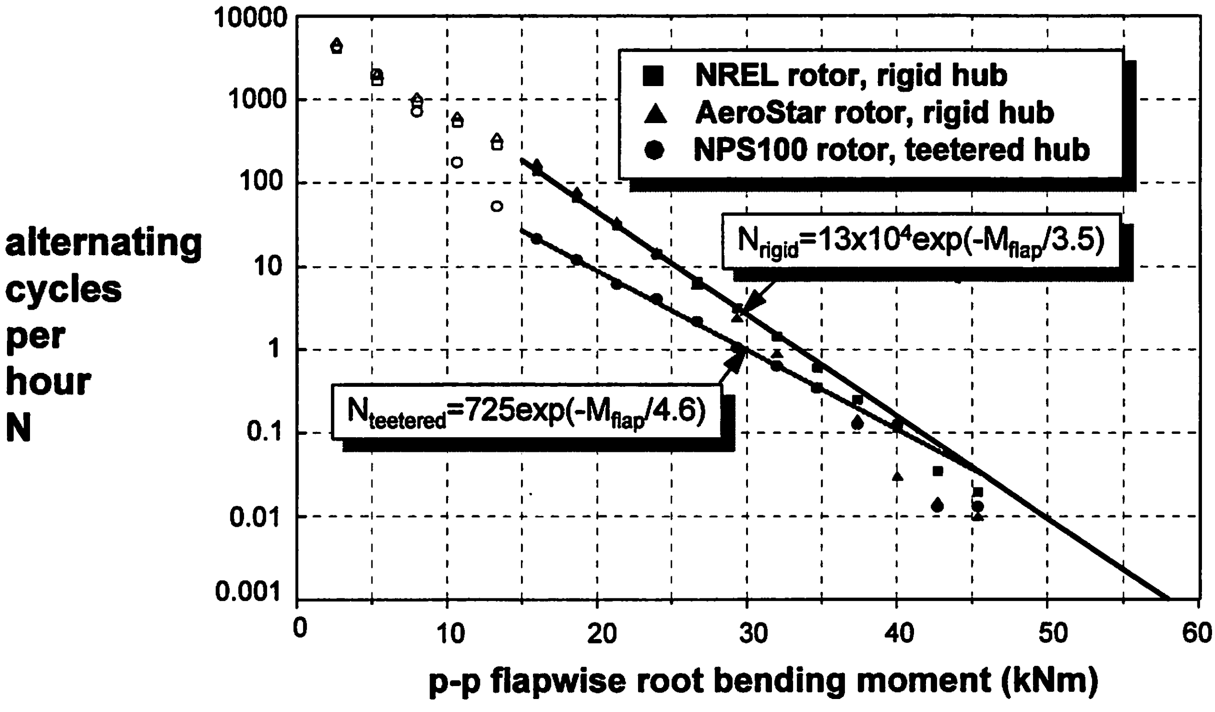


Figure 1. Comparison of rigid- versus teetered-hub low-cycle alternating root flapwise bending loads.

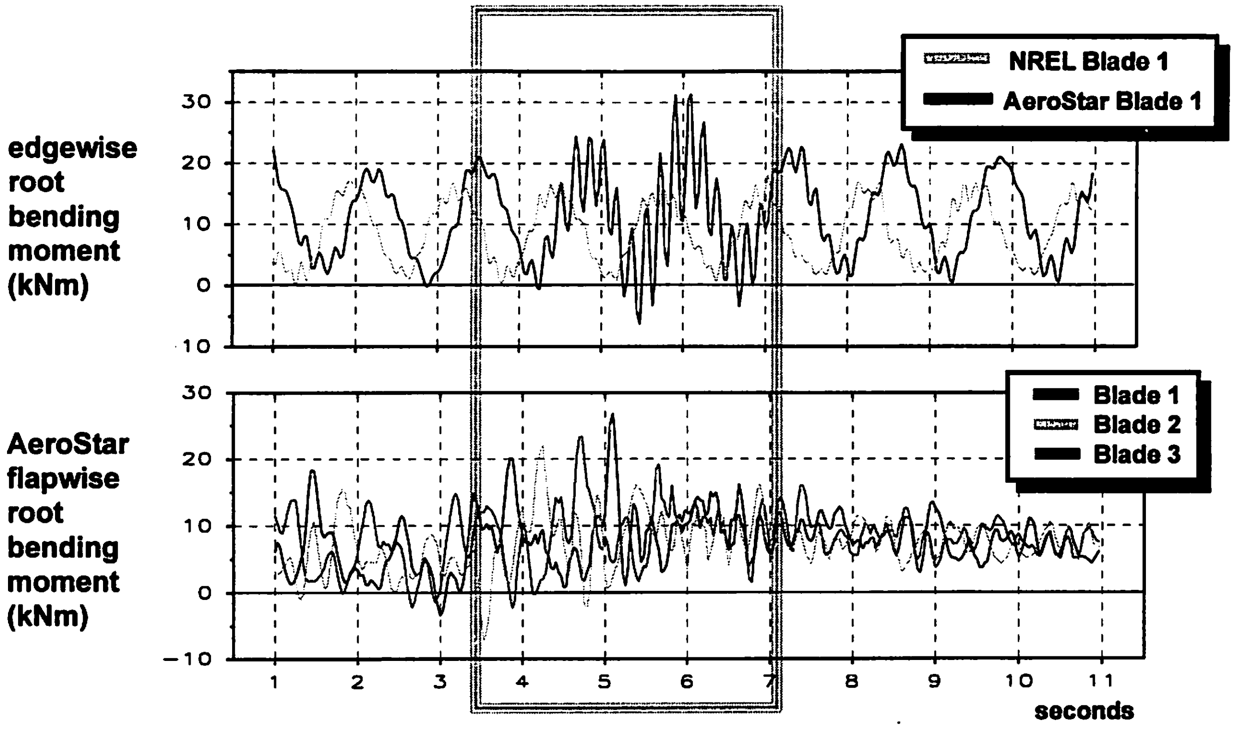


Figure 2. An example of a rotor encountering a coherent turbulent structure.

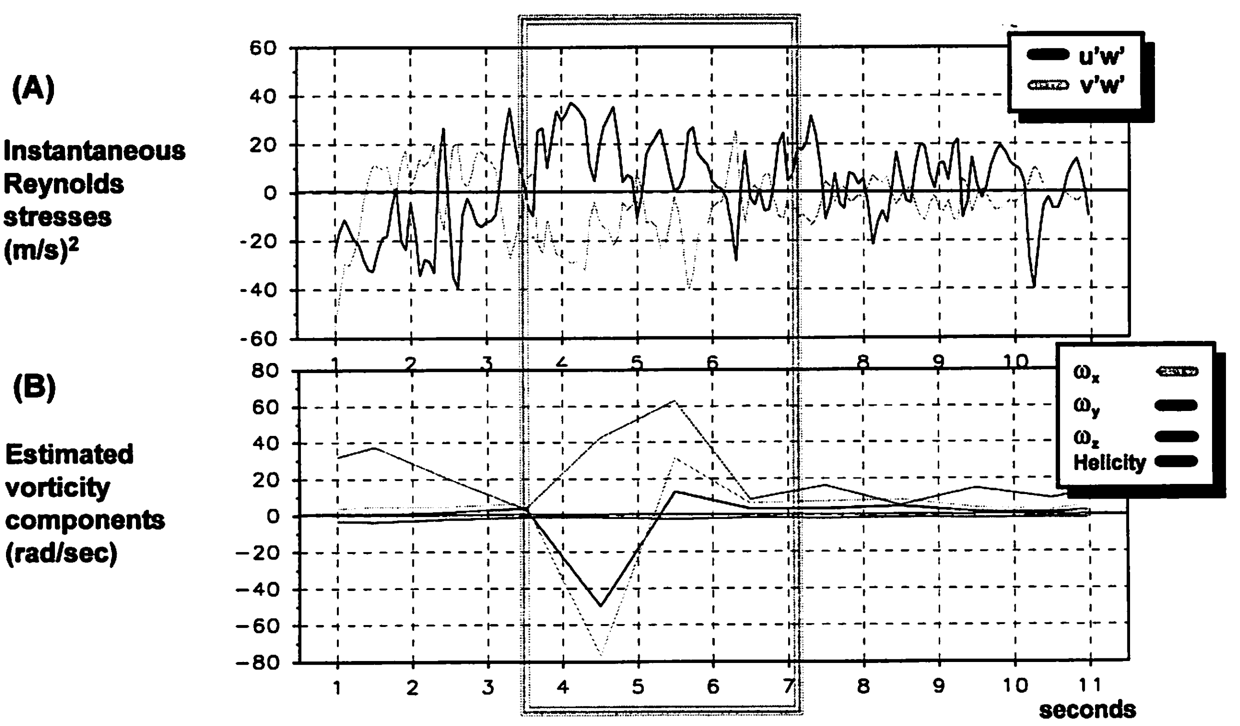


Figure 3. Turbulence characteristics at hub height associated with the response shown in Figure 2.

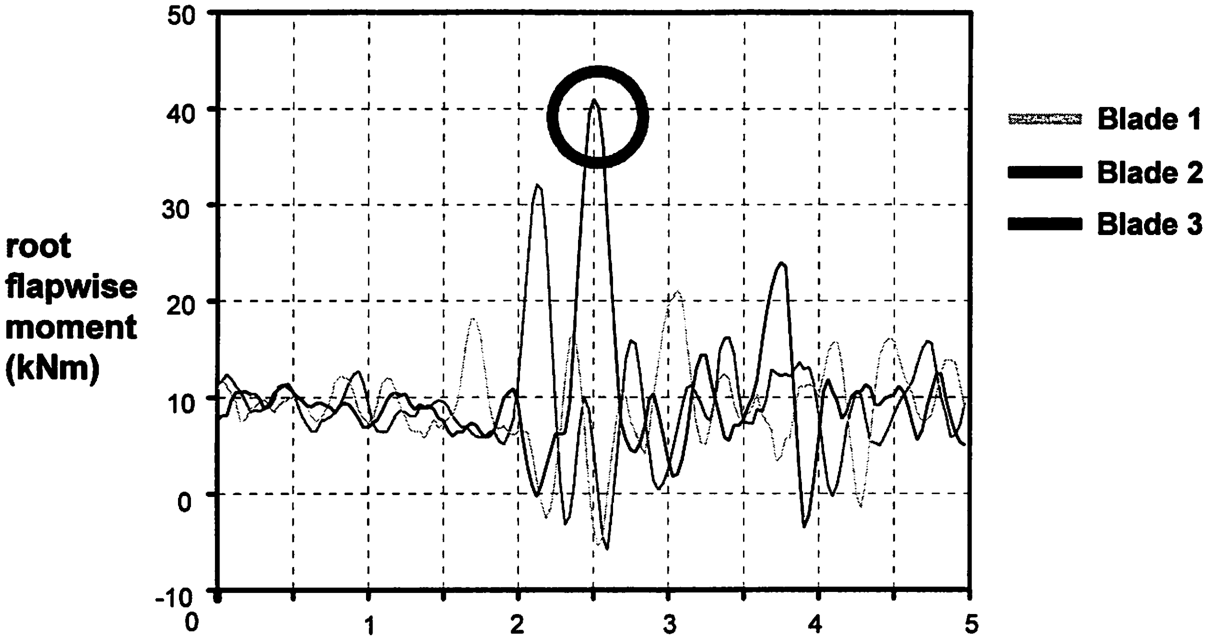


Figure 4a. Largest positive (tension) peak stress cycle observed for the NREL rotor.

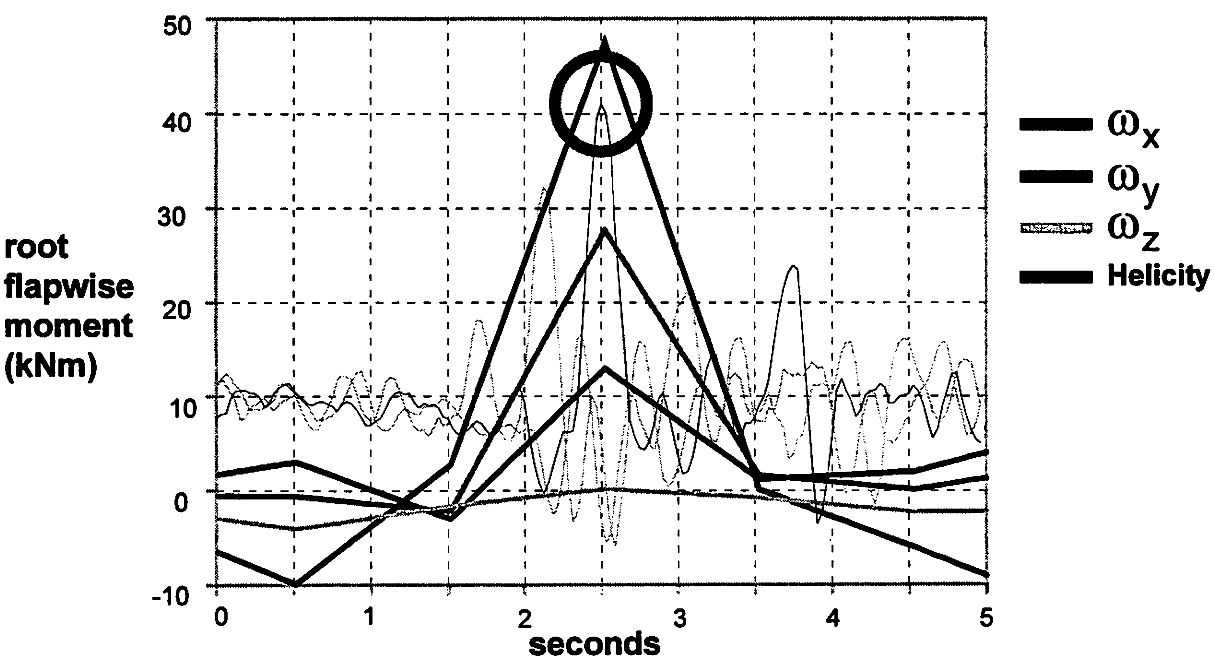


Figure 4b. Hub-height vorticity/helicity estimates aligned with peak flapwise moment.

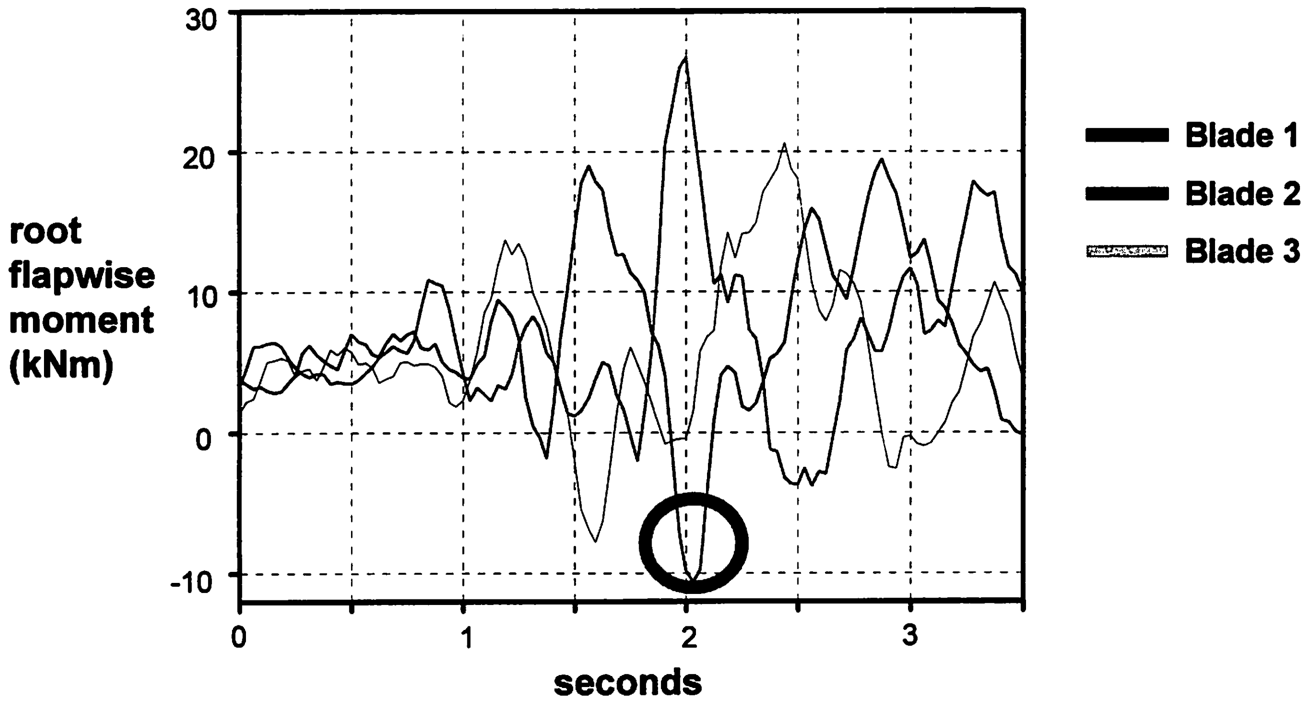


Figure 5a. Large negative (compression) peak stress cycle observed for the NREL rotor.

