

EXPERT GROUP STUDY
ON
**RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING
AND EVALUATION**

**11. WIND SPEED MEASUREMENT
AND USE OF CUP ANEMOMETRY**

1. EDITION 1999

second print 2003

*Submitted to the Executive Committee
of the International Energy Agency Programme
for
Research and Development
on Wind Energy Conversion Systems*

RECOMMENDED PRACTICES FOR
WIND TURBINE TESTING

**11. WIND SPEED MEASUREMENT AND USE OF CUP
ANEMOMETRY**

1. EDITION 1999

second print 2003

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FOREWORD

The procedures needed for testing and evaluation of Wind Turbines or Wind Energy Conversion Systems (WECS) must encompass aspects ranging from energy production, quality of power, reliability, durability and safety to cost effectiveness or economy, noise characteristics, impact on environment, electromagnetic interference, lightning protection and electromagnetic compatibility.

Development of internationally agreed procedures for testing and evaluation in each of these areas is needed to aid the development of the industry and to strengthen confidence in the technology and prevent chaos in the market.

It is the purpose of this series of Recommended Practices for Wind Turbine Testing and Evaluation to contribute to the development of such internationally approved procedures. The Executive Committee of the IEA Wind Agreement, through Annex XI to this agreement, continues to pursue this effort by periodically holding meetings of experts, to define and refine consensus procedures in each of the following areas:

- | | |
|-----------------------------------|-------------|
| 1. Power Performance | 2. ed. 1990 |
| 2. Cost of Energy from WECS | 2. ed. 1994 |
| 3. Fatigue Loads | 2. ed. 1990 |
| 4. Measurement of Noise Emission | 3. ed. 1994 |
| 5. Electromagnetic Interference | 1. ed. 1986 |
| 6. Structural Safety | 1. ed. 1988 |
| 7. Quality of Power | 1. ed. 1984 |
| 8. Glossary of Terms | 2. ed. 1993 |
| 9. Lightning Protection | 1. ed. 1997 |
| 10. Measurement of Noise Immision | 1. ed. 1997 |
| 11. Wind Speed Measurement | 1. ed. 1999 |

This document addresses item 11. In many areas of testing, accurate and reliable measurements of wind speed are very important. It is felt that the information and the recommendations put forward can be of great value to all who carry out field testing, and therefore justifies the presentation of the document in this series of Recommended Practices.

The Executive Committee will seek to gain approval of the procedures in each member country through the IEA agreement. The recommendations shall be regularly reviewed, and areas in need of further investigation shall be identified.

B. Maribo Pedersen

Operating Agent, Annex XI

April 1999

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INTRODUCTION

When evaluating or testing a wind turbine, particularly for performance determination, one of the most critical measurements is that of wind speed.

Uncertainty in wind speed measurements, be they made during a site assessment, a site calibration or a wind turbine performance test, all contribute to the overall uncertainty in predicted annual energy yield. In economic terms, this translates into financial risk and in turn into higher cost of energy.

By adopting best practice in the design, selection, calibration, deployment and use of anemometry, uncertainty can be minimised.

There is no other branch of meteorology, science or technology where the importance of low uncertainty in wind speed measurement is as great as in wind energy.

Until very recently¹ there has been no clear guidance, even in standards relating to wind turbine testing, on best practice in the use of anemometry.

This document, drawing upon several years of experience and research by the authors aims to fill this gap.

SCOPE AND FIELD OF APPLICATION

The advice given in this volume is focused primarily on the use of cup anemometry for power performance evaluation of a wind turbine. Other types of anemometer and other types of test application are mentioned, but are given lower priority.

The aim throughout is to provide guidance on best practice. The text is designed to give a comprehensive overview of each issue. Good quality references are provided for those wishing to follow-up a particular aspect.

RECOMMENDED PRACTICES FOR WIND SPEED MEASUREMENT AND USE OF CUP ANEMOMETRY IN WIND TURBINE TESTING

1. THE USE OF ANEMOMETRY IN TESTING WIND TURBINES

When evaluating the power performance, mechanical loading, power quality or acoustic emission of a wind turbine, wind speed is an important, usually dominant, independent parameter. Hence when testing a wind turbine, wind speed must always be measured.

There are various types of anemometer (wind speed measuring device) on the market. Some are highly responsive and can be used for defining the detailed turbulent structure of the wind, whilst others are better suited to measuring the underlying mean wind speed.

For many applications such as wind resource assessment, power performance testing and characterisation of acoustic emission, it is the mean speed (usually averaged over 10 minutes) at a particular height above ground that is of interest. The most appropriate type of instrument for such applications is undoubtedly the three-cup anemometer.

Other types of instrument are available, and can be more appropriate in other applications. A review of these and their potential applications, advantages and shortcomings is given in Appendix 1. Such instruments include propeller-vane, fixed propeller, sonic, thermal, laser Doppler (LDA) and SODAR anemometers.

The focus of this document is however on cup anemometry, primarily in the context of power performance testing.

The aims of the document are twofold:

- to provide general guidance to users
- to provide the basis for specifying cup anemometers.

2. SELECTING A CUP ANEMOMETER

Cup anemometers are widely used for a number of very good reasons. They are generally well suited to definition of mean wind speed (or more accurately wind run), they tend to be cost attractive in comparison to other types of instrument and they can be very robust.

Cup anemometers are not without their generic limitations, the principal ones being related to:

- ‘non-ideal’ sensitivity to angle of attacks outwith the horizontal plane
- dynamic response
- non-linearity of calibration and variation in calibration caused by mechanical friction or due to the shape of the cups

and, in some cases

- changes in calibration sensitivity with horizontal wind direction

When selecting or specifying a cup anemometer, it is important to be aware of these effects both in terms of their causes and their consequences.

2.1 What a Cup Anemometer Measures

A cup anemometer conventionally consists of three hemispherical or conical cups, arranged in a horizontal rotor configuration around a central vertical shaft that drives a signal generation device.

Cup anemometers are ostensibly adirectional i.e. they should respond identically to winds coming from different directions within the horizontal plane. Thus in terms of a standard x,y,z co-ordinate system with velocity components u , v and w , the cup anemometer is primarily designed to measure the horizontal wind speed, $\sqrt{u^2+v^2}$, not the magnitude of the horizontal vector.

For the w (vertical) component of wind speed, two types of 'ideal' sensitivity are possible:

- if a cup anemometer displays a cosine weighted sensitivity to angle of deviation of the total wind vector from the horizontal plane, then the instrument will measure purely the horizontal wind speed, i.e. $\sqrt{u^2+v^2}$.
- if a cup anemometer is insensitive to angle of deviation of the total wind vector from the horizontal plane, then the instrument will measure total wind speed, i.e. $\sqrt{u^2+v^2+w^2}$.

For wind speed measurement above sloping terrain, or when testing wind turbines whose rotors have the ability to rock (teeter), it can be argued that the ideal cup anemometer to use is one which measures total, not horizontal wind speed, since total wind speed does indeed represent what is available for power conversion.

Unfortunately, no cup anemometer currently on the market perfectly displays either type of behaviour, although this issue is being addressed².

The issue of vertical sensitivity will be dealt with in more detail later.

2.2 Design Parameters

Although cup anemometers from different manufacturers may seem superficially similar, there are subtle design differences that can have a significant influence on behaviour and accuracy.

The principal design parameters are noted in Table 1 below, with an indication of their importance in relation to key behavioural limitations.

Users should be aware of such design influences.

Design Parameter	Qualitative influence on ...			
	... sensitivity to vertical components of wind	... linearity of calibration	... dynamic responsiveness	... calibration sensitivity to horizontal wind direction
Rotor geometry (shape of cups, cup to rotor size ratio)	<i>Very important, although a detailed understanding sufficient for optimisation does not yet exist.</i>	<i>Some influence from edge profile.</i>	<i>Responsiveness depends upon balance between aerodynamic and inertial forces. Short arms (high cup to rotor size ratio) will give better response.</i>	<i>Not influential.</i>
Size of rotor	<i>Not important.</i>	<i>Bigger rotors will have better linearity since mechanical friction will become relatively unimportant.</i>	<i>Bigger rotors will have greater inertia and will be less responsive.</i>	<i>Not influential.</i>
Shaft length	<i>Important - the longer the shaft the less the body distorts the flow over the rotor.</i>	<i>No influence.</i>	<i>Not important.</i>	<i>Helps minimise effects of body.</i>
Body geometry	<i>Affects differences in sensitivity between upward and downward components in vertical winds. Shape and size affects magnitude of flow disturbance over the rotor.</i>	<i>No influence.</i>	<i>Not important.</i>	<i>If body is not of uniform profile, then calibration will have a directional dependency.</i>
Miscellaneous protrusions (e.g. cable entries, external shaft heaters etc)	<i>Could be of slight influence.</i>	<i>No effect.</i>	<i>No effect.</i>	<i>Major influence of unexpected significance.</i>
Type of bearings	<i>Not significant.</i>	<i>Major influence, the magnitude of which may vary with temperature.</i>	<i>Second order effect.</i>	<i>May have an effect.</i>
Type of signal generation device	<i>No effect.</i>	<i>May have an effect if the rotor is 'loaded' by the signal generator.</i>	<i>Second order effect is possible.</i>	<i>No effect.</i>

Table 1 *Cup Anemometer Design Parameters and Their Qualitative Influence on Operational Characteristics*

At present, there is no formal 'standard' classification scheme for cup anemometers (this document recommends one in Section 2.3).