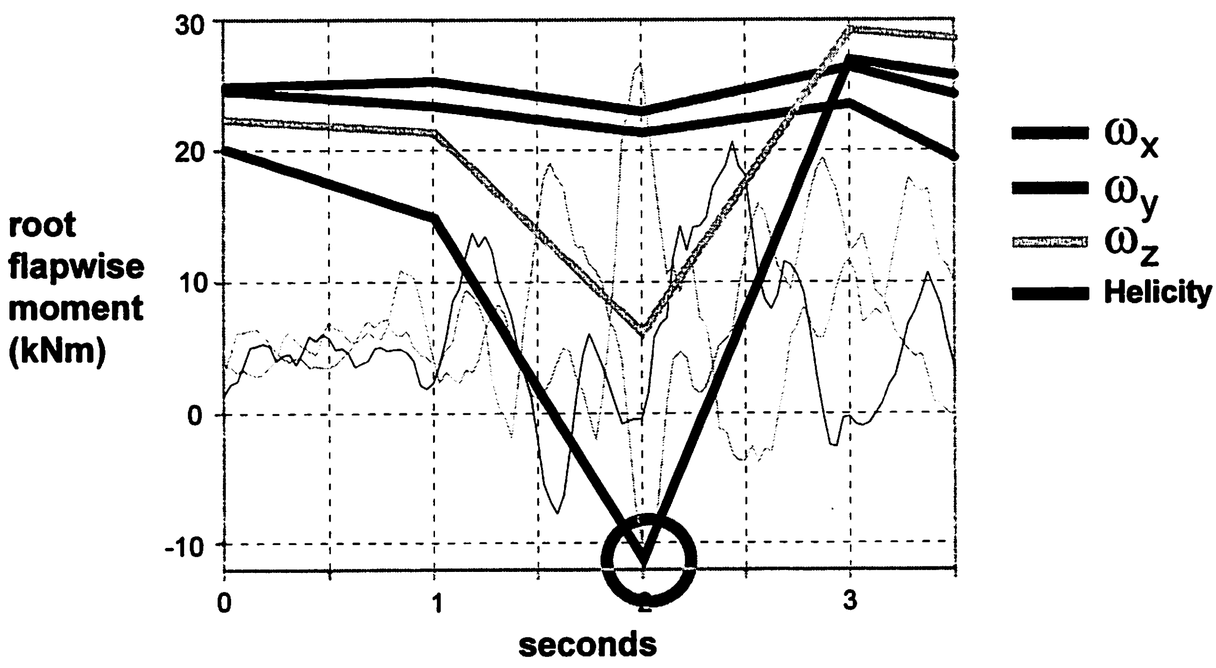


Figure 5b. Hub-level vorticity/helicity estimates overlaid on the record containing the negative peak.

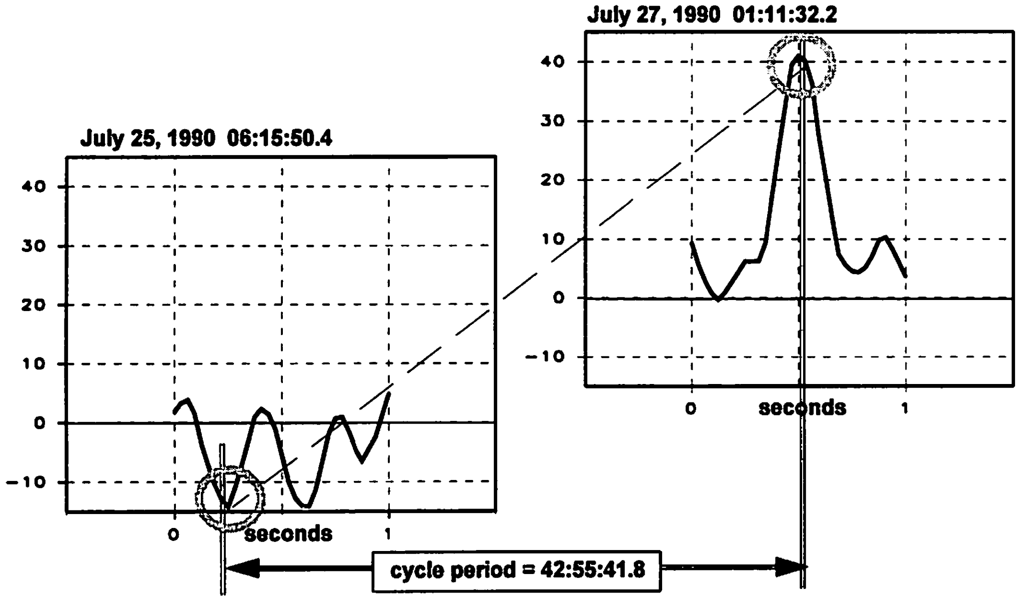


Figure 6. Largest root flapwise bending cycle for the Micon 65 with the NREL rotor.

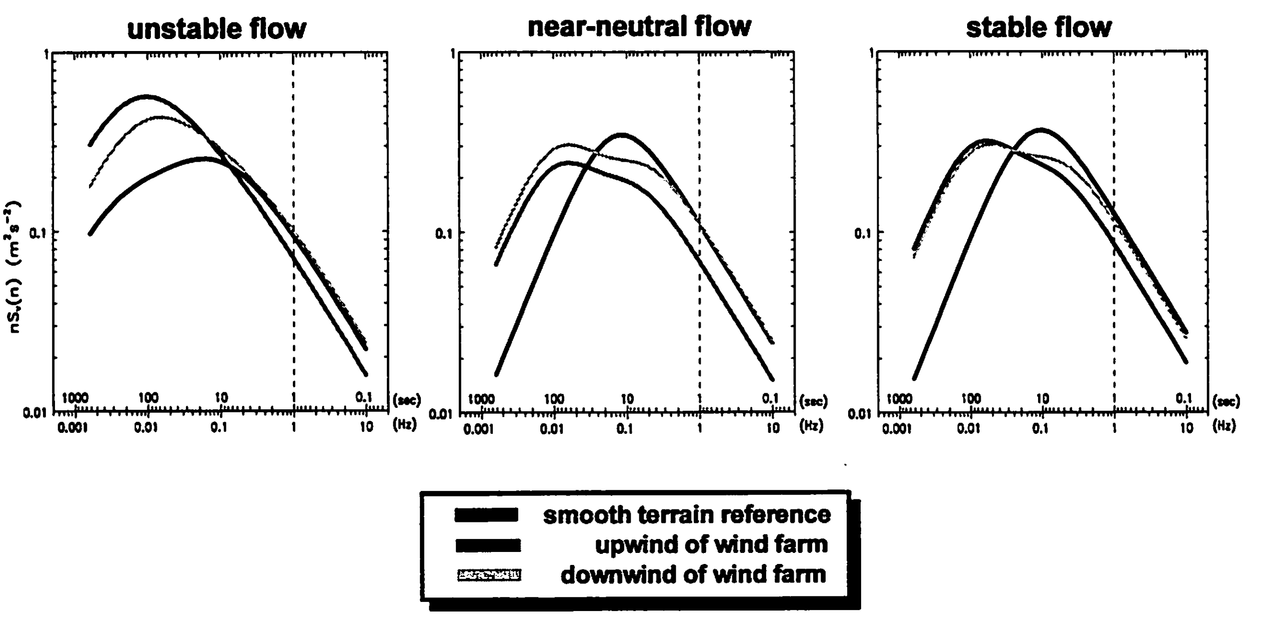


Figure 7. Comparison of predicted crosswind (v) velocity spectra for a 12 ms^{-1} mean wind speed.

Measured Vertical Coherence Decrements

[*Coh²(n)*]

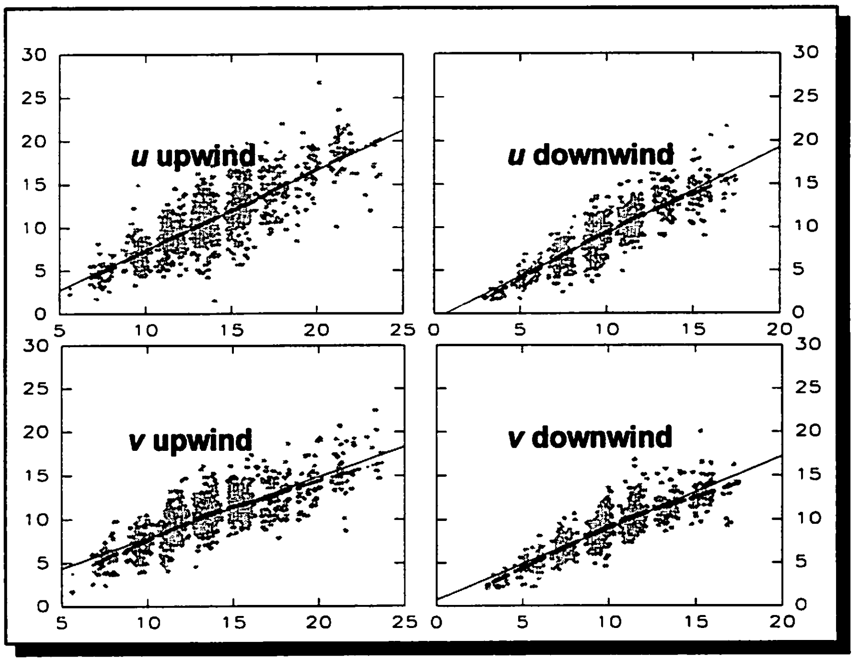


Figure 8. Observed vertical coherence decrements with linear regression lines shown.

WIND CLIMATE AT A WINDFARM SITE

John Wills

1. INTRODUCTION

The Risø meeting was called to discuss the definitions of wind conditions used in the draft IEC Standard *Safety of Wind Turbine Generator Systems*. This paper describes measurements of wind speeds made at a typical small windfarm site at Cold Northcott, Cornwall, U.K. in the period August 1991 - March 1993, and makes comparisons with the recommended values in the draft document.

2. MEASUREMENTS

Wind speeds on the site were measured with Vector Instruments A100K cup anemometers. These are of light aluminium construction with a starting speed of 0.25m/s and a claimed distance constant of 5m. Generally, ten-minute averages and peak values are recorded for later retrieval and analysis, using the cellular phone network for data transmission. The anemometers and other instruments are mounted at heights up to 50m on a free-standing (unguyed) lattice tower, and corrections to the readings for flow distortion caused by the tower have been obtained from wind-tunnel tests on a 1:25 scale model.

The windfarm is located in typical English countryside, gentle rolling landscape with hedges and few trees, used mainly for grazing. Most of the measurements were made in the 12 months August 1991 - July 1992, before windfarm construction started, so the results are typical of the undisturbed site.

Generally, the results have been converted to hourly mean values, standard U.K. meteorological practice, although raw samples at a rate of 2Hz have also been recorded for conversion to spectra, etc. Fig. 1 shows the monthly and annual mean for August 1991 - July 1992 at 25m height, the hub height of the 300kW generators used on the site. The annual mean of 6.93m/s, believed to be somewhat lower than the long-term mean, puts the site in the Class III category of the IEC standard. It is interesting to note that the monthly averages do not differ from the annual by more than $\pm 25\%$ except in the case of March, traditionally the windiest month.

Fig. 2 shows the annual mean wind speed profile normalised to the 25m height value. At lower heights the profile conforms quite closely to the IEC power-law index of 0.2, but above 25m the fit is much closer to an index of 0.14. We expect the lower value of the index to be more appropriate for the terrain at the site, based on past experience, and regard a value of 0.2 as somewhat unrealistic to be applied as standard to all windfarms. The fact that 0.2 fits our measured data at heights below 25m is not considered to be support for such a value, because results at the site were strongly affected by local disturbances in the form of hedges and walls in the lowest 3-5m, close to the towers.

A similar effect can be seen in the log profile plot of Fig. 3, where results above 25m fit well to a log law $u/u_* = 2.5 \text{ lu } (z/z_0)$ with $z_0 = 0.03$m. A value of z_0 of 0.03m is widely accepted as appropriate to typical grassland with occasional trees, hedges, etc, such as that at this site, and should certainly extend down 10m at an otherwise undisturbed site.

Fig. 4 shows the vertical profile of turbulence intensity, as recorded by the cup anemometers. For comparison, the IEC draft standard assumes a uniform turbulence intensity of 0.17 at hub height for all classes. The site measurements yield a value of 0.16 at the hub height of 25m, in fairly close agreement, but the value at other heights depends on how turbulence intensity is defined. If it is based on local mean velocity, it varies from 0.18 at 10m height to 0.14 at 50m; if it is normalised on the 25m height velocity, it is almost constant at 0.15-0.16 from 10m to 50m. If the IEC definition is interpreted in this manner, agreement with these measurements is close, except that the intensity is closer to 0.15 than 0.17. The lower value is consistent with the lower roughness of the site observed in the mean wind speed profile.

Fig. 5 shows an estimate of the extreme hourly mean wind speed obtained from only 20 months of recorded data. The method is that described in ref. 1, although there it is assumed that 5–7 years of complete data are available. A peak value is taken from each storm (independent storms are separated by at least 2 days), and plotted as a Fisher-Tippett type I distribution. A least-squares straight-line fit is made to these points, from which the extreme value for any return period can be found. It is generally found that a better fit is obtained if dynamic head rather than wind speed (that is, $(\text{wind speed})^2$ rather than wind speed) is used for the ordinate, and this has been done here. The 50-year return period hourly mean wind speed is estimated at 32.7m/s. For comparison, the IEC value is 37.5m/s for a Class III site, the difference being attributable to the use of 10-minute rather than hourly means.

Finally, Fig. 6 shows a composite spectrum obtained from 58 sessions of 50-minute recordings of wind speed at 25m height samples at 2Hz. These spectra were recorded when the windspeed rose above 10m/s. The IEC draft spectrum has been fitted to the mean curve by eye, using the length scale L_x as the adjustment parameter, thus yielding a value of L_x of 137m. The fit is good except at the two extremes. At high frequencies, the measured spectrum falls because of inadequate frequency response of the cup anemometers. At low frequencies the IEC spectrum overestimates the energy by assuming that the turbulence energy fits a –5/3 power law at any frequency. Although this is a good assumption at medium to high frequency, it certainly does not apply at low frequency, as many studies have shown (e.g. ref. 2).

3. CONCLUSIONS

Measurements made at a windfarm site in Cornwall, U.K. have generally shown good agreement with the IEC draft standard. However, mean wind and turbulence profiles shown somewhat smoother site characteristics than those assumed in the draft standard.

REFERENCES

1. Cook, N.J. The designer's guide to wind loading of building structures. Part I. Background, damage survey, wind data and structural classification. Butterworths, London, 1985.

2. Kaimal, J.C., Wyngaard, J.C., Izumi, Y. and Coté, O.R. Spectral characteristics of surface-layer turbulence. *Quart. J. Roy. Met. Soc.* 98, 563-589.

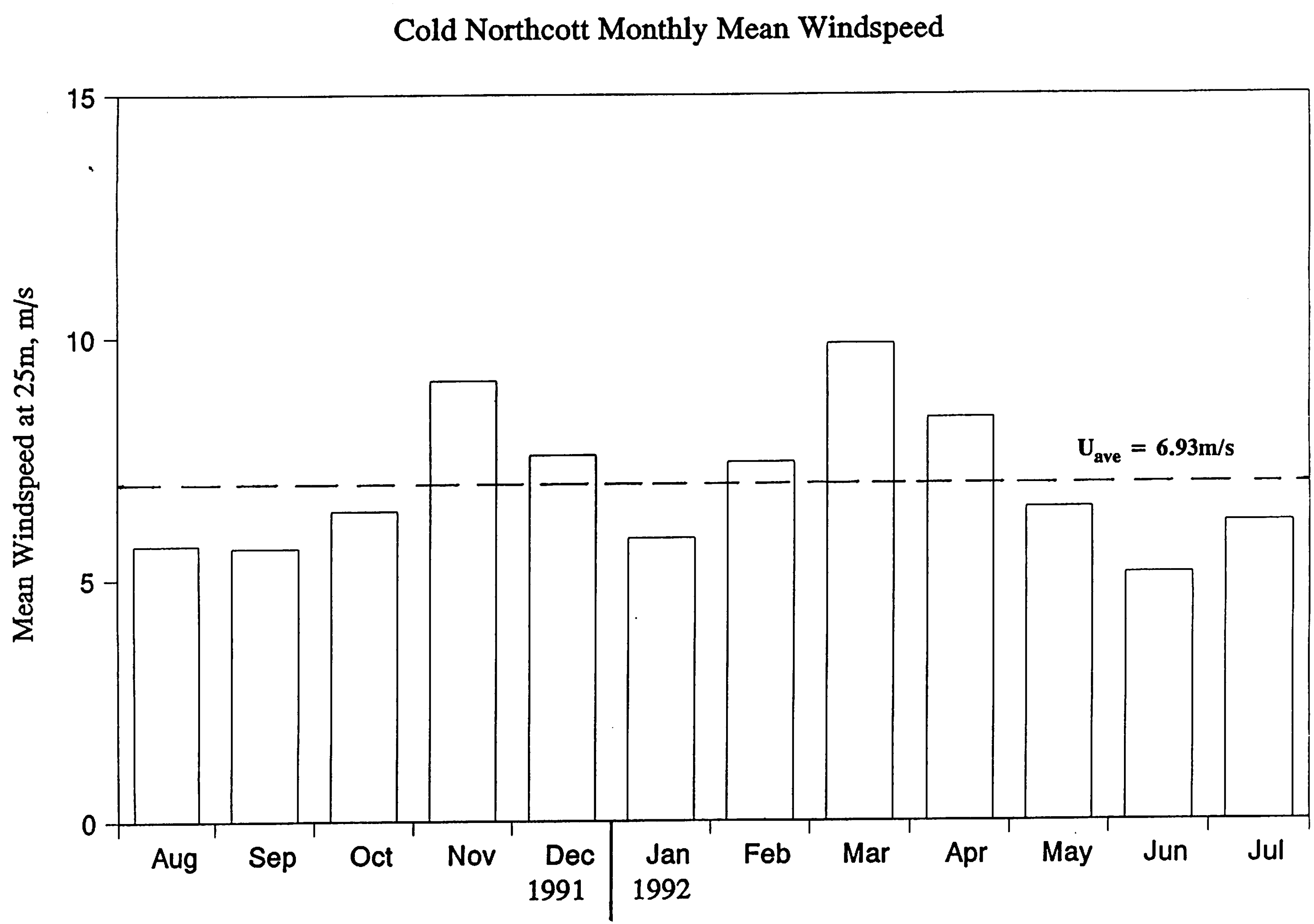


Figure 1 **Mean monthly wind speed at tower A50, 25m height**

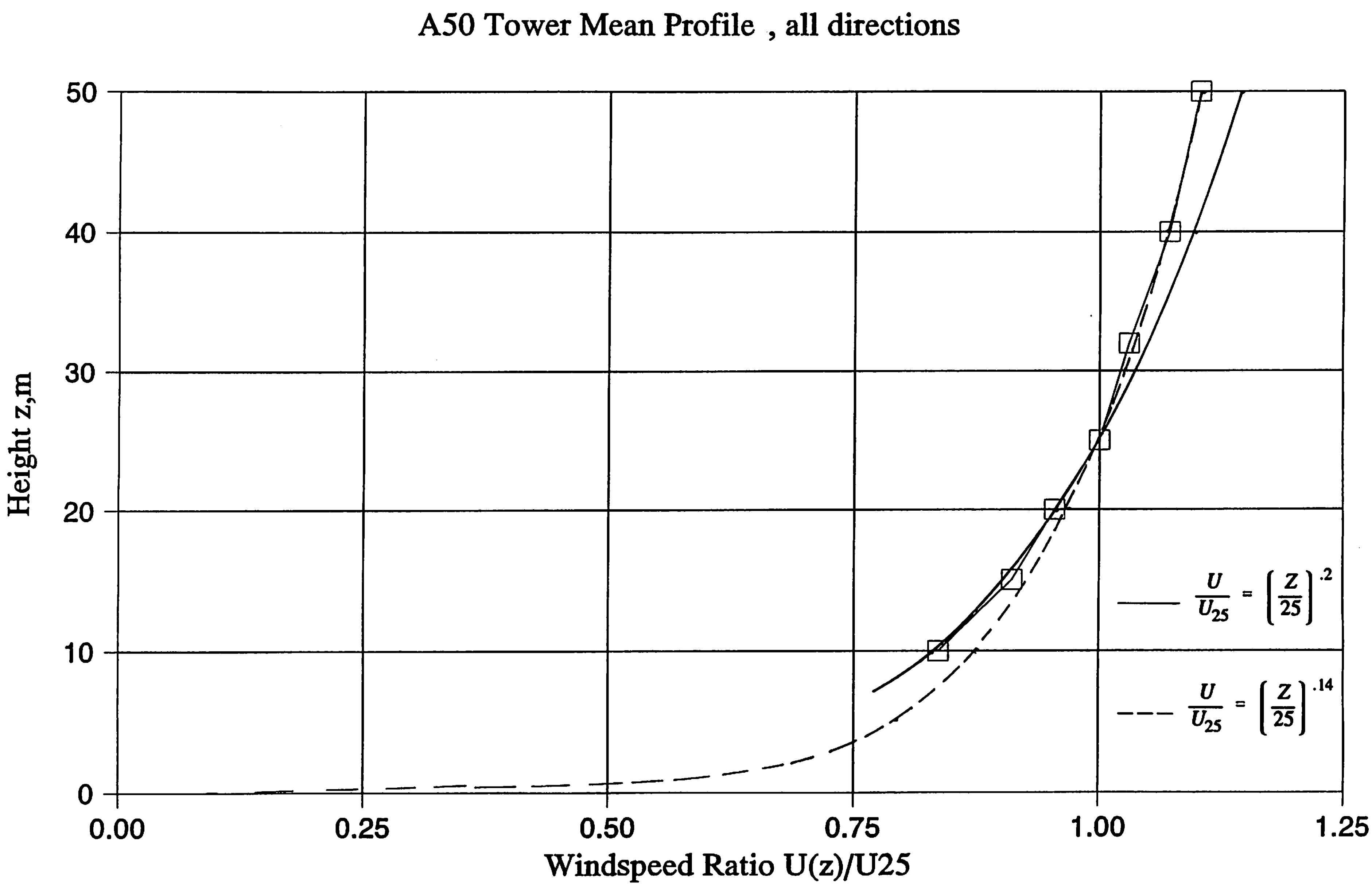


Figure 2 Mean wind profile at A50 tower, all directions combined

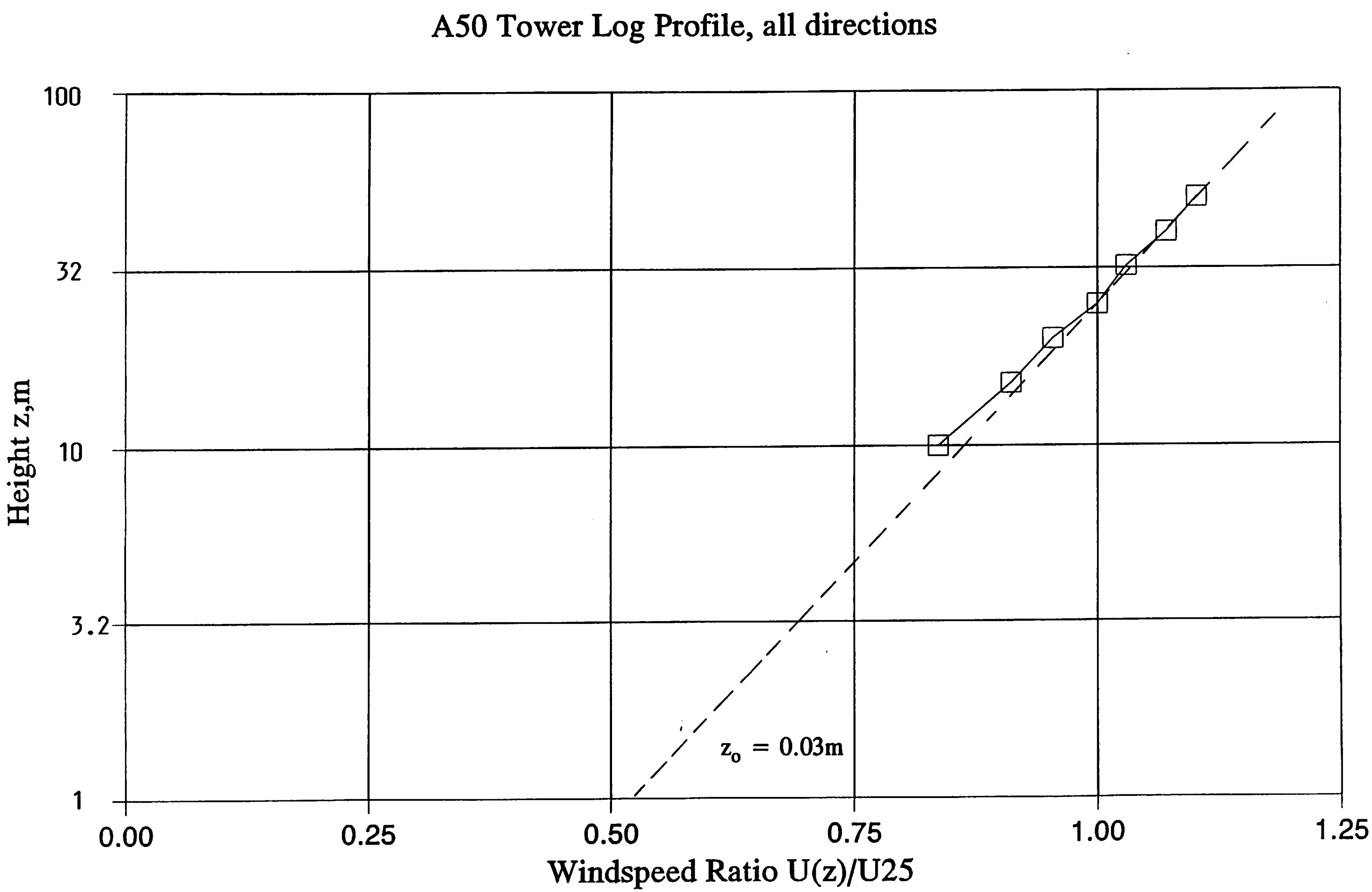


Figure 3 Mean wind log profile at A50 tower

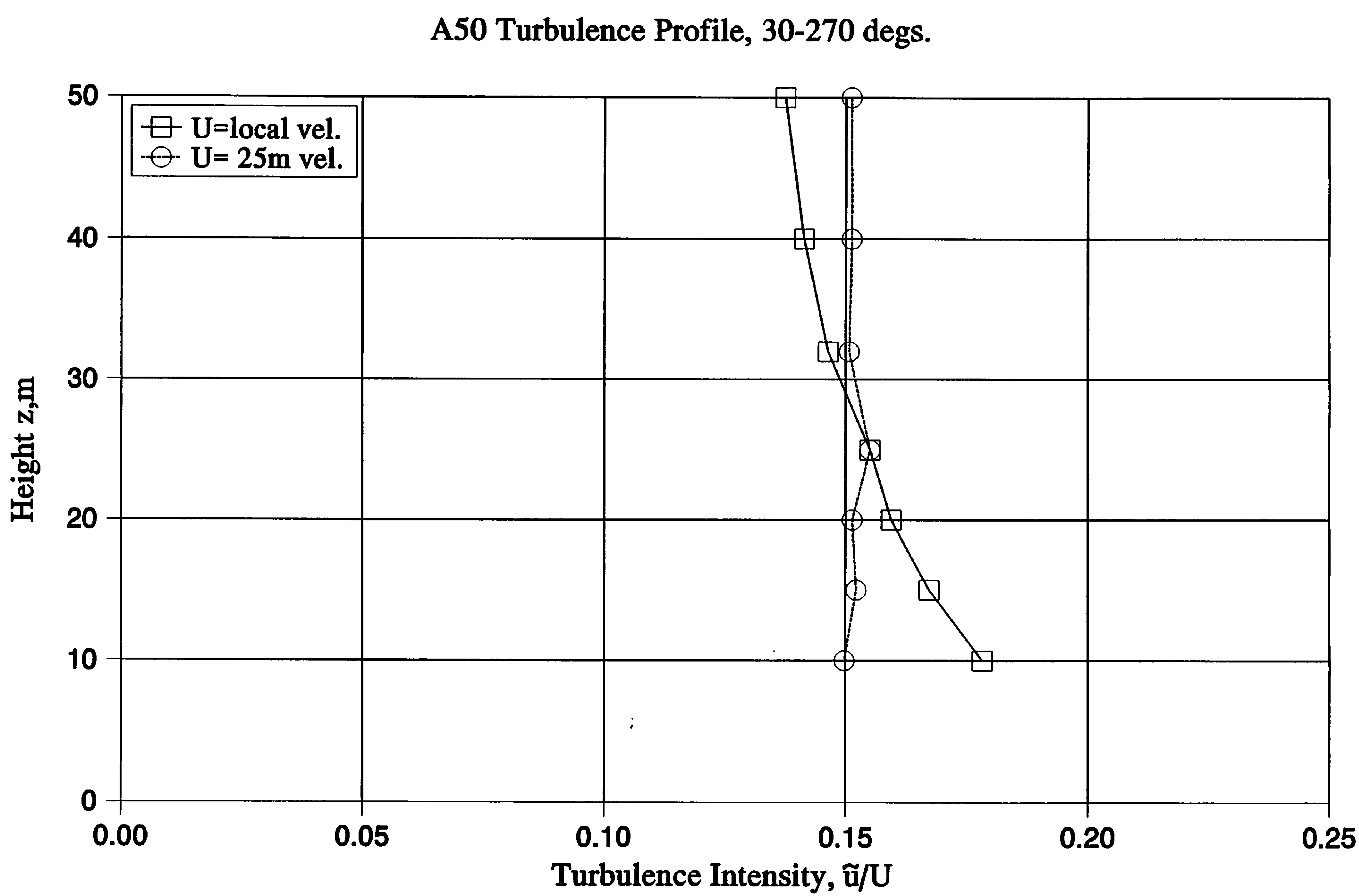
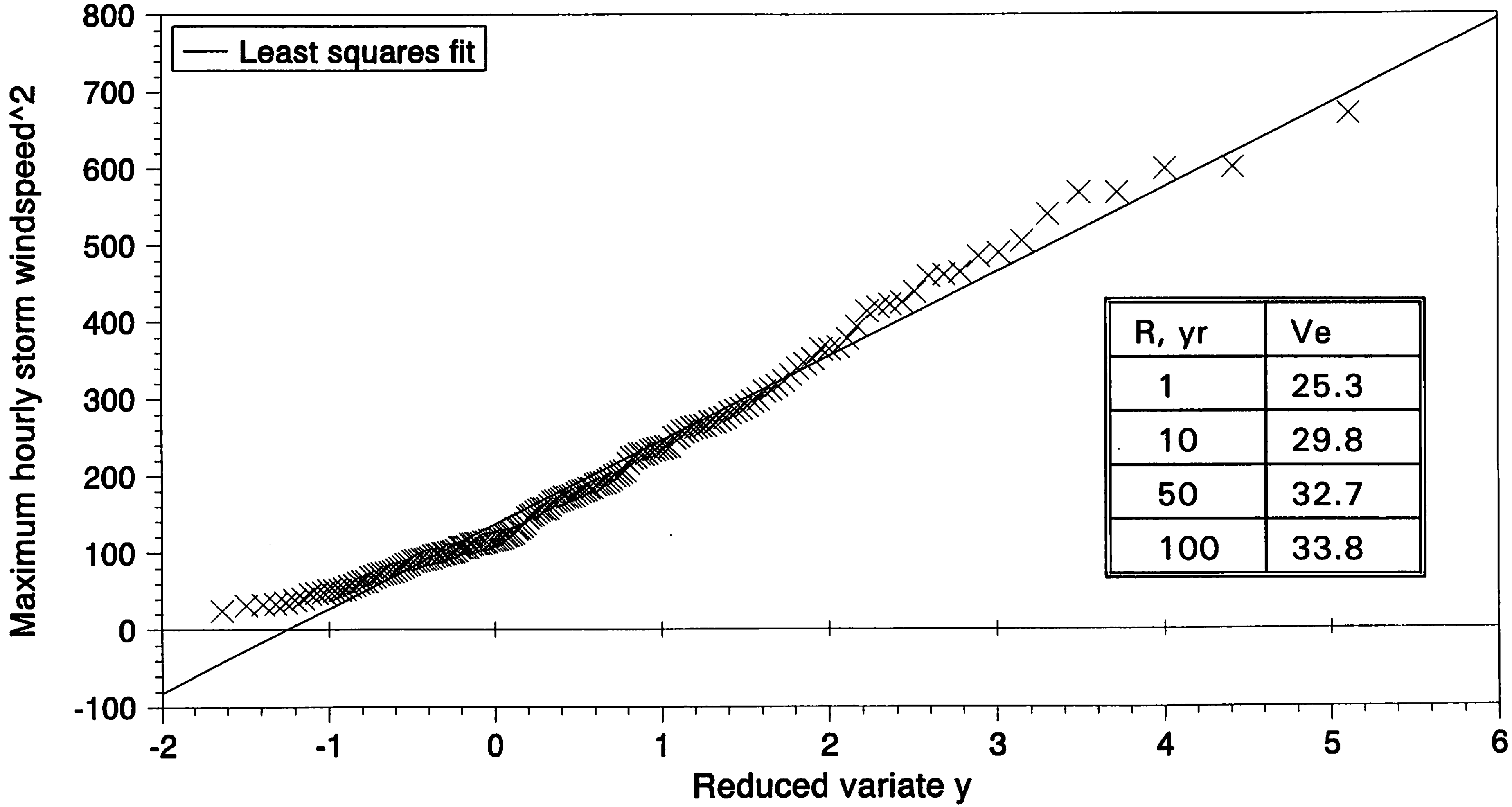