The absence of a scheme makes it difficult at present, even for ‘experts’, to select cup anemometers. Generally, a user will have two major queries:

- is the anemometer suited to the application
- what inherent uncertainty does the anemometer have.

A reputable manufacturer should be able to discuss these issues knowledgeably.

By inspecting an instrument, it is often possible to identify whether the anemometer has been carefully designed. Typical attributes of a ‘well designed’ instrument are shown in Figure 1a whilst a poorer instrument is shown in Figure 1b. The figures are not based on specific anemometers.

Users should be aware of the general characteristics and features of a ‘well designed’ cup anemometer.

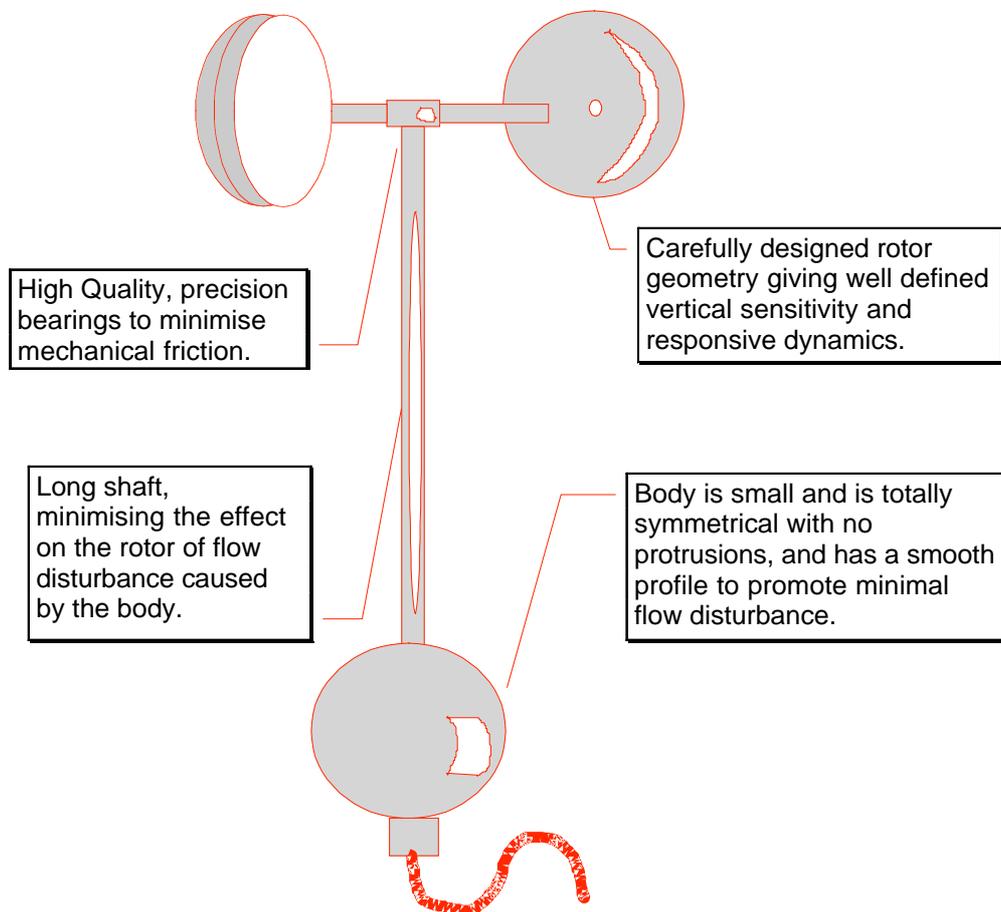


Figure 1a *Schematic of a ‘Well Designed’ Cup Anemometer*

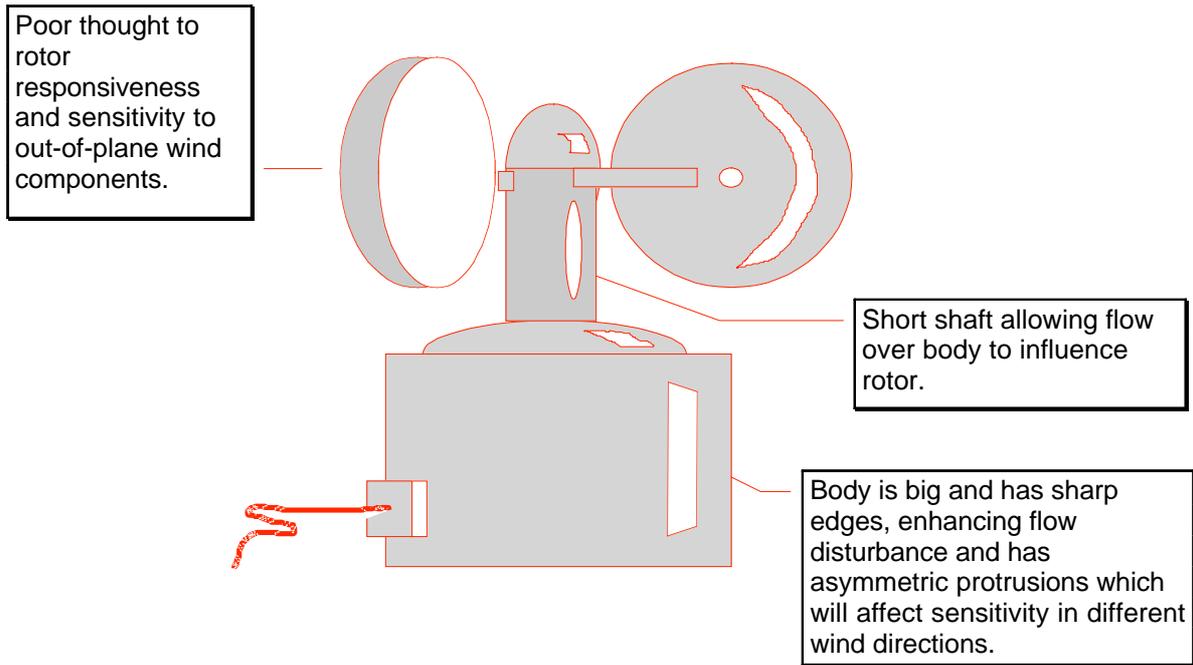


Figure 1b Schematic of a Poorly Designed Cup Anemometer

2.3 A Classification Scheme for Cup Anemometers

A cup anemometer being used for wind energy applications can be expected to experience a range of environmental conditions during operation. Table 2 shows the operating range in which accuracy is important for power performance assessment. The limit values reflect wind turbine operating ranges and typical climatic conditions.

Parameter	Units	Minimum Value	Maximum Value
Wind Speed (10 minute average)	<i>m/s</i>	<i>4</i>	<i>16</i>
Turbulence Intensity (10 minute)	%	<i>5</i>	<i>100 * (1.13 / u + 0.12), where u is the prevailing wind speed⁸</i>
Air Temperature	∞C	<i>-10</i>	<i>40</i>
Air Density	<i>kg/m³</i>	<i>0.90</i>	<i>1.35</i>
Slope of Terrain	∞	<i>-10</i>	<i>10</i>

Table 2 Ranges Within Which Cup Anemometers Intended for Wind Energy Applications (Specifically Power Performance Evaluation) Should Perform to Claimed Accuracy

A competent anemometer manufacturer should be able to provide information on the accuracy of its anemometer within these envelopes.

It has been suggested that this level of accuracy should form the basis of a formal classification system.⁴

If a particular application site is known to have climatic parameters outside these ranges, then a revised, special specification should be used.

A number of fundamental physical parameters and characteristics of an anemometer define its behaviour and accuracy. These are:

- rotor arm length
- cup area
- rotor inertia
- drag coefficient on convex face of cup
- drag coefficient on concave face of cup
- static, dynamic and parabolic mechanical friction coefficients for temperature range
- sensitivity characteristic to out-of-plane attack
- linearised calibration curve.

These parameters can be used as the input to a modelling based evaluation of accuracy.

3. CALIBRATION

All cup anemometers used for wind assessment or for wind turbine evaluation should have a current calibration.

Type calibrations are inadequate for wind energy purposes - each instrument must have its own specific calibration certificate.

Anemometers should be calibrated prior to deployment. After field tests have been completed, the calibrations should ideally be repeated or at least verified, e.g. by field comparison with a newly calibrated instrument.

For extended deployment, re-calibration should be carried out at least every six months.