Figure 4 **Local turbulence intensity, ũ/U, at A50 tower, all directions 30°–270°**



R, yr	Ve
1	25.3
10	29.8
50	32.7
100	33.8

Mode = 136.6 $(m/s)^2$ Dispersion = 109.4 $(m/s)^2$

Figure 5 **Extreme value plot – windspeed squared – August 1991-March 1993**

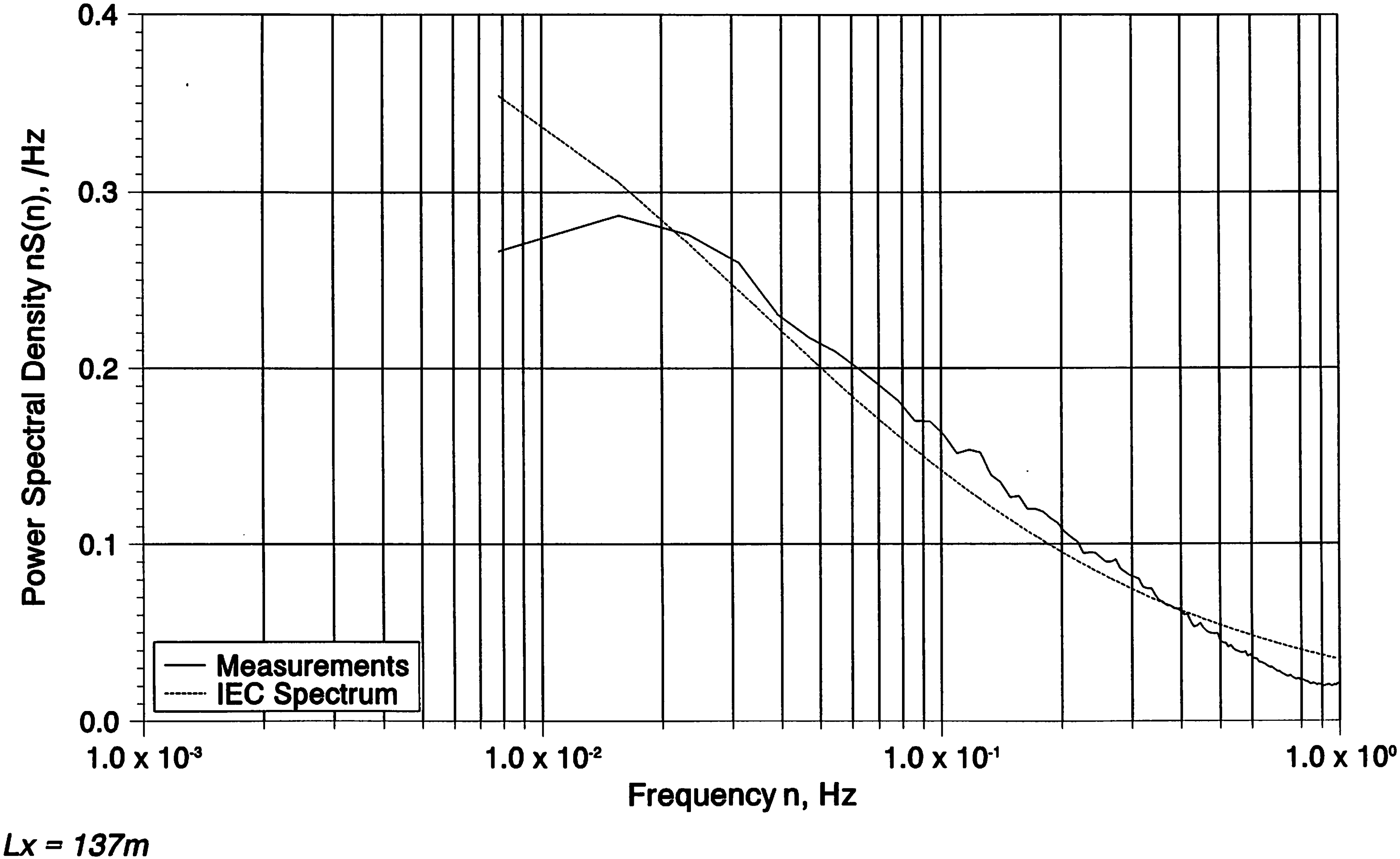


Figure 6 Cold Northcott Turbulence Spectra at 25m

Fatigue loads and fatigue spectrum due to wind, based on a wind matrix and dynamic calculations.

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Summary.

Designing wind turbines is very extensive. It comprises static as well as fatigue design. The static part depends on extreme conditions due to wind conditions and turbine situations. Fatigue loads may be divided in high cycle and low cycle fatigue. Load variations due to turbine rotation, space distribution of wind and dynamic respons of turbine structure contribute to high cycle fatigue loads. Low cycle loads are dominated by mean wind speed variations. Wakes, yawing and start/stopp situations also contribute to these fatigue loads. A total load spectrum applicable for design has to consider all these parts.

The aim of the presented method is to take this whole load spectrum into account [1]. Main parts of the method are the Rain Flow Count (RFC) wind matrix [2] containing wind data and a time simulation program (VIDYN) capable of calculating loads, regarding dynamics of the turbine system .

The method is based on time and space behaviour of wind and from frequency point of view. This background is shown i fig 9

The wind matrix is based on long term wind measurements and contains at every mean wind speed statistical information of wind structures covering the turbine area. It also describes variations of mean wind speed, how often and how fast these variations occur. For the purpose of fatigue design these variations are also evaluated according the RFC-method, see fig 10.

Loads of different parts of the turbine system are calculated by the simulation program. The calculations are arranged in a way (see fig 14-16), where the mean wind speed is increased step-wise and at each mean wind speed different conditions are introduced, e.g. different space distribution of wind over the turbine area. Results from this only calculation are the relation of loads, levels as well as variations, due to all normal wind conditions including dynamics of the turbine. Loads at

special turbine situations as e.g. start/stopp, yawing and wakas are calculated seperately.

Load spectrum in the "RFC sense" is then easily created by using frequencies of wind situations in the RFC wind matrix in combination with calculated loads at these wind situations, see fig 17-19. Thus this load spectrum is based on spacial wind conditions at different mean wind speed as well as changes of the mean wind speed itself. Variabel speed of turbine rotation and influence of power control may also be treated directly in this way.

Load spectra are calculated for representative quantities of main parts of the turbine, e.g. blade, hub, nacelle and tower. Introduction of material properties, as allowed static and fatigue stresses makes, it possible to calculate what dimensions are required to fullfill these stress requirements, see fig XXX. In case of a total load spectrum the method takes static as well as fatigue demands into account and even tells the designer what design drivers there are.

Reference:

[1] :Calculation of total load spectrum and component dimensions of Wecs, based on wind matrix and simulation. Hans Ganander, IEA R&D WECs Annex XI Meeting at FFA 7-8 of march 1991.

[2] :Fatigue Design by using a modified RFC description of the wind. Hans Ganander and Hjalmar Johansson, AWEA, Honolulu, Hawaii 1988.

Introduction

Fatigue design of wecs is a very complex problem

- **lots of situations, especially due to wind situations**
- **representative set of situations**
- **normal as well as extreme situations (0.1 %)**

There are several uncertainties

- **aerodynamics**
- **structural dynamics**
- **material properties**

The designer has to ask questions, answer them and make decisions

To make that possible and practical, appropriate approximations has to be introduced. This is what engineering very often is about.

Fig 1

Designers situation

Determine dimensions of different components $(\sigma = \frac{M}{W} \leq \sigma_{allowed})$

- **blades**
- **hub**
- **shafts**
- **bearings**
- **nacelle structure**
- **tower**

Material properties

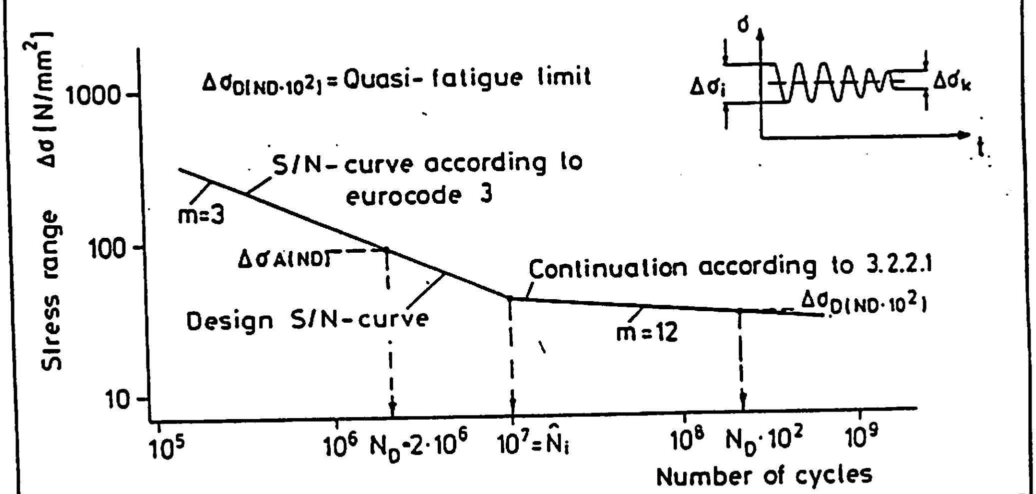
- **steel (welded, non welded, forged, cast iron,...)**
- **wood**
- **frp (laminar, matrix,...)**

Loads

- **static**
- **variable**

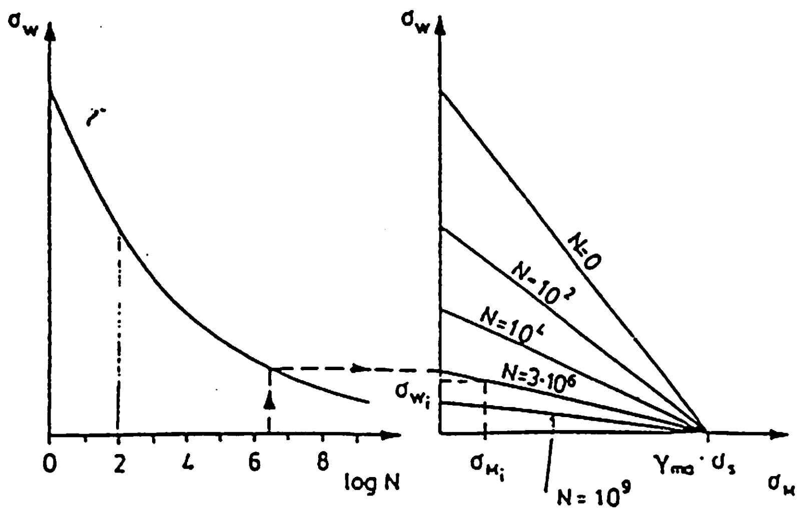
Fig 2

Diagrams for fatigue design, examples from Germanische Lloyd's Preliminary Regulation, June 1989.



S/N-curves for welded constructions general shape

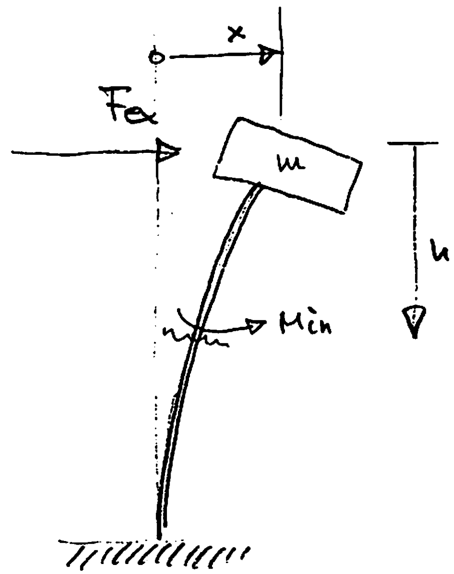
Fig. 6.2



Wöhler - Diagram

Goodman - Diagram

Fig 3



$$\sigma = \frac{M_{in}}{W} \leq \sigma_{allowed} \Rightarrow W \geq \frac{M_{in}}{\sigma_{allowed}}$$

$$M_{in} = (F_{ex} - m \cdot \ddot{x}) \cdot h$$

Determination of internal loads => { **External loads due to wind** / **Structural dynamics** }

Fig 4

Behaviour of wind

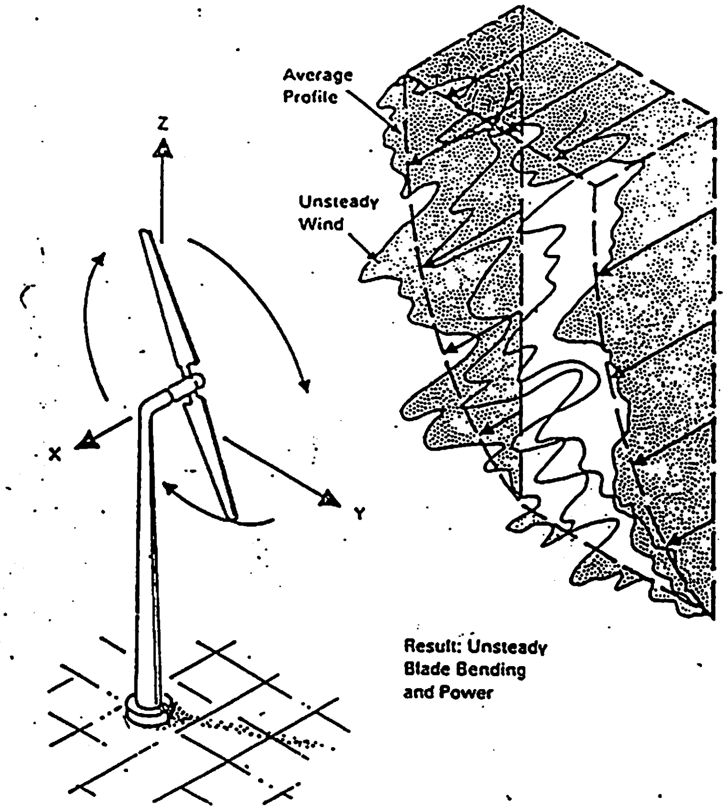
- time variations
- space distribution
  - shear
  - gradients
  - turbulance

How fast
How often
How strong

or

- ΔVv	Vertical shear
- ΔVh	Horisontal shear
- Δθ	Direction changes
- wakes	

Fig 5



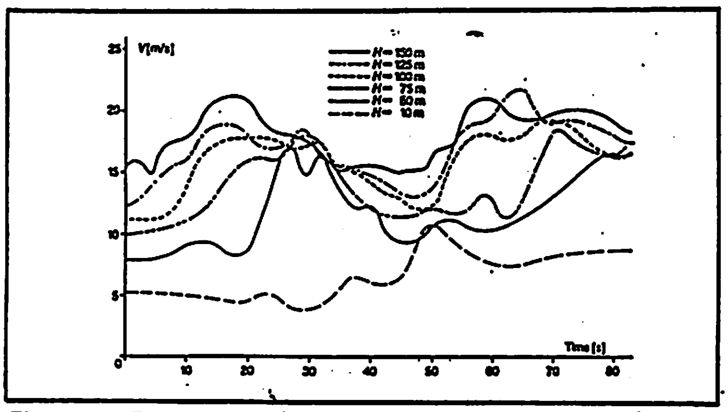


Figure 1. Extreme wind fluctuations at different heights plotted against time

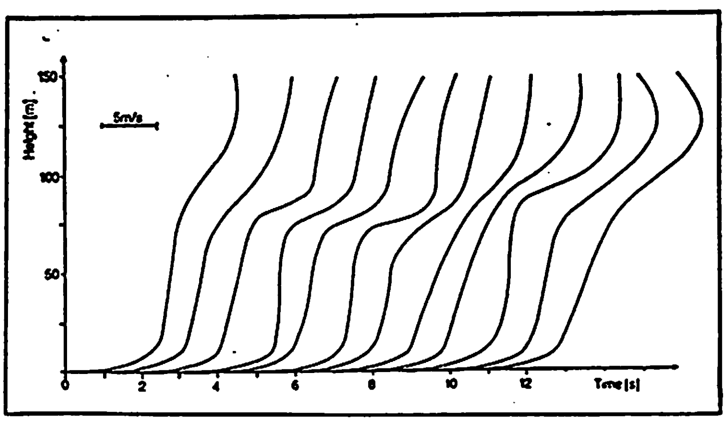


Figure 2. Wind velocity distribution at different times collected at the Growian site plotted against height and time

Fig 6

Turbulence spectrum and Coherence as function of frequency

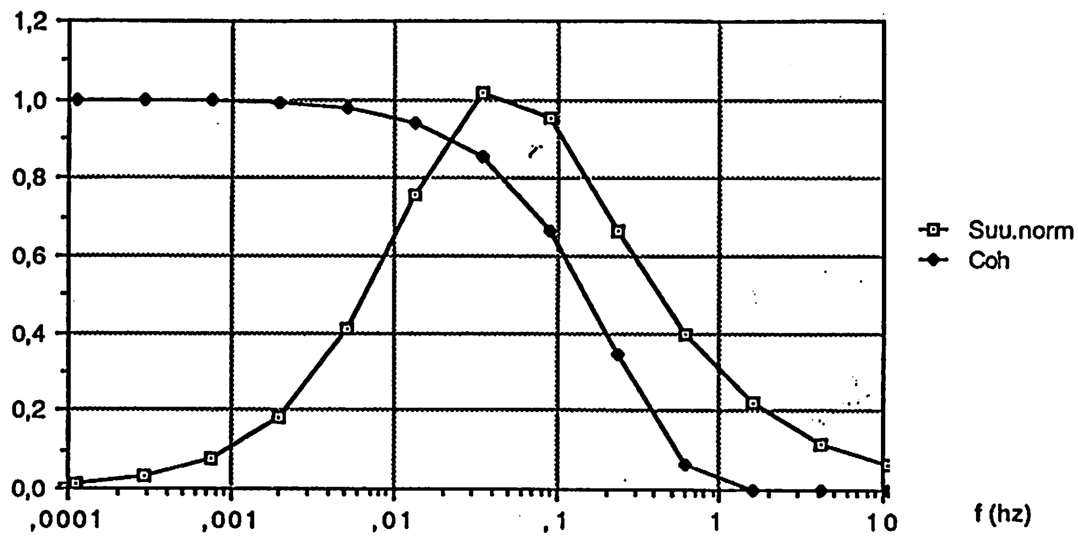


Fig 7.

Structural dynamics

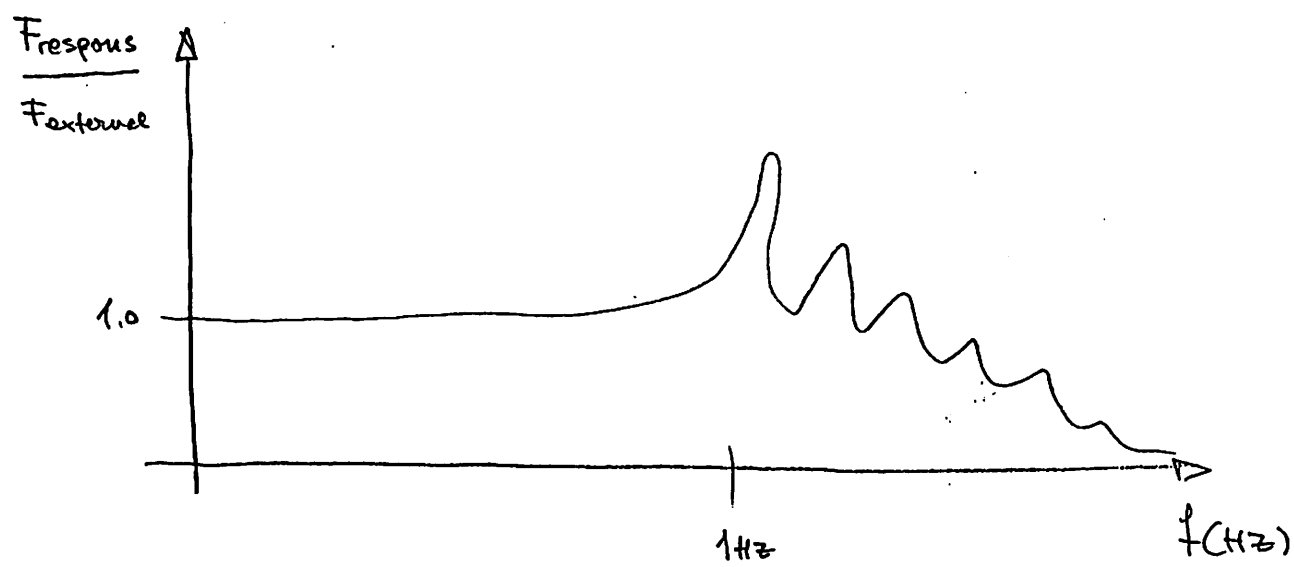
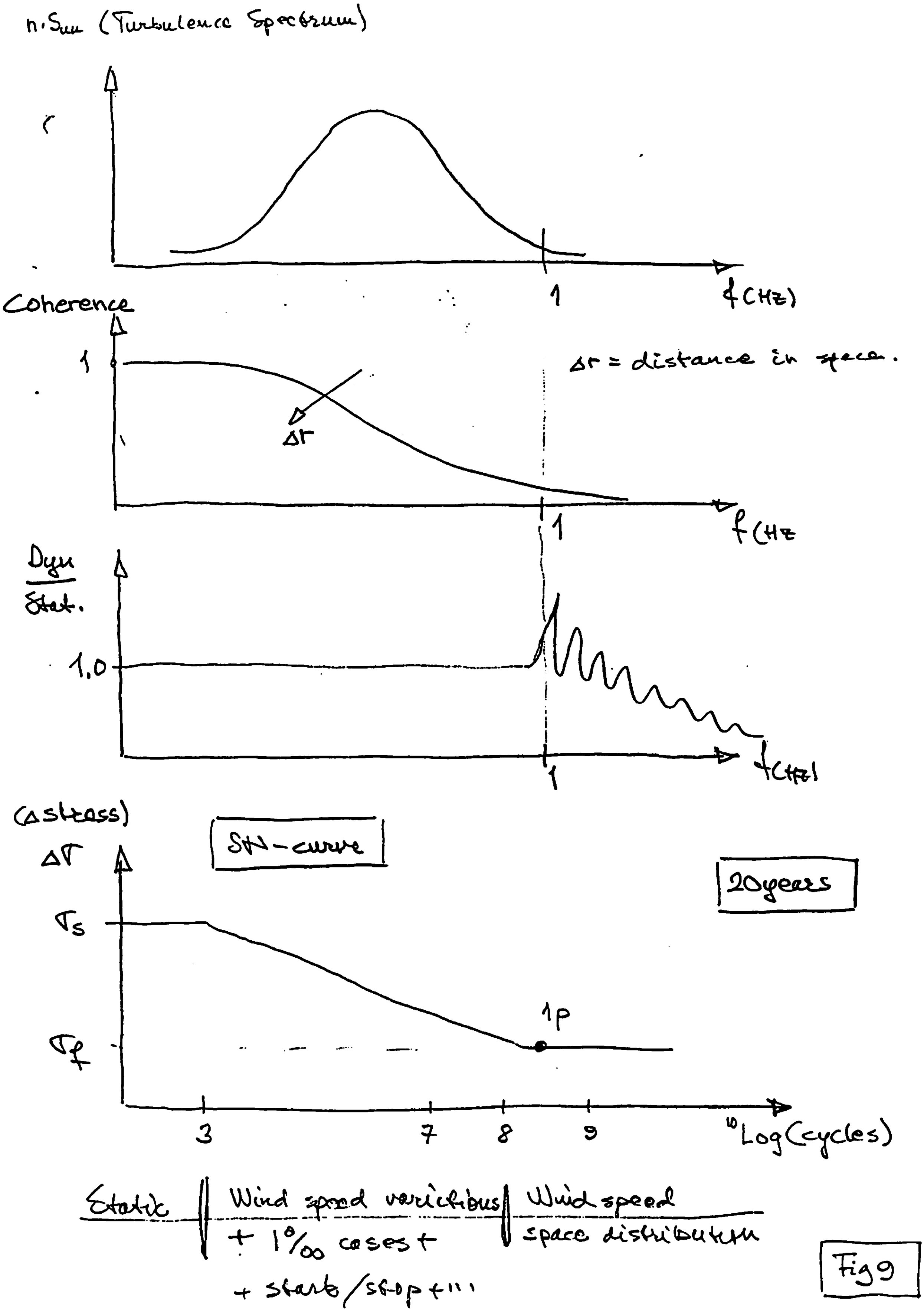


Fig 8

Basics about wind, dynamics and fatigue



Peak Valley -> RFC wind matrix

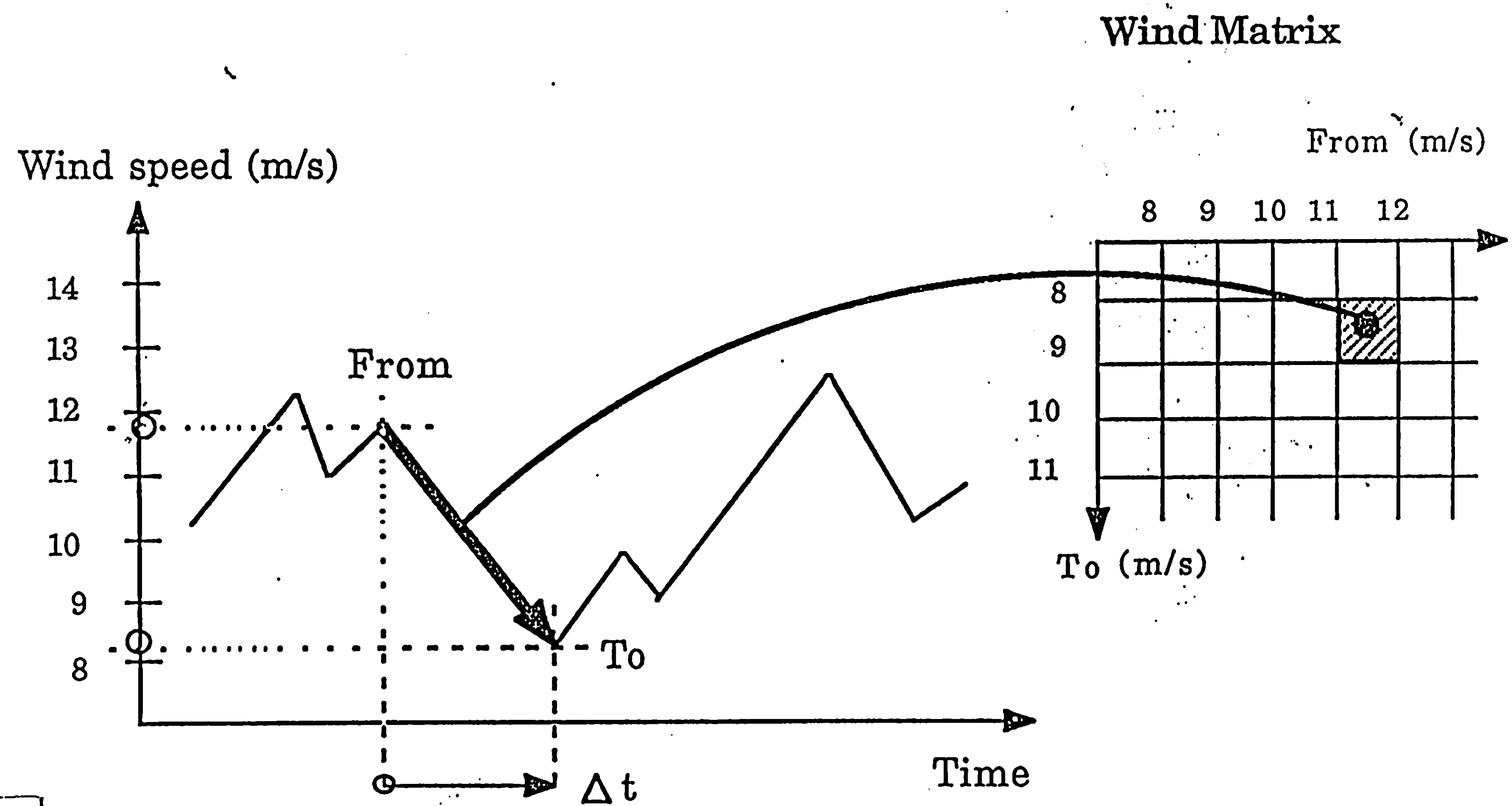
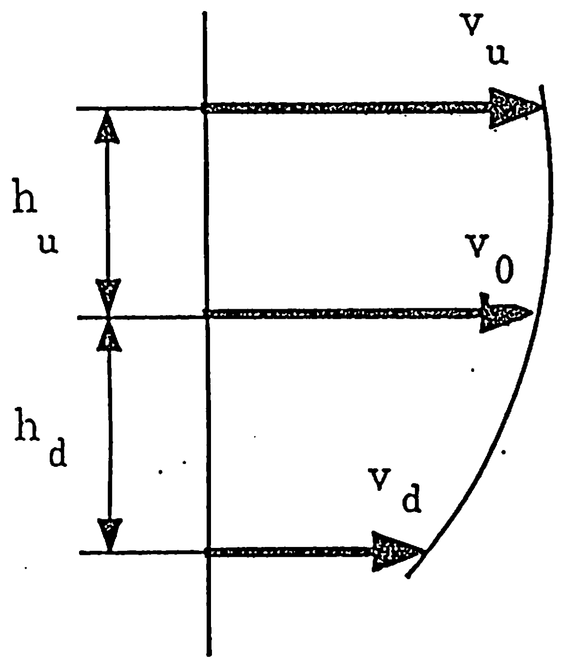