Calibration should be carried out in a wind tunnel and users should only use calibration institutions that can demonstrate:

- traceability to national standards and inter-comparability with other competent organisations
- technical quality assurance (e.g. in Europe to EN45001 requirements), and
- full understanding of the wind tunnel's flow characteristics.

Details of what a competent institution should be able to demonstrate are given in Appendix 3.

3.1 Calibration Procedure

The calibration procedure (again fuller details are provided in Appendix 3), should comprise:

- prior calibration of the wind tunnel to relate conditions at a reference position with those at the position of the anemometer
- calculation of wind speeds from measurements of dynamic head and air density, the latter being based upon measurement of ambient temperature, barometric pressure and relative humidity
- correction of wind speeds to account for blockage effects
- calibration at 1m/s intervals from 4 up to 16 m/s

- sampling of steady state behaviour at each wind speed over 30 second periods.

Calibration coefficients should be derived by carrying out a two parameter linear regression of wind speed upon averaged anemometer output.

3.2 Uncertainty Evaluation

It is vitally important that a thorough uncertainty statement based upon recognised principles⁵ supports the calibration certificate.

The uncertainty assessment should take account of:

- calibration uncertainty of the wind tunnel
- calibration uncertainty for all transducers and instrumentation (pitot tubes, pressure transducers, barometers, thermometers, humidity probes, amplifiers, filters and data systems)
- resolution uncertainty, e.g. quantisation within digital data loggers
- uncertainty in blockage corrections
- statistical uncertainty in derivation of mean values.

Details of an uncertainty assessment are given in Appendix 4.

Although individual steady-state calibrations are required for each instrument, it is sufficient for other behavioural attributes to be defined from type tests.

3.3 Non-Linearity and Mechanical Friction

The equations of motion of a cup anemometer (see Appendix 2) demonstrate that in the absence of mechanical friction, steady state calibration results should be perfectly linear. However friction is always present to some degree. Friction can be represented by static, dynamic and parabolic terms (i.e. by terms that comprise coefficients factored by speed to the zero, first and second powers). The effect of friction is firstly to introduce an offset to the calibration to overcome the static term and secondly to introduce a non-linearity to the calibration.

Unfortunately these friction coefficients are temperature dependent, so an anemometer which behaves well in a warm wind tunnel laboratory environment may not have the same calibration characteristic in an in-service cold atmosphere.

Appendix 6 outlines a procedure whereby the friction coefficients and their temperature dependency can be characterised experimentally whilst Appendix 2 includes advice on using this information to assess likely linearity of calibration.

4. ANEMOMETER DYNAMICS AND BEHAVIOUR IN THE REAL ATMOSPHERE

Using quality assured steady state calibrations obtained in a wind tunnel will not automatically guarantee accuracy in field measurements.

Real atmospheric flow fields are not steady and errors and uncertainties in measurement can be introduced by turbulence and by related variations in flow angles.

Three aspects of cup anemometer behaviour are of particular concern:

- non-ideal sensitivity to vertical wind components

- overspeeding in turbulent winds
- dynamic filtering in turbulent winds.

These aspects are of greater importance in complex terrain where ground induced flow disturbances are more pronounced, but even in smooth terrain, they cannot be ignored.

4.1 Vertical Sensitivity

Although full research into the topic has not yet been completed, it would appear that sensitivity of cup anemometers to winds having vertical flow components depends upon:

- the design of the anemometer (both the rotor and the body)
- the wind speed
- whether the anemometer is in the free atmosphere or a wind tunnel.

Figures 3a-d show sensitivities for two anemometers in common use⁶.

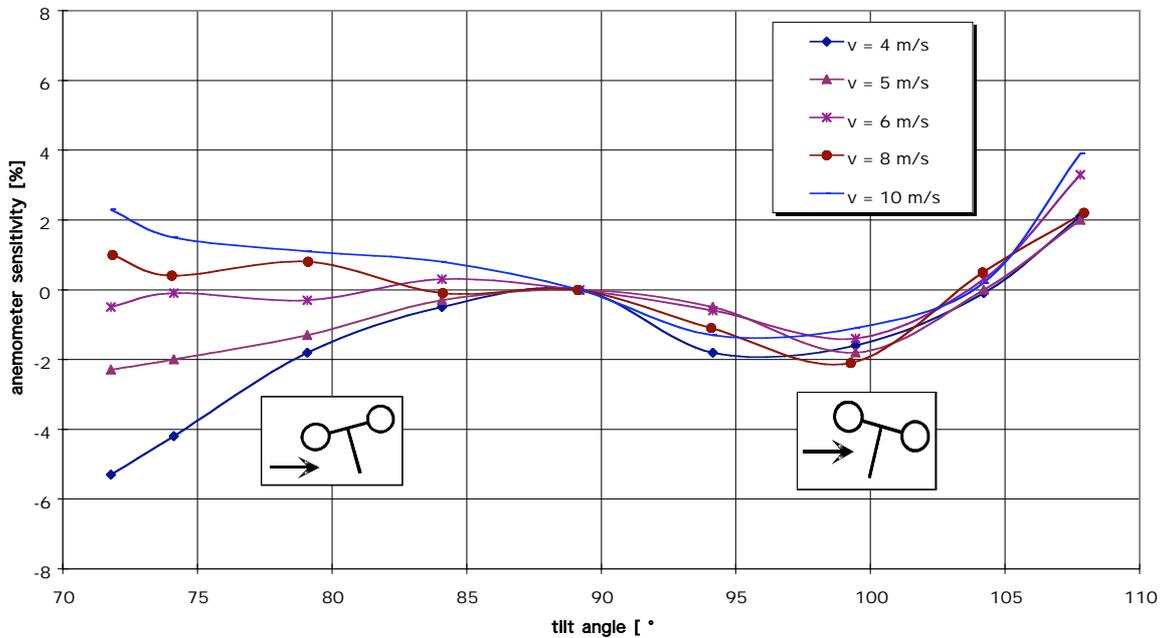


Figure 3a Percentage Difference Between Indicated Wind Speed and True Total Wind Speed for Cup Anemometer 'A' in the Wind Tunnel for Various Angles of Attack at Various Wind Speeds.

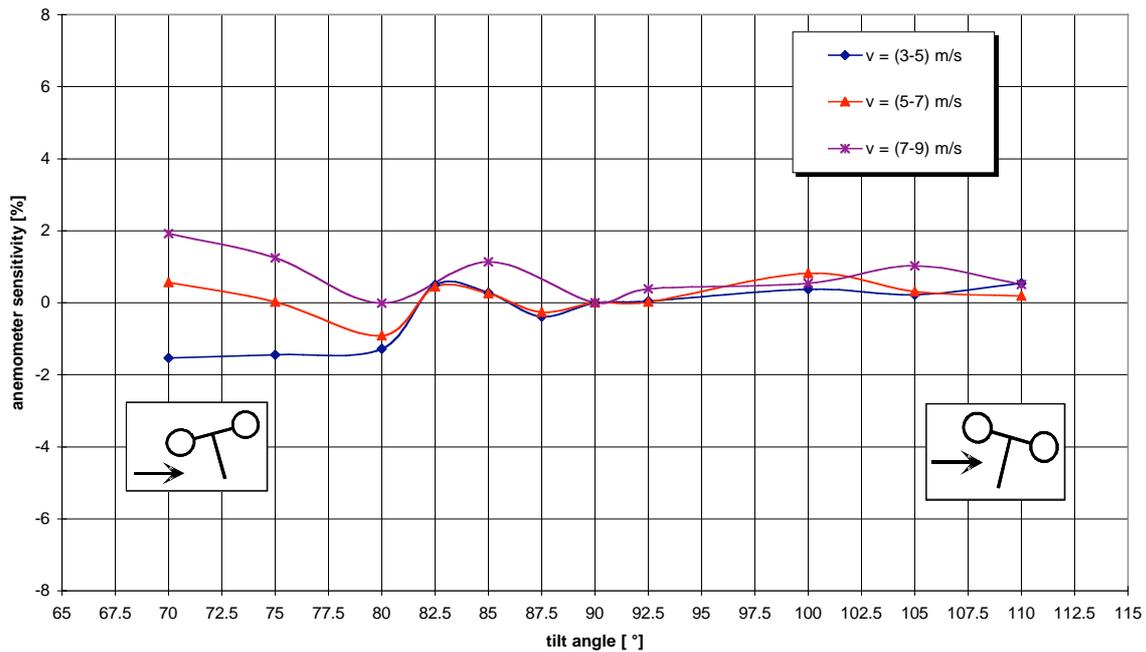


Figure 3b *Percentage Difference Between Indicated Wind Speed and True Total Wind Speed for Cup Anemometer 'A' in the Free Atmosphere for Various Angles of Attack at Various Wind Speeds.*

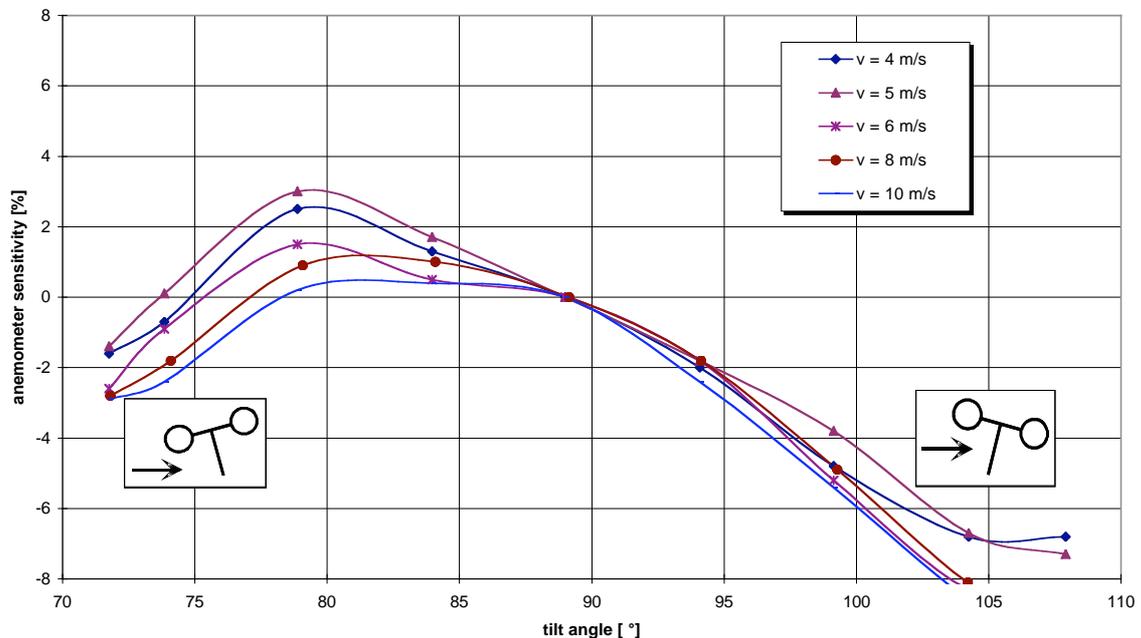


Figure 3c *Percentage Difference Between Indicated Wind Speed and True Total Wind Speed for Cup Anemometer 'B' in the Wind Tunnel for Various Angles of Attack at Various Wind Speeds.*

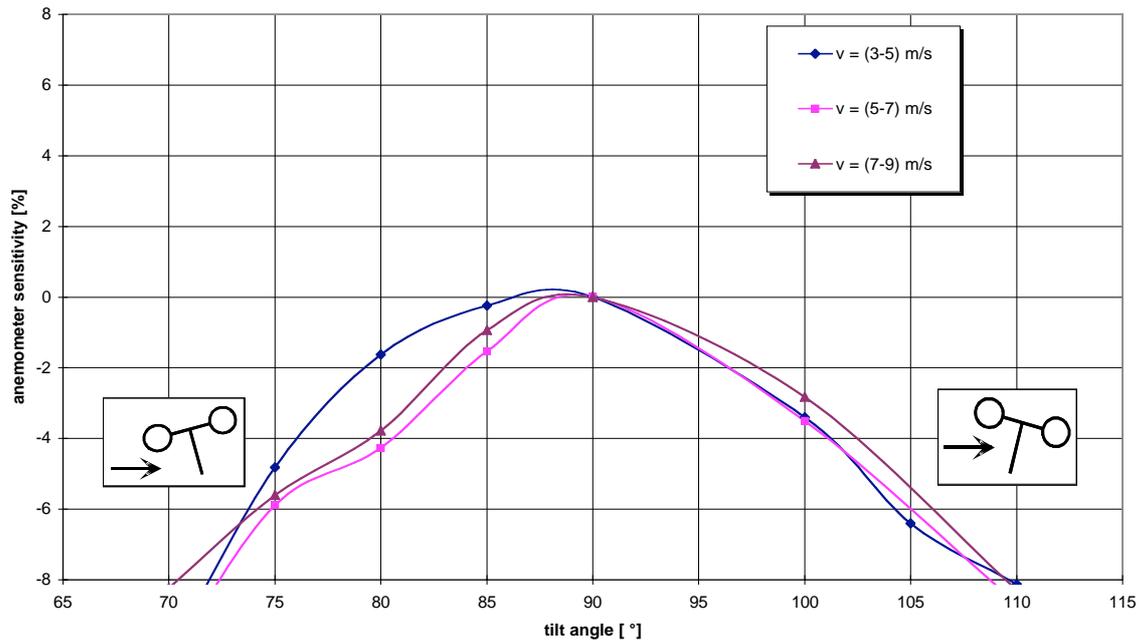


Figure 3d *Percentage Difference Between Indicated Wind Speed and True Total Wind Speed for Cup Anemometer 'B' in the Free Atmosphere for Various Angles of Attack at Various Wind Speeds.*

As suggested in section 3.1, for wind turbine evaluation the wind speed quantity that should ideally be measured is the full, not just the horizontal plane, wind speed. This implies a requirement for the cup anemometer to have a flat sensitivity to angle of attack. Anemometer 'A' is better than anemometer 'B' in this regard.

Were the objective to measure the horizontal plane wind speed, then a cosine sensitivity would be desired, and anemometer 'B' would be the preferred choice.

Manufacturers and users should be aware of such characteristics and their consequences. Methods are outlined in Appendix 5 whereby vertical sensitivities can be assessed experimentally.

4.2 Overspeeding

Many measurement instruments have a time constant that indicates at what rate they can respond to changes in an input parameter. The time to react is generally independent of the actual magnitude of the change or the starting value.

Cup anemometers do not behave exactly in this way and, to a first approximation, exhibit a 'distance constant'. This is analogous to a time constant, except that the response measure is a given wind-run, not a given elapsed time.

Appendix 2 provides more details, but the key consequence of such behaviour is that a cup anemometer responds more quickly to positive changes in wind speed than to negative ones, and also that responsiveness is better at higher wind speeds. This means that in a fluctuating wind,

the mean indication from a cup anemometer will be higher than the true average wind speed, and this effect is termed ‘overspeeding’.

Despite previous indications to the contrary, it is now accepted that this is not a major source of error in measurement of mean wind speed.

In the limiting case of an anemometer with infinite inertia, overspeeding errors of only 1.1% and 4.4% will occur in turbulence intensities of 10% and 20%⁷.

Simple models⁸ indicate that the overspeeding error in percent can be fairly approximated by the expression:

$$E = I^2 \cdot (1.8d - 1.4)$$

where E is the percentage error, I is the turbulence intensity and d is the distance constant for the anemometer.

Thus for an anemometer having a 5 m distance constant, an overspeeding error of 0.17% will occur for a wind having a turbulence intensity of 0.15.

This expression can be used as the basis for correction of indicated wind speeds and for uncertainty estimation.

Appendix 7 outlines a method whereby an anemometer’s distance constant can be estimated in a consistent and repeatable manner.

4.3 Dynamic Filtering

For most wind turbine tests and evaluations, it is relatively unimportant to measure the spectral content of the wind. However, should this be required, for example for wind loading studies, then the limitations of cup anemometers should be realised.

Cup anemometers being mechanical devices cannot follow wind speed fluctuations exactly, and the higher the frequency of the fluctuation, the less able the anemometer will be to provide an accurate representation of the changes.

Reducing its inertia can clearly enhance the responsiveness of a cup anemometer.

Less obviously, responsiveness can be improved by making the cup arms as short as possible. Responsiveness depends upon the ratio of driving torque to rotational inertia. Driving torque increases linearly with arm length whereas inertial torque goes up to the square power.

Unfortunately, very short arms will cause the anemometer to exhibit a distinct speed ripple due to flow interaction between cups.

By having a twin rotor, six-cup arrangement with the two rotors offset from one another by 60°, it is possible to obtain a highly responsive, low ripple instrument⁹. Suitable optimisation of the separation of the two rotors can also produce the added benefit for some applications of a very close fit to a cosine response to non-horizontal wind attack.

Due to the filtering effect, the spectral power indicated by a cup anemometer will be lower than what is actually in the wind, and this in turn will lead to an underestimate of the true turbulence intensity. Analysis has shown¹⁰ that for a typical wind spectrum, an anemometer with a distance constant of 3.5 metres will fail to report 5% of the turbulent energy. Thus a 20% turbulence intensity will be seen as only 19%.

Cup anemometers are not suited to detailed measurements of turbulent structure and alternative instruments will be needed (see Appendix 1).

5. FIELD PRACTICE - BOOMS AND MOUNTINGS

How an anemometer is deployed can introduce uncertainties equally as significant as those caused by calibration and design. It is quite clear that if an anemometer is operating in the wake of the host meteorological mast then its indication will not be a true reflection of the free field wind speed. Less obvious is the fact that flow distortion upstream of the tower or above a mounting boom can be significant, and adequate separation must be allowed between the rotor and the host structure to keep such effects to an acceptably low level.