Fig 10

Symmetric and Asymmetric Gradient



$$\gamma_s = \left(\frac{v_u - v_0}{h_u} - \frac{v_0 - v_d}{h_d} \right) * 0.5$$

$$\gamma_a = \left(\frac{v_u - v_0}{h_u} + \frac{v_0 - v_d}{h_d} \right) * 0.5$$

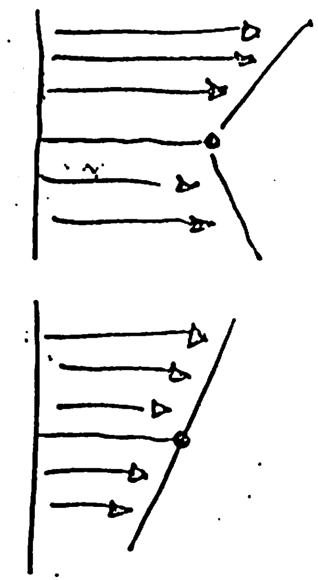


Fig 11

Load variations due to symmetric and asymmetric wind gradients

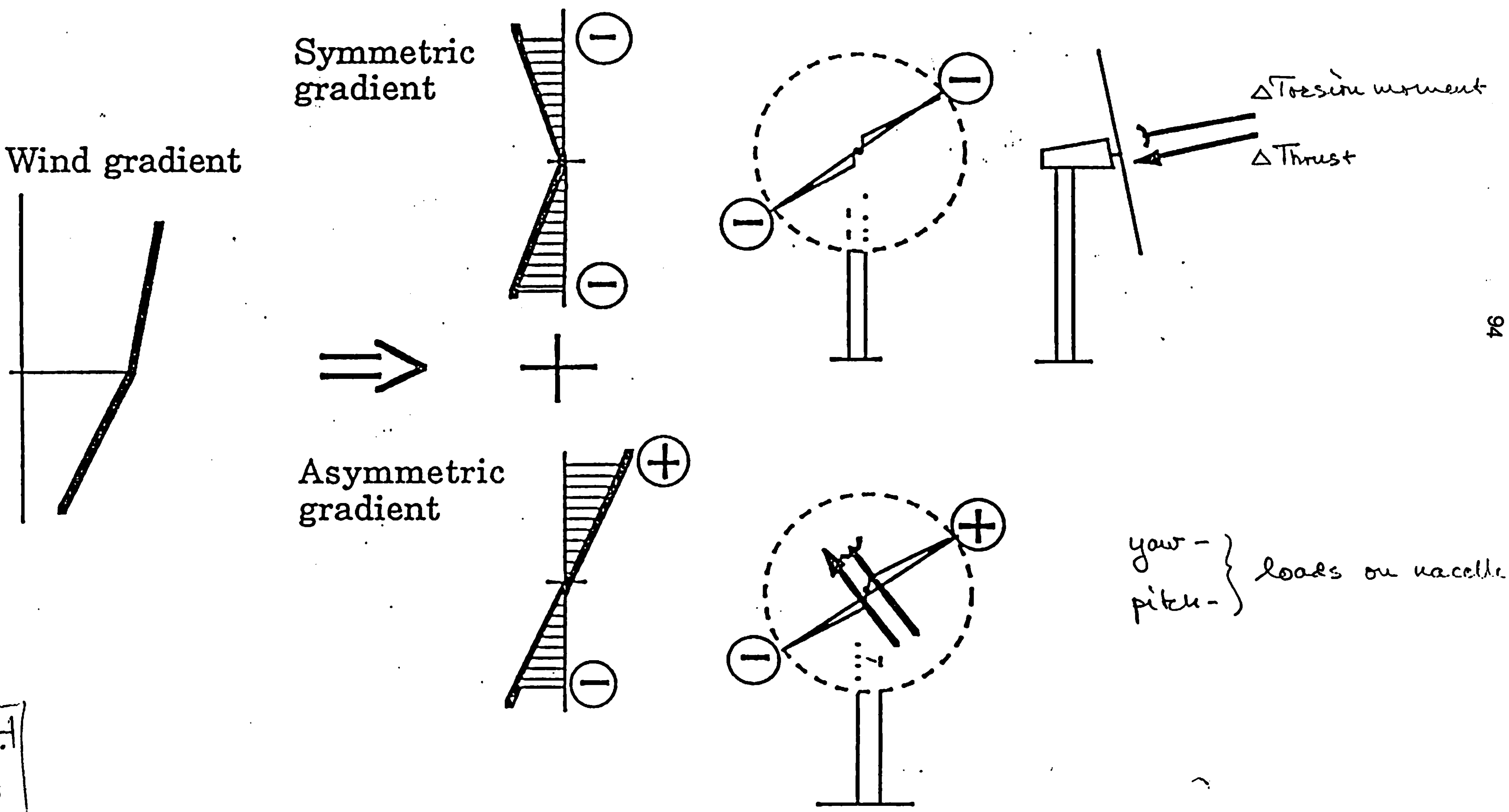


Fig 12

Example of a Wind Matrix

NASUDDEN 821006, H=77 m, dT=1s. Anemometers at 135, 77 and 11 m.
Total reg. time 52464 sec = 14.57 h. Sym. and asym. gradient related to H=77 m.

Elements outside diagonal:

Peak-Valley:
- Number of shifts
- Mean time per shift
- Min. time per shift

RFC:
- Number of half cycles
- Mean time per half cycle
- Min. time per half cycle

Diagonal elements:

- Wind speed duration
- Mean of asym. gradient
- Std.dev. of asym. gradient
- -
- Mean of sym. gradient
- Std. dev. of sym gradient

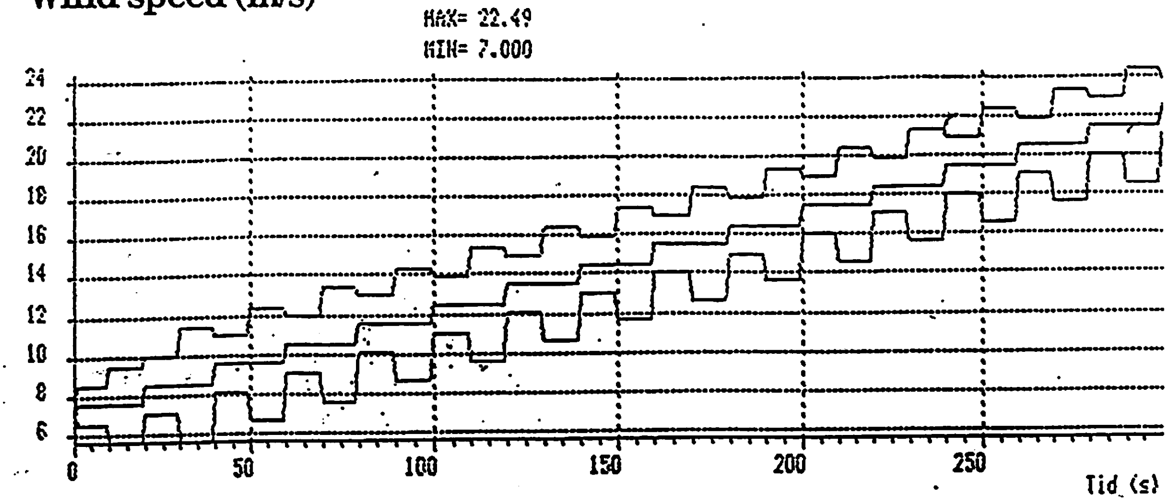
[ΔV/Δz] = (mrad/sec)

To (m/s) \ From (m/s)	6	7	8	9	10	11	12	13
7	0	**3**	0	0	0	1	1	0
7	0	**51**	0	0	0	30	41	0
7	0	**10**	0	0	0	30	41	0
7	0	**-**	0	0	0	0	0	0
7	0	**38**	0	0	0	0	0	0
7	0	**13**	0	0	0	0	0	0
8	0	0	**384**	8	62	62	15	1
8	0	0	**43**	6	11	18	22	31
8	0	0	**10**	2	1	2	2	31
8	0	0	**-**	0	0	2	12	2
8	0	0	**12**	0	0	9	96	114
8	0	0	**12**	0	0	9	33	114
9	0	0	8	**4506**	179	308	133	29
9	0	0	5	**42**	6	9	13	18
9	0	0	2	**11**	1	1	1	6
9	0	0	16	**-**	116	200	66	50
9	0	0	5	**2**	7	17	55	85
9	0	0	2	**12**	1	2	7	6
10	0	1	61	179	**11125**	263	392	187
10	0	2	8	7	**41**	5	9	13
10	0	2	1	1	**12**	1	1	1
10	0	0	54	312	**-**	316	246	144
10	0	0	16	6	**-5**	5	10	28
10	0	0	1	1	**13**	1	1	2
11	0	1	61	312	260	**13736**	305	368
11	0	13	13	9	5	**41**	5	8
11	0	13	3	1	1	**13**	1	1
11	0	0	108	316	326	**-**	394	307
11	0	0	54	11	4	**-12**	5	5
11	0	0	3	1	1	**14**	1	1

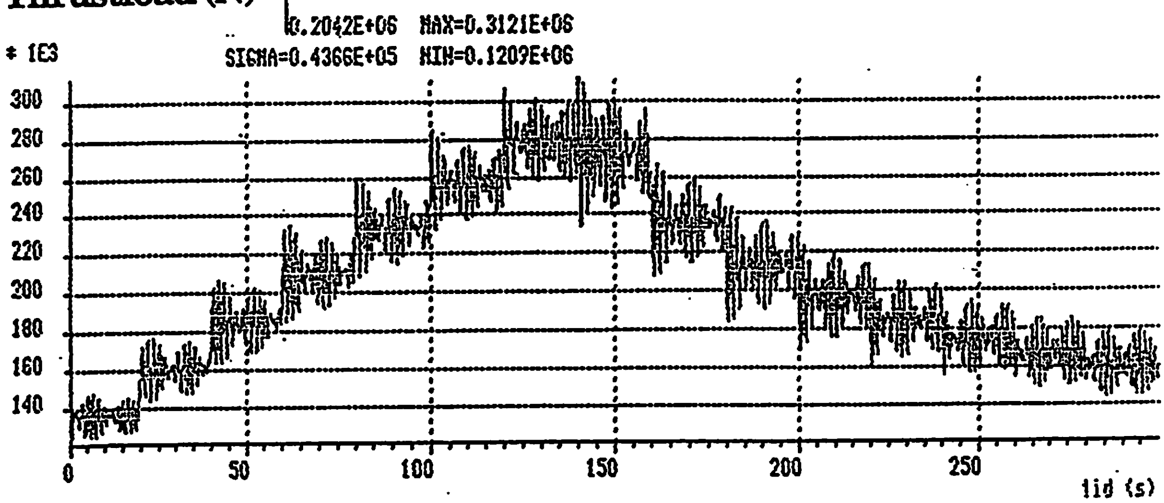
Fig 13

Loads calculated for increasing wind speed with two superimposed windshears.

Wind speed (m/s)



Thrustload (N)



Yaw moment (Nm)

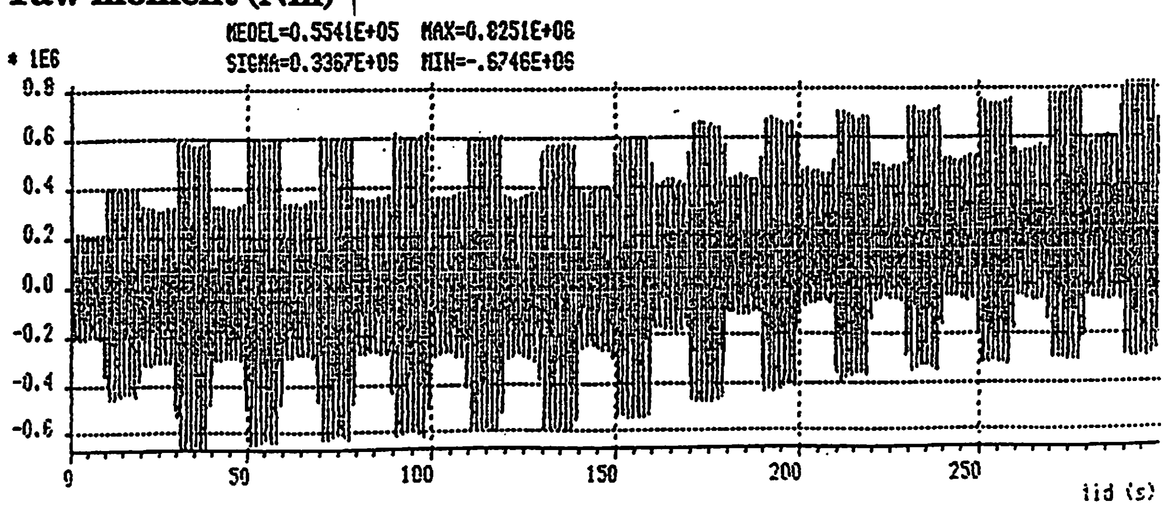


Fig 14

Loads calculated for increasing wind speed with two superimposed windshears.

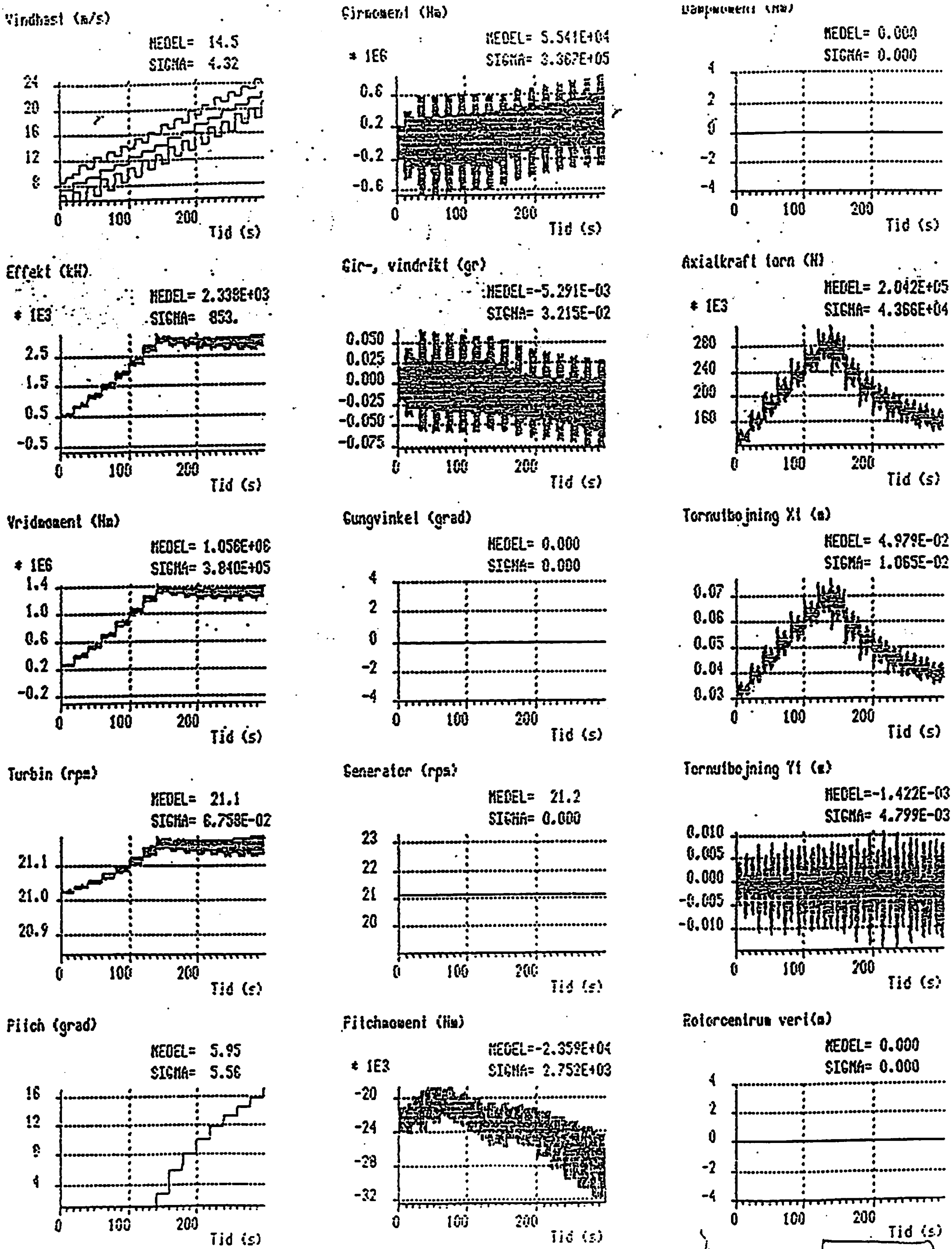


Fig 15

Loads calculated for increasing wind speed with two superimposed windshears.