It is largely up to the user to determine what degree of disturbance and hence uncertainty is acceptable, but a suitable aim should be to avoid mast and boom induced flow distortions greater than 0.5%.

To avoid problems, it is undoubtedly preferably to place the anemometer on a vertical pole clear of the top of the tower, but this may not always be practicable or desirable, for example if wind speed needs to be monitored at various heights to determine wind shear.

For wind turbine power performance evaluation, however, the preferred location for the reference anemometer is indisputably on a mast-top, vertical pole. To avoid flow disturbance caused by the mast, the anemometer rotor and the tower top should be vertically separated by no less than the separation recommended for that type of mast for horizontal booms (see sections 5.1 and 5.2 below).

One of the requirements of performance evaluation is for the reference anemometer to be 'at hub height'. The height of a mast will depend upon its section lengths, and this may dictate that using the recommended vertical separation makes it impossible for the anemometer to be exactly at hub height. This, however, is preferable to adopting a reduced separation.

Meteorological masts can either be of cylindrical or lattice construction and the required separation (either vertically or horizontally in the case of boom mounting) of the anemometer from the tower depends upon the mast's type and solidity.

5.1 Cylindrical Towers

The separation between the mast and the anemometer should reflect the level of uncertainty that is deemed acceptable.

A first approximation to the flow disturbance in the vicinity, but not downstream of a tubular mast can be obtained from simple potential flow theory. However, this gives non-conservative results and a more complex but more exact Navier-Stokes analysis is to be preferred.

Figure 4 shows an iso-speed plot of the flow round a circular cylinder resulting from such an analysis.

The free-stream flow is from the left. Least disturbance can be seen to occur if facing the wind at 45° . For a site with a very unidirectional wind, pointing the boom directly into the wind is therefore not necessarily the best arrangement.

More generally, it can be seen that there is a retardation of the flow upwind of the mast, acceleration round it, and a wake behind it.

The predicted drag coefficient for the case shown is 0.62.

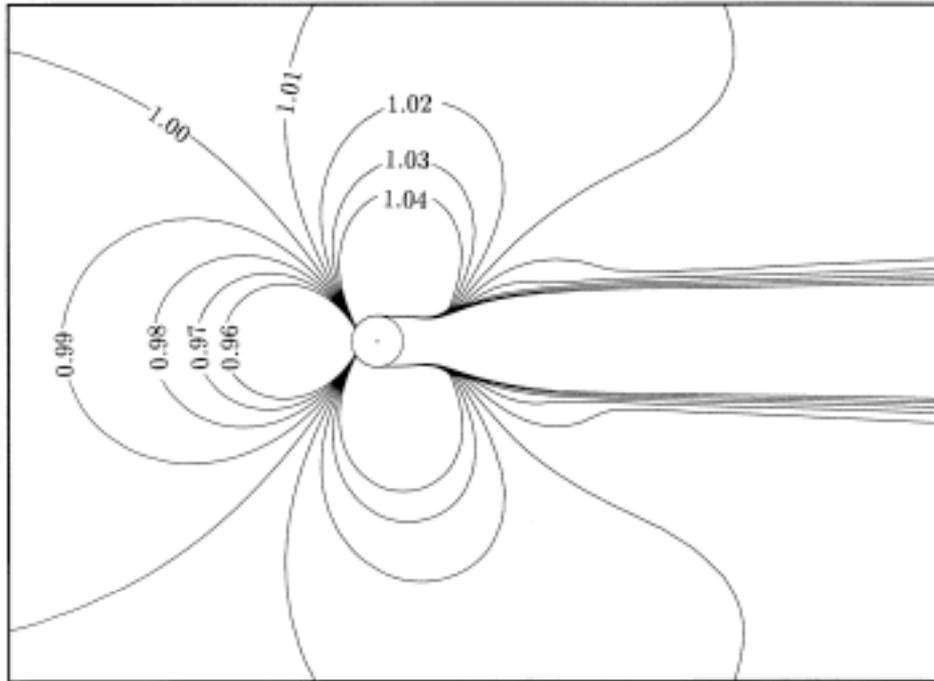


Figure 4 *Iso-speed plot, with local speed normalised by free-field wind speed, of flow round a solid mast of cylindrical cross section; analysis by 2 dimensional Navier-Stokes computation.*

Looking in the upwind direction, the centre-line deficit can be plotted as a function of distance. Figure 5 presents the results in this way.

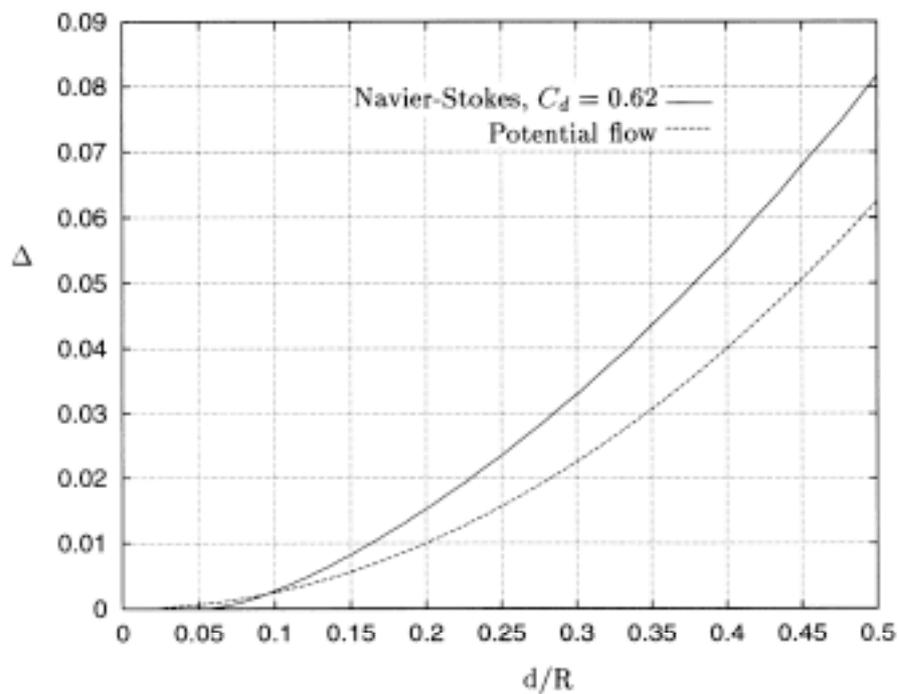


Figure 5 *Centre-line wind speed deficit as a function of reciprocal distance R from the axis of a solid mast of cylindrical cross section and diameter d .*

The plot confirms the lack of conservatism in a simple, analytical, potential flow solution.

A 1% deficit in wind speed is seen to occur at a value of d/R of approximately 0.17. For this level of distortion, a boom-mounted anemometer should thus be no closer than six mast diameters from the centre of the mast.

The corresponding figure for a 0.5% deficit is roughly 8.5 mast diameters.

5.2 Lattice Towers

Analysis of the flow round a lattice structure is less straightforward and the advice given here is based upon a combination of actuator disc and Navier-Stokes theory and analysis¹¹. The results have been validated with field data.

The degree to which flow is disturbed by the mast is a function of the solidity of the mast, the drag of the individual members, the orientation of the wind and the separation of the measurement point from the mast.

Figure 6 shows the representation of the mast used for the analysis.

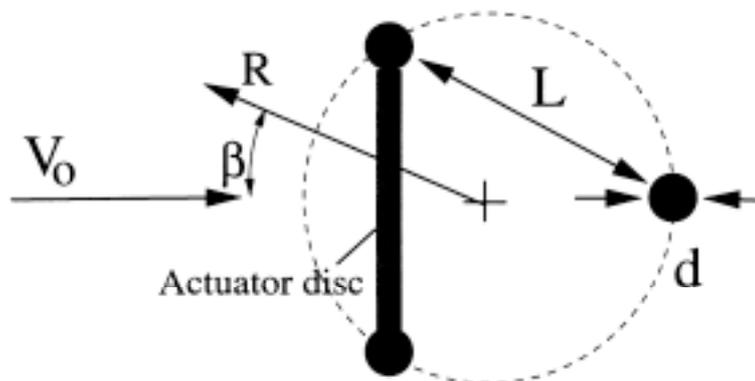


Figure 6 *Representation of a 2 dimensional lattice mast showing the major geometrical parameters and the system for describing nearby points in space.*

The flow distortion is a function of the assumed thrust coefficient, C_T , which in turn depends upon the porosity of the mast and the drag on the individual members. C_T can be regarded as the total drag force, D , per unit length of the tower, divided by the dynamic pressure q and the face width, L .

Figure 7 shows the computed flow round a lattice tower having a C_T of 0.486. There are subtle difference from the case of the solid cylindrical tower, in particular there is very little flow disturbance at 90° to the flow direction, indicating that a side mounted boom is to be preferred in unidirectional wind climates.

Figure 8 shows the computed centre-line deficits for lattice towers having various C_T values. Notice that the plots are very linear unlike in the case of the solid cylindrical tower.

For a lattice tower with a C_T of 0.5 (a tower of relatively low porosity) a 1% deficit in wind speed is seen to occur at a value of L/R of approximately 0.27. For this level of distortion, a boom-mounted anemometer should thus be no closer than 3.7 mast diameters from the centre of the mast. For a deficit of 0.5% the required separation is 5.7 mast diameters.

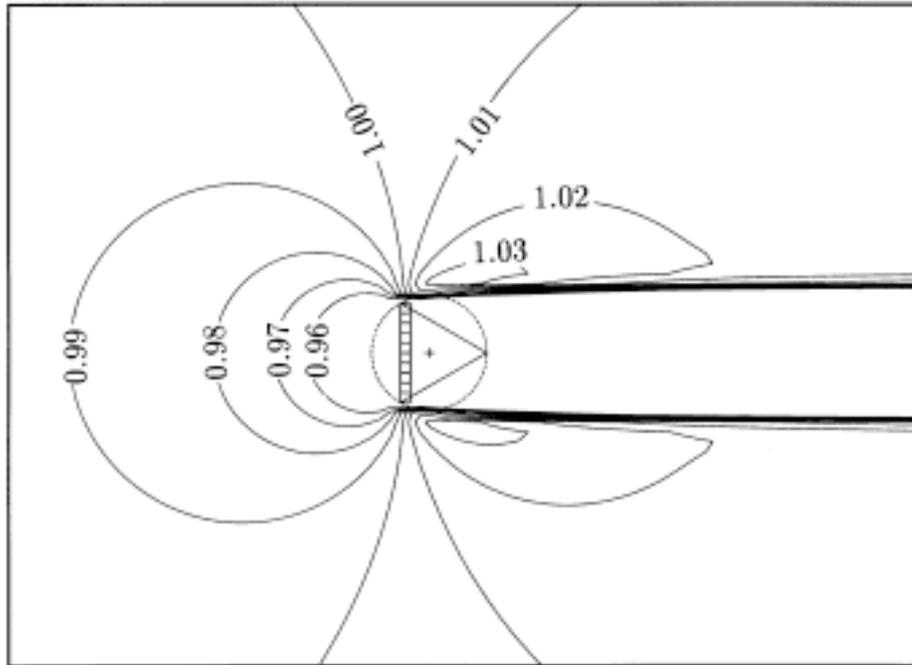


Figure 7 *Iso-speed plot, with local speed normalised by free-field wind speed, of flow round a triangular lattice mast; analysis by 2 dimensional Navier-Stokes computation and actuator disc theory and a C_T of 0.486.*

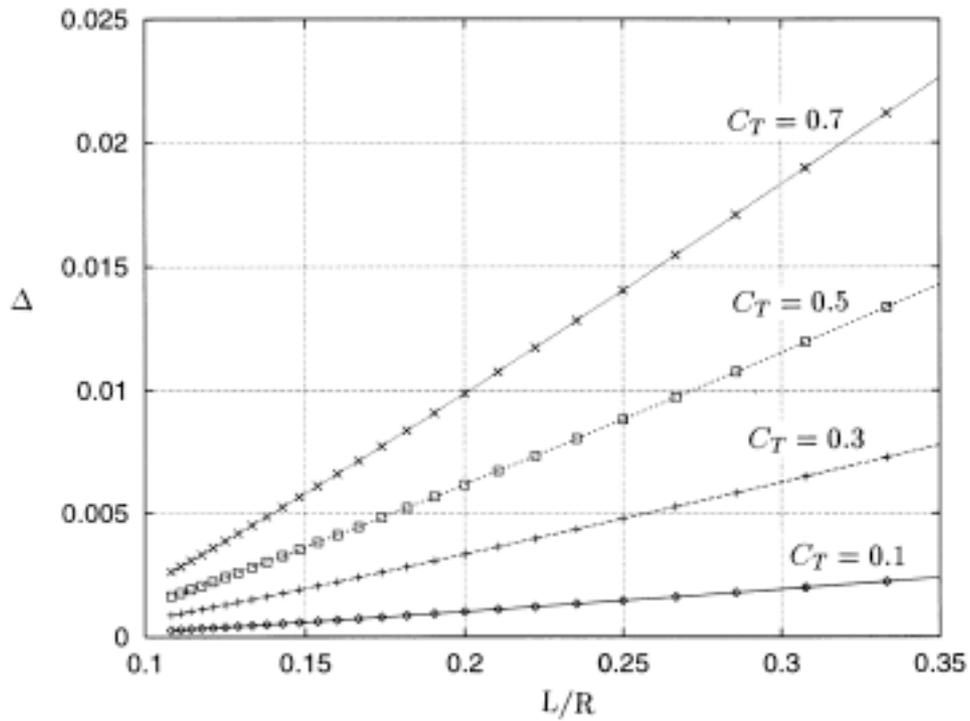


Figure 8 *Centreline wind speed deficit as a function of reciprocal distance R from the axis of a triangular lattice mast of face width L for various C_T values.*

The slope, α , of the deficit versus normalised reciprocal distance lines of figure 8 can usefully be plotted as a function of the parameter C_T . This has been done in figure 9, which again shows remarkable linearity.

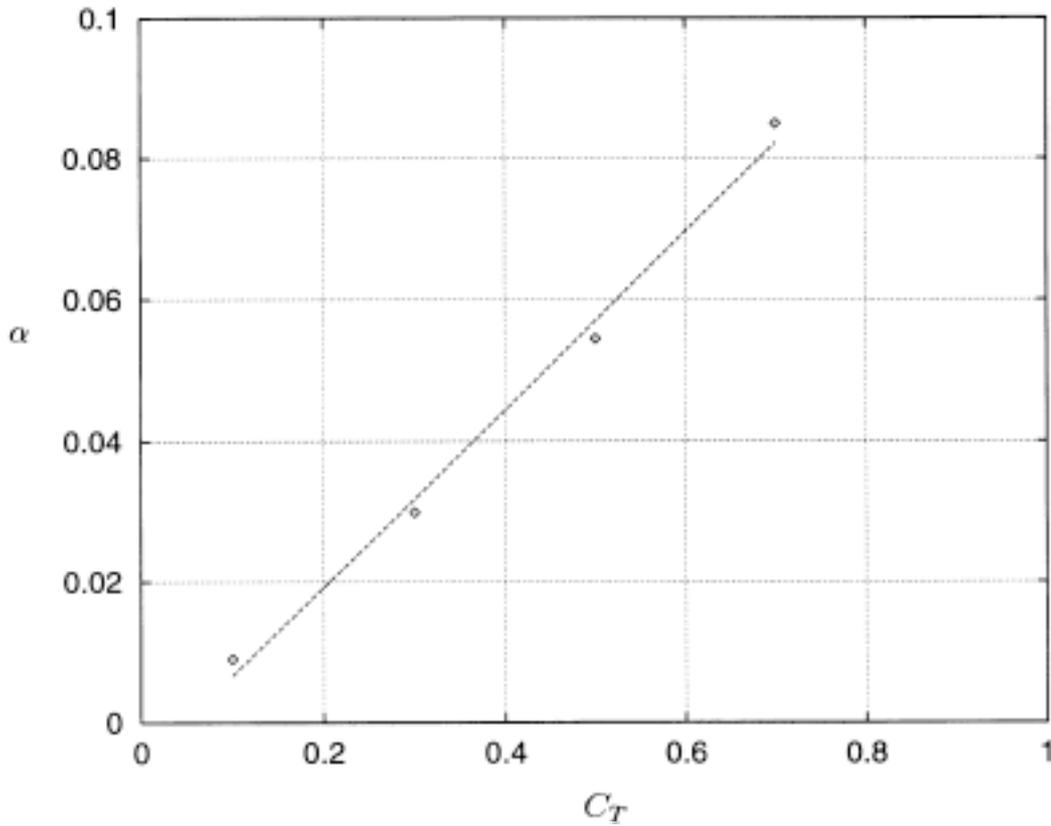


Figure 9 Sensitivity of centre-line wind speed deficit to normalised reciprocal distance (see figure 8) plotted as a function of thrust coefficient C_T .

Curve fitting figures 8 and 9 suggests that the centre-line velocity deficit, Δ , for a lattice mast face-on to the wind can be evaluated as:

$$\Delta = (0.126C_T - 0.006) \left(\frac{L}{R} - 0.08 \right)$$

This expression should be used as the basis for evaluating the mast to anemometer separation required for a desired maximum flow distortion and a given tower C_T . C_T can be estimated from local building codes. The Danish code as an example prescribes the following.

Defining t as the ratio of the projected area of all structural members on the side of the tower to the total exposed area, C_T can be evaluated as shown in table 3.