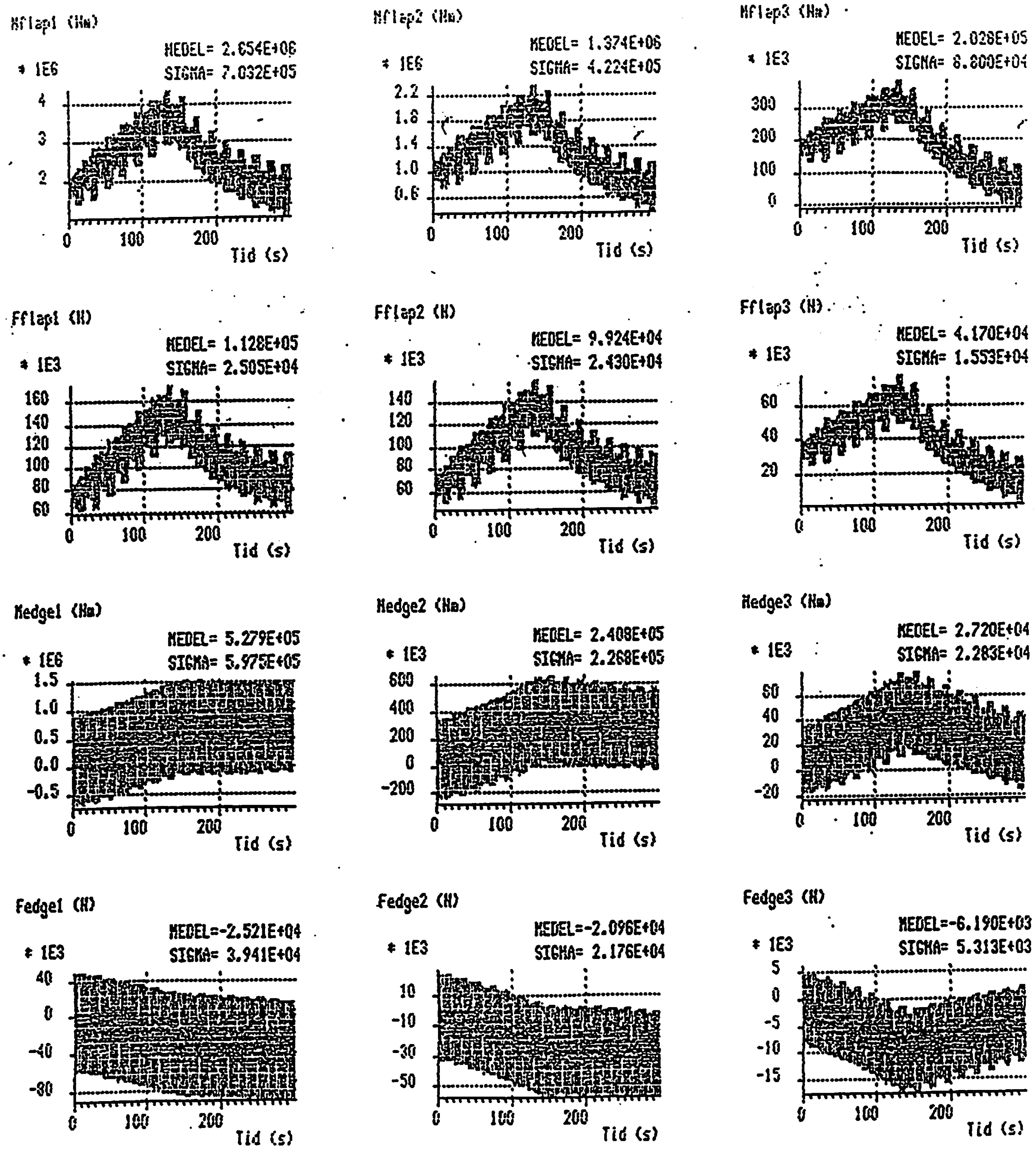
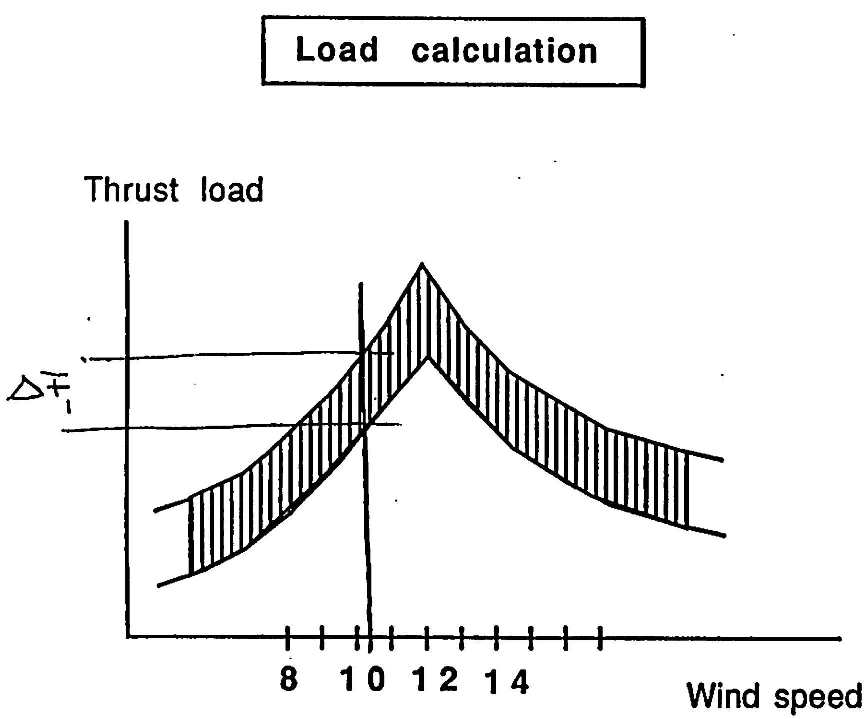
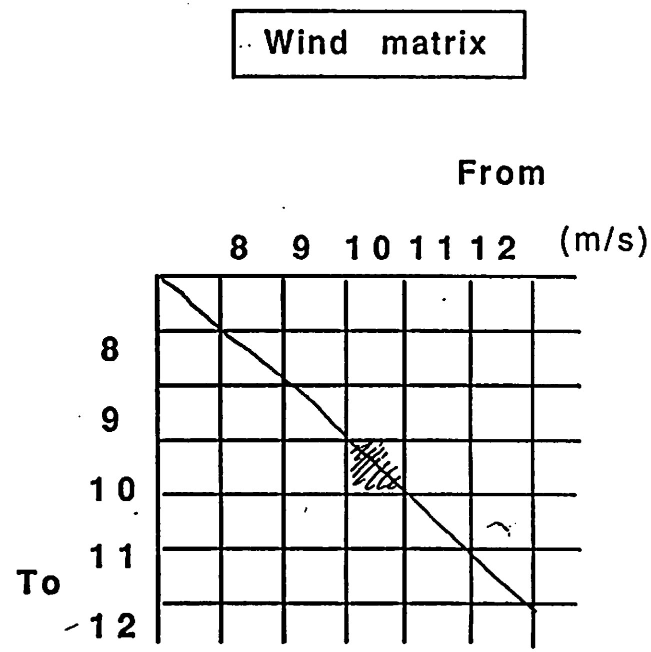


Fig 16

Load spectrum calculation



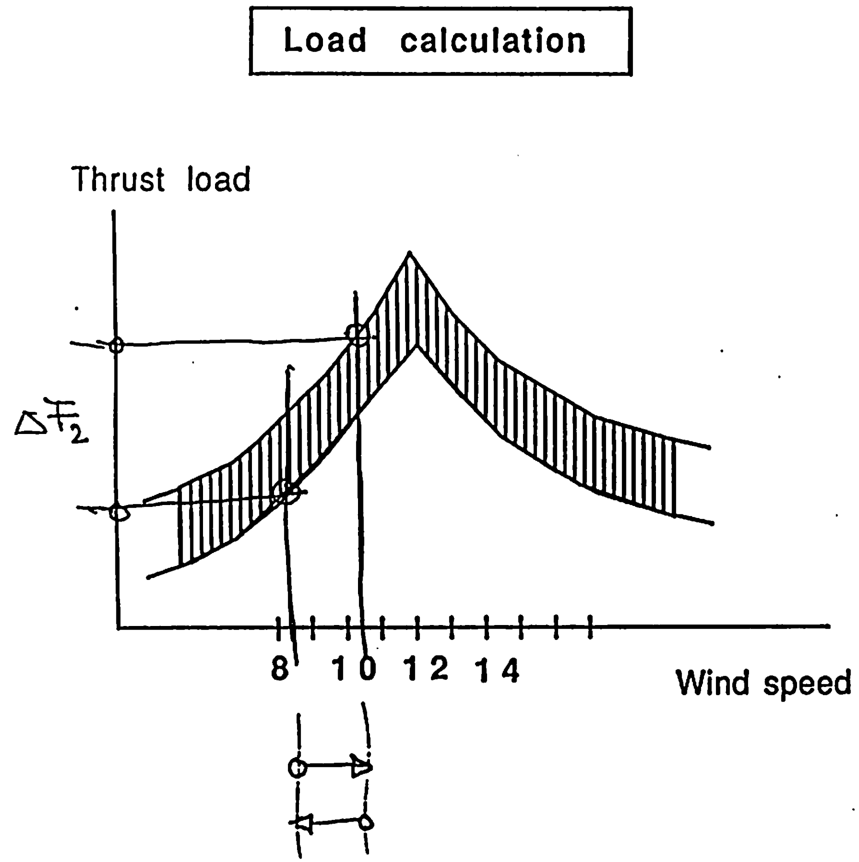


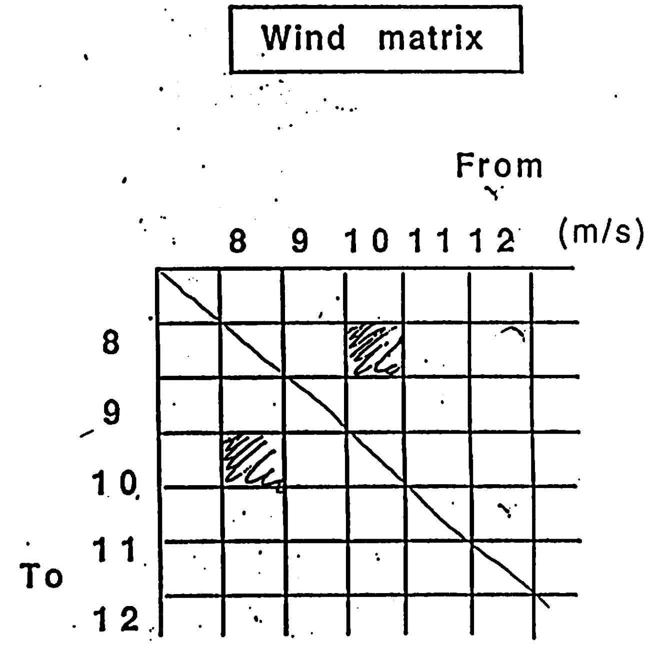
Operating time × rot. speed ⇒ cycles. (n_1)

ΔF_1 ; n_1

Fig 17

Load spectrum calculation



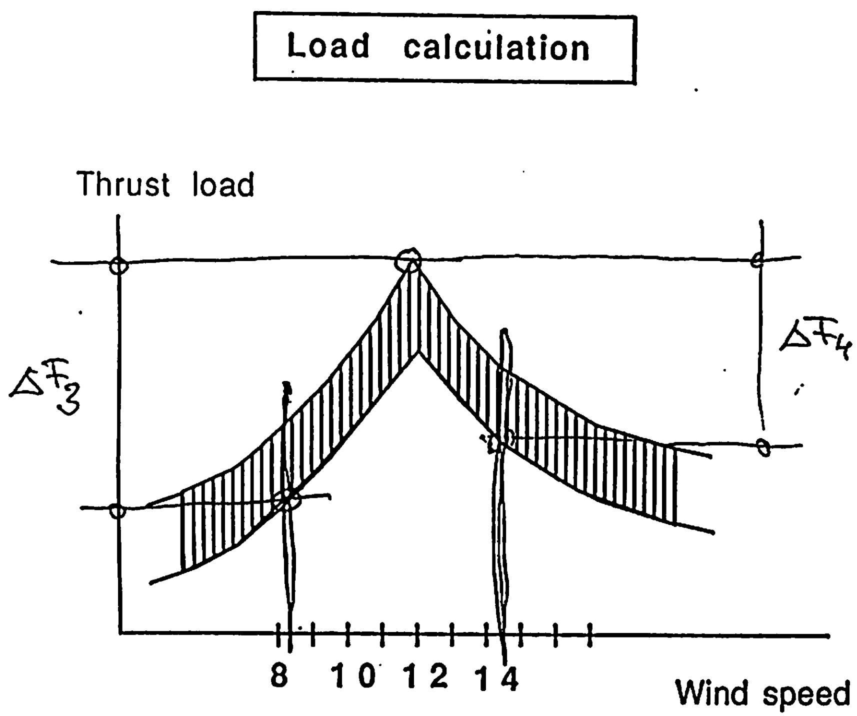


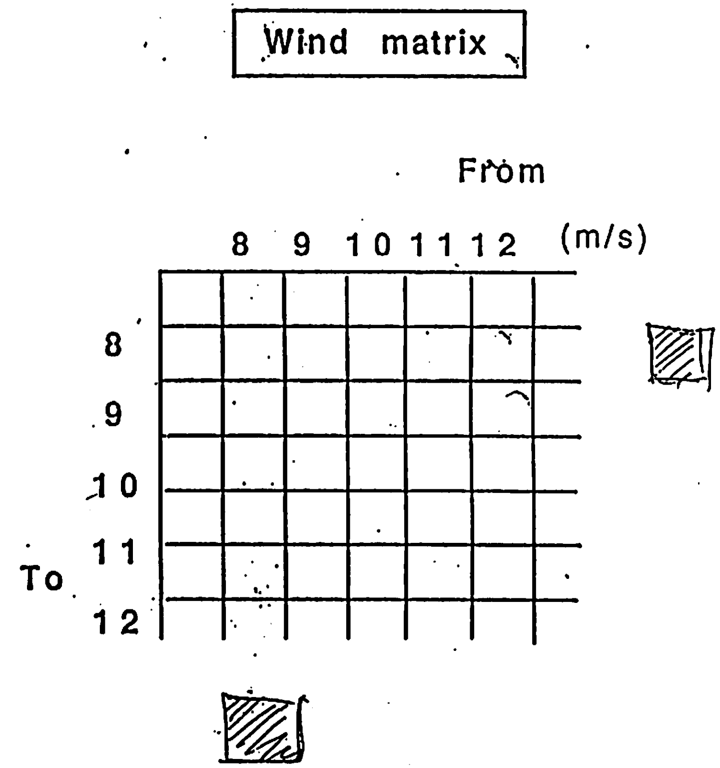
Number of changes ⟹ cycles (n_2)