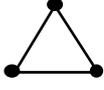
Type of tower	Plan Section	Expression for C_T	Valid Range
Square cross section, members with sharp edges		$4.4(1-t)t$	$0.1 < t < 0.5$
Triangular cross section, round members		$2.1(1-t)t$	$0.1 < t < 0.3$
Square cross section, round members		$2.6(1-t)t$	$0.1 < t < 0.3$

Table 3 Estimation method for C_T for various types of lattice tower according to Danish wind loading standards.

5.3 Booms and Ancillaries

In some cases it will be impractical, impossible or undesirable to locate anemometers at the top of the host mast and booms must be used.

Care should be exercised in selecting a boom orientation. Figures 4 and 7 suggests that booms should lie at 45° to the wind direction in the case of a tubular mast or perpendicular to the wind direction in the case of a lattice mast. If the wind at the site is very directional in nature then this is the best arrangement. However, at most sites the wind is spread over a wide variety of directions, and the best way to avoid mast wake effects is to have the boom point either towards the prevailing wind direction or away from the wind turbine being tested.

Boom effects can be responsible for surprisingly large flow distortion. The degree of distortion will depend upon the separation of the rotor to the boom and also upon the relative orientation of the boom to the wind (maximum disturbance occurring when the boom is face-on to the wind).

Experimental wind tunnel evidence^{12 13} suggests that to keep disturbances below 0.5%, a rotor to boom separation of 12 to 15 boom depths may be needed. In most cases this is easily achievable.

It is preferable for the boom to be of circular rather than square or angle cross section.

In deploying a system, it is important to recognise and avoid other sources of flow disturbance. Significant flow distortion and therefore erroneous wind speed indications can result from:

- crude and bulky clamping arrangements between the boom and the anemometer support (these should be kept compact and symmetrical)
- untidy cabling (cables should be routed where possible inside the support pillars and booms, or where this is not possible, spirally wrapped)
- wakes from tower guys (see also section 7.2)
- lightning finials

In all cases the scale of disturbance can be surprisingly large and should not be ignored, but with care and prior thought, effects can be minimised.

5.4 Sheared Flow

The discussion of mast and boom effects has concentrated on gross changes to point wind speed brought about by flow disturbance.

Users of cup anemometry should also be aware that the degree to which the flow is sheared across the frontage of the anemometer rotor can introduce secondary errors¹⁴.

It might be thought in the presence of a uniformly sheared flow across the face of a cup anemometer, that the anemometer should indicate the mean flow speed. This in fact is not the case as a study of the cup anemometer equation of motion (Appendix 2) demonstrates.

In a flow regime which has a uniform shear across the face of the anemometer resulting in the 'left hand cup position' seeing a flow surplus of 0.2 % and the 'right hand cup position' seeing a flow deficit of 0.2 %, the anemometer will indicate a wind speed which will either be in error by +0.7 % or -0.7 %, depending on whether it is the convex or concave cup face which sees the flow deficit. The anemometer does not average out the sheared flow to indicate the correct mean value.

This effect can be minimised by adopting mast and boom separations at least as wide as those suggested in 5.1, 5.2 and 5.3 and by using an anemometer whose rotor has a small radius and whose cups have high drag coefficients.

This effect is also of particular importance during calibration in a wind tunnel where wall friction can induce sheared flow.

5.5 Summary of Good Practice

Figures 10a and 10b summarise illustratively good and bad practice in mounting anemometry.

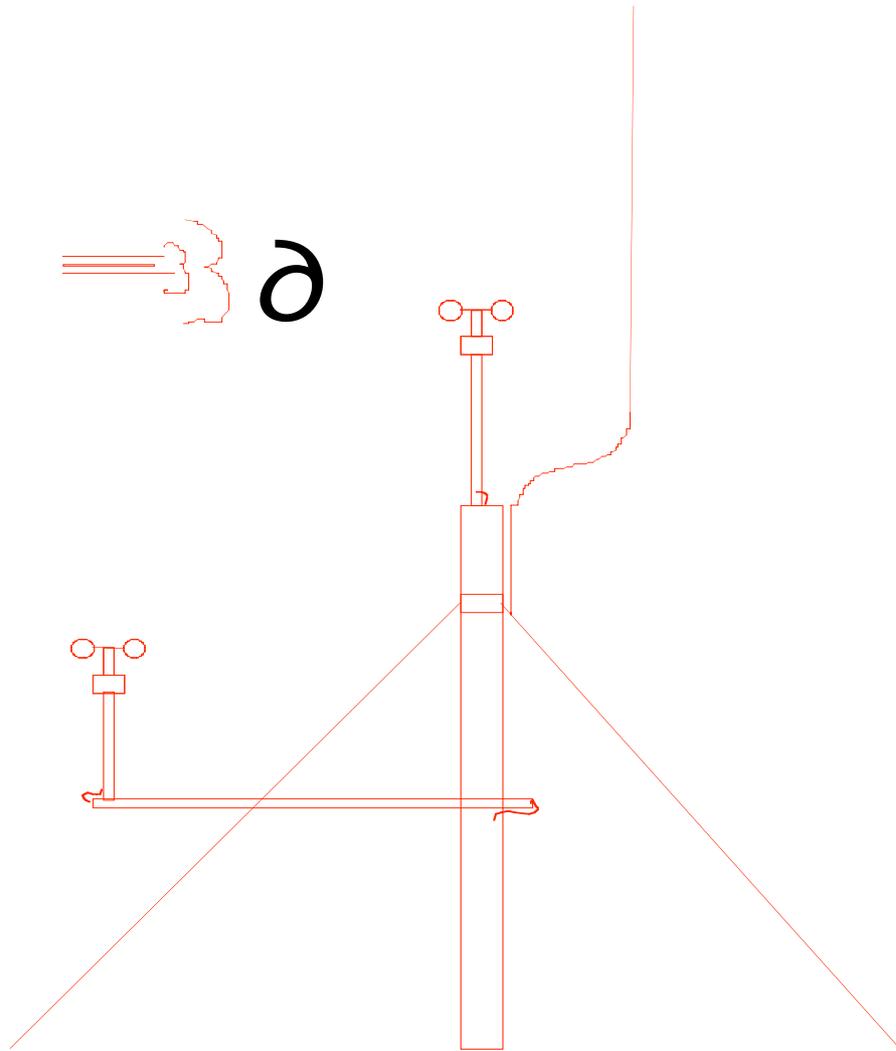


Figure 10a *Example of good practice in deployment of cup anemometry*

This shows:

- a top anemometer mounted on a pillar free from tower effects
- a round section boom which separates the lower anemometer from the tower in accordance with section 5.1 or 5.2
- a pillar which separates the lower anemometer rotor from the boom by at least 15 boom widths in accordance with section 5.3
- the lower anemometer free from the influence of guy wires and other transducers
- all orientations designed to minimise flow disturbance on the anemometers when the wind is in the prevailing direction
- absence of unnecessary protrusions caused by cables, connectors and clamps
- minimal disturbance on the anemometer caused by the lightning finial.

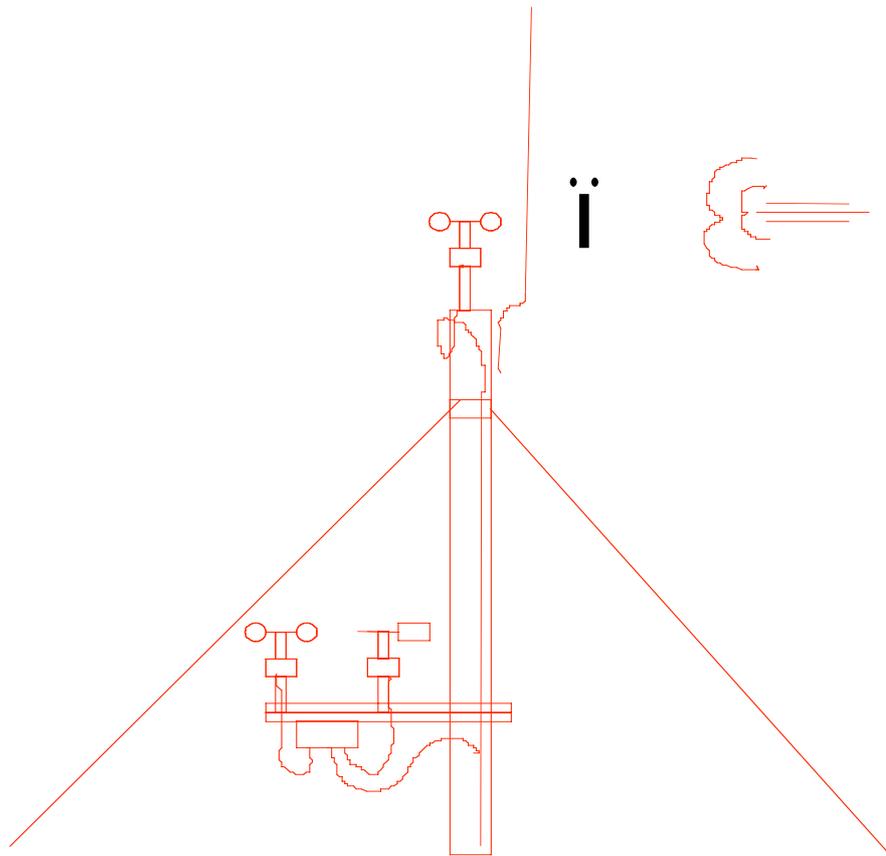


Figure 10b *Example of poor practice in deployment of cup anemometry*

This shows:

- a top anemometer mounted so close to the tower top, it will be influenced by flow distortion effects
- a sharp, angle section boom hosting a lower anemometer which has insufficient separation from the tower
- a pillar which gives insufficient separation between the lower anemometer rotor and the boom
- the lower anemometer in a position which is likely to be influenced by guy wire wakes and which is too close to other transducers
- orientations likely to give maximum flow disturbance on the anemometers when the wind is in the prevailing direction
- little regard to the flow disturbance effects of protrusions caused by cables, connectors and clamps.