ΔF_2 ; n_2

Fig 18

Load spectrum calculation





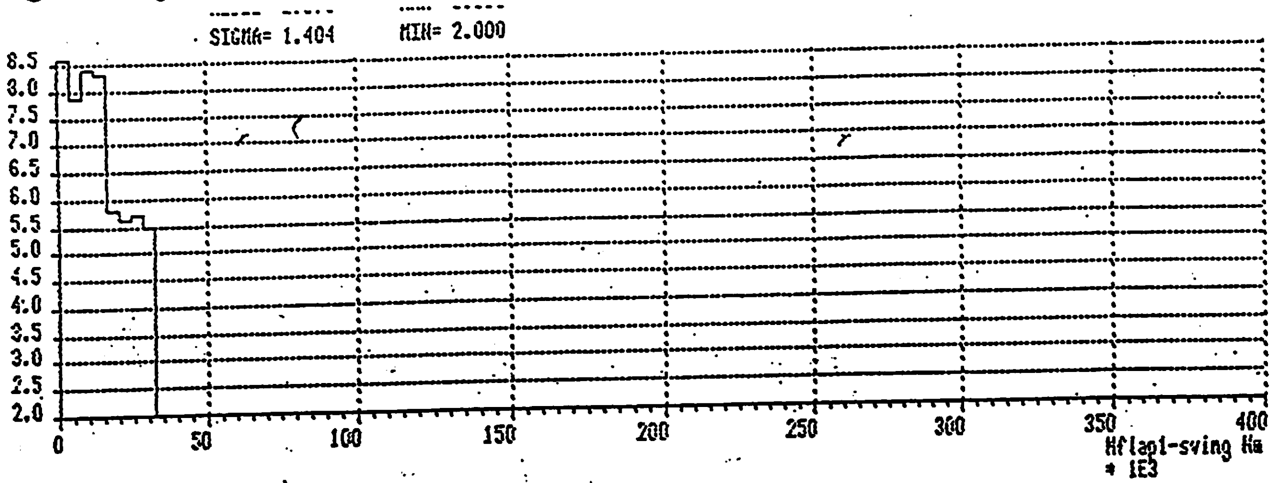
Number of changes ⇒ cycles (n_3)

ΔF_3 ; n_3	
ΔF_4 ; n_3	

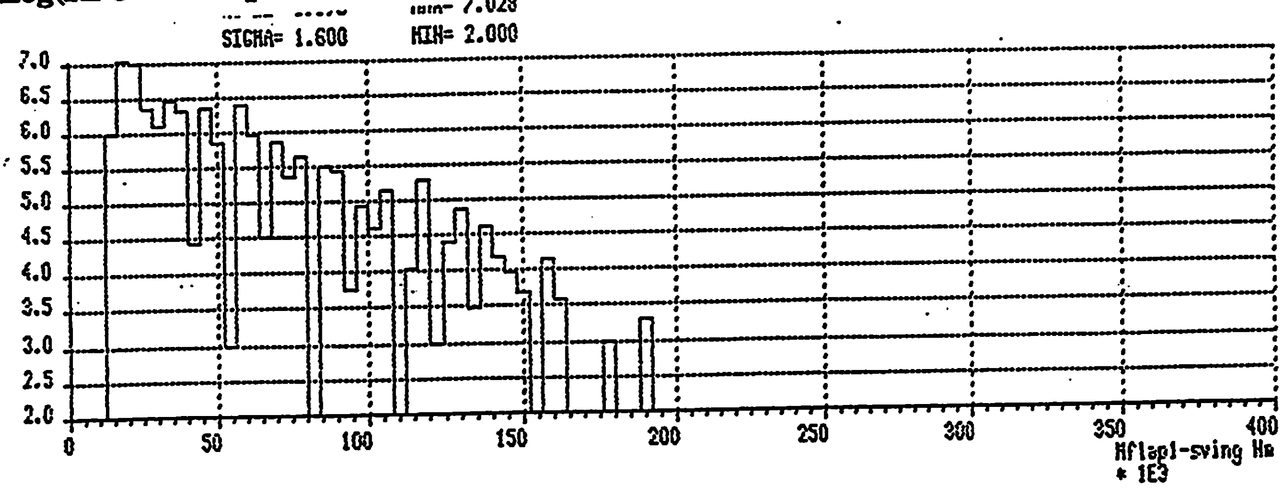
Fig 19

Number of RFC-cycles of flap blade moment during 30 years

Log(RFC - cycles at mean wind speed)



Log(RFC - wind speed changes)



Log(RFC - total)

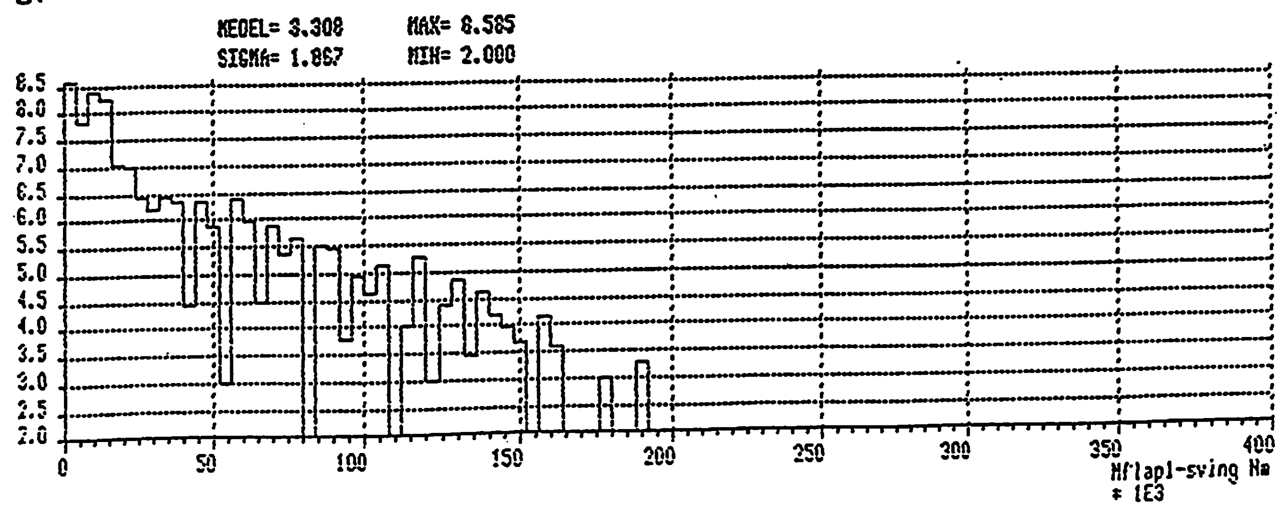
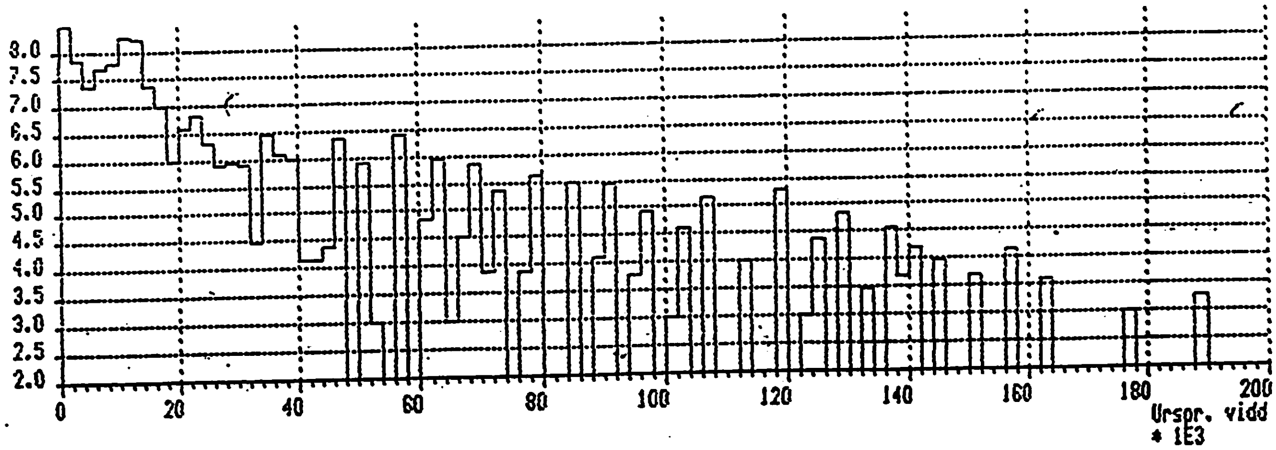


Fig 20

Final choise of section modulus (I/c = W)
Comparison of stress spectrum and SN curve (steel)



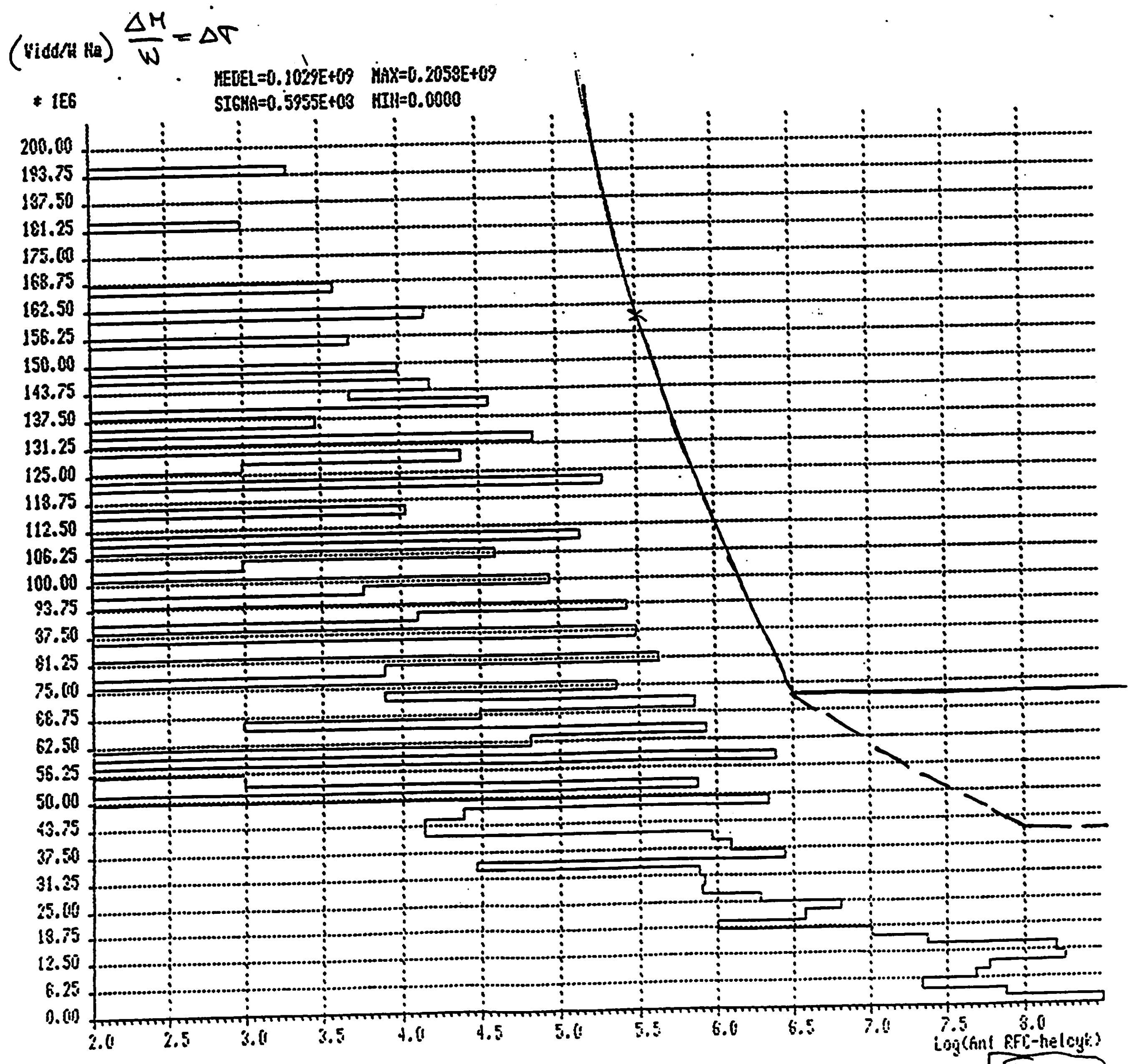


Fig 21

Conclutions

In this way the method we use include

- **the whole spectrum**
- **mean wind speed changes**
- **structural wind distributions**
- **control**
- **dynamics**

with introduced appropriate approximations , practical to use for the designer

Work is going on with

- **further wind measurements, including wind direction changes**
- **studying questions about time and space filters**
- **normalizing the wind matrix, for different topological and meteorological conditions**

IEA-meting 29–30 April 1993
Risø, Denmark
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PLEASE NOTE THAT JUST AFTER JUNE 15, 93
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TO: +45 46 77 46 77

IEA-Implement Agreement R+D WECS - Annex XI
Topical Expert Meetings

1. Seminar on Structural Dynamics, Munich, October 12, 1978
2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979
3. Data Acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, Sept. 26-27, 1979
4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21-22, 1980
5. Environmental and Safety Aspects of the Present LS WECS, Munich, September 25-26, 1980
6. Reliabiltiy and Maintenance Problems of LS WECS, Aalborg, April 29-30, 1981
7. Costings for Wind Turbines, Copenhagen November 18-19, 1981
8. Safety Assurance and Quality Control of LS WECS during Assembly, Erection and Acceptance Testing, Stockholm, May 26-27, 1982
9. Structural Design Criteria for LS WECS, Greenford, March 7-8, 1983
10. Utility and Operational Experiences and Issues from Mayor Wind Installations, Palo Alto, October 12-14, 1983
11. General Environmental Aspects, Munich, May 7-9, 1984
12. Aerodynamic Calculational Methods for WECS, Copenhagen, October 29-30, 1984
13. Economic Aspects of Wind Turbines, Petten, May 30-31, 1985
14. Modelling of Atomospheric Turbulence for Use in WECS Rotor Loading Calculation, Stockholm, December 4-5, 1985
15. General Planning and Environmental Issues of LS WECS Installations, Hamburg, December 2, 1987
16. Requirements for Safety Systems for LS WECS, Rome, October 17-18, 1988
17. Integrating Wind Turbines into Utility Power Systems, Herndon (Virginia), April 11-12, 1989
18. Noise Generationg Mechanisms for Wind Turbines, Petten, November 27-28, 1989
19. Wind Turbine Control Systems, Strategy and Problems, London, May 3-4, 1990
20. Wind characteristics of Relevance for Wind Turbine Design, Stockholm, March 7-8, 1991
21. Elektrical Systems for Wind Turbines with Constant or Variable Speed, Göteborg, October 7-8, 1991

22. Effects of Environment on Wind Turbine Safety and Performance, Wilhelmshaven, June 16, 1992
23. Fatigue of Wind Turbines, Golden (Colorado), October 15 - 16, 1992
24. Wind Conditions for Wind Turbine Design, RisÝ, April 29 - 30, 1993
25. Increased Loads in Wind Power Stations, "Wind Farms", Göteborg, May 3 - 4, 1993
26. Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control System Milan, March 8-9, 1994

Note: Nr. 25-26 to be published