6. OTHER PRACTICAL CONSIDERATIONS

When planning a test campaign prior thought needs to be given to ensuring that the measurement system has reliability and that the data will have good integrity.

Specific attention needs to be paid to the possible effect of the climatic environment. Key aspects may be lightning, precipitation and low temperatures.

6.1 Lightning

It is normally essential to protect the meteorological mast installation from lightning strike. Relevant advice for protection of wind turbines is contained in another IEA publication¹⁵, much of which is pertinent to protection of met masts.

Due to their nature, met masts cannot avoid being struck by lightning and the challenge therefore is to ensure that a strike does not damage the test equipment.

A number of key precautions can be taken:

- a lightning finial (attractor) should be mounted at the top of the tower, in such a position that it affords the tower top anemometer with protection (normally a 60° protection umbrella can be assumed) - it is normally adequate to use the tower as the path to ground, but added protection can be afforded by running a separate cable
- an adequately sized earth connection (earthing rod) should be strapped to the tower base
- the instrumentation system should be designed so that it does not provide a low resistance path to earth, the aim being to encourage the strike to pass via the structure
- lightning surge arrestors should be used should the data system not have in-built protection.

Sometimes the probability of lightning strike will be very low, and it may be decided not to use a lightning protection finial so as not to disturb the mast top anemometer.

6.2 Precipitation

In many countries, where winds are driven more by large scale weather systems than by local thermal effects, there can be a direct correlation between wind speed and likelihood of rain.

It is not unexpected therefore that anemometers themselves are normally designed to be able to withstand wet weather.

Problems, where they do occur, are more frequently linked to inadequate protection of cables, connectors and data system enclosures.

Good practice involves:

- avoiding any kind of in-line cable connection (it is preferable where-ever practicable to hard wire the anemometers directly to the data system), but where it is unavoidable, protecting the connection by using environmentally rated connectors and giving them added protection by for instance housing them within the host boom
- using enclosure for the data system which are appropriately rated for the climate
- using bottom entry glands for all entries/exits from enclosures and junction boxes.

6.3 Low Temperatures

Low temperatures can cause particular problems for cup anemometers.

Clearly the accumulation of rime ice or snow in the cups will cause a change in aerodynamic behaviour, and appropriate measures need to be taken to detect when such conditions occur so that data can be rejected. Preventing accumulation is extremely challenging and can involve the use of special coatings and/or remote infra-red heaters, but such measures are rarely justifiable.

A more pernicious problem is that of the temperature effect on mechanical friction. For many sites, it is adequate to simply reject data when temperatures fall below a given threshold (say 2°C), but in cold climates, it may well be necessary to use shaft heating (this is an option with many anemometers).

When specifying shaft heaters, it is vitally important to recognise that externally applied devices which are asymmetric or which have external cable connections will disturb the flow characteristics and will render the anemometer with directionally dependent variations in calibration.

Only using heating elements that are fully enclosed within the anemometer shaft best solves the problem.

7. DATA CAPTURE, QUALITY ASSURANCE AND UNCERTAINTY

By adopting the principles outlined in the foregoing sections for the selection and deployment of anemometers, it should be possible to obtain good accuracy and reliability in an experimental evaluation.

7.1 Planning for Integrity and High Success in Data Capture

It is worth noting some points that have not yet been covered.

Anemometers are generally available with either pulse or analogue voltage output. Unless there is very good reason to do otherwise (e.g. available data loggers may not be able to cope with pulse output), pulse output instruments are to be preferred to their analogue counterparts. Analogue instruments tend to be more expensive (the analogue signal is often derived from a pulse generator via an additional frequency to voltage converter) and are more subject to signal degeneration and interference during transmission. High pulse-rate anemometers are to be preferred to low pulse-rate models due to the additional ease with which turbulence intensity can be derived.

Anemometers like other instruments can fail totally, or more seriously can partially fail. For instance a bearing might begin to seize, or a cup break loose. Building in redundancy to the measurement system, for instance by providing additional anemometers, is often desirable.

There can often be delays in recognising data failures and subsequent mobilisation for repair can lose further valuable time. Two months can be lost out of a test programme very easily unless contingency action plans are prepared in advance.

The most important preventative activity that can be carried out is regular inspection of the mast and regular inspection and quality assurance of the data. Technology now allows remote recovery of data e.g. via microwave, modem or cellular telecommunications technologies, and it is

relatively easy to set up data screening programs that will automatically check the integrity of incoming data. Such processes can ensure that problems are recognised early.

7.2 Quality Assurance

Before passing any wind speed and other meteorological data for analysis, it is absolutely essential that they are first subjected to quality assurance screening checks.

Visually scanning time series graphs can be useful for identifying obvious problems, but more objective numerical scrutiny should always also be carried out.

This should include:

- ensuring that all data lies within instrument specifications (e.g. for ambient temperature and supply voltage)
- ensuring that there is no physical reason for data rejection (e.g. when an anemometer is known to be operating in the wake of the tower)
- ensuring that no 'impossible' physical phenomena are being implied (e.g. excessively high turbulence, which might be caused by wakes from guy wires or prolonged aberrant behaviour of the shear layer).

Test conditions for data acceptance can normally be set up using a set of logical condition tests (IF, AND etc)

Attempts to explain and rectify problems should always be made.

7.3 Uncertainty Assessment

Any evaluation of wind speed, be it for wind speed assessment of a site, for calibration of wind flow over a site or for power performance evaluation of a wind turbine, should be accompanied by a thorough assessment and numerical statement of uncertainty.

Uncertainty assessment should be carried out in accordance with recognised ISO guidelines.

Type A uncertainty in derivation of mean wind speed is readily derived from the statistics of the measured data, but objective and comprehensive evaluation of type B uncertainty is more challenging.

In a 10m/s wind having a turbulence intensity of 10%, a typical standard uncertainty in the derivation of a 10 minute average wind speed will be 0.5%.

Type B uncertainty sources include:

- steady state calibration (1.0%;5%)
- possible variation or change in calibration (0.2%;3.0%)
- flow inclination effect on calibration (0.2%;1.5%)
- possible overspeeding caused by instrument dynamics (0.2%;1.0%)
- flow distortion from the mast (0.5%;2.0%)
- flow distortion from the boom (0.5%;2.0%)
- flow distortion from mounting clamps and other protrusions (0.1%;2.0%)
- asymmetry of flow (shear) incident on anemometer (0.2%;2.0%)
- instrumentation system uncertainties including calibration and quantisation effects (0.2%;1.0%).

For each item in the list, two percentage figures are given. The first indicates typical standard uncertainty for a good quality installation. The second figure would not be untypical of a poor quality installation. Adding all of these sources in quadrature gives a combined total uncertainty of 1.5% for the good quality installation (this should be regarded as the best achievable) whilst the figure for an installation where best practice has not been adopted is in excess of 7%.

8. SUMMARY

The foregoing sections and the accompanying appendices provide working overviews of the current state-of-the-art of understanding of cup anemometer behaviour and of good experimental practice.

The following key qualitative recommendations can be given (more quantitative information can be found elsewhere in the document):

- for studies which require the accurate definition of mean wind speed, such as power performance evaluation and wind climate assessment, cup anemometers should be used in preference to other types of anemometer
- when selecting a cup anemometer due regard should be given to factors which might affect sensitivity to vertical winds, directional uniformity of calibration, responsiveness and, finally, linearity and stability of calibration as a function of temperature
- instruments with a high rate pulse output are in general to be preferred to analogue designs
- the compatibility of a cup anemometer to the expected range of environmental conditions (its classification) should be assessed as part of the selection process
- anemometers should always carry an individual, current calibration obtained from a competent and accredited calibration organisation
- calibrations should always be supported by clear definition of calibration uncertainty
- the ideal location for mounting an anemometer is on a vertical pole, clear of the top of the host meteorological mast, but where this is impractical care should be taken to ensure that the anemometer is mounted on a boom and pillar whose lengths are sufficient to ensure that flow disturbance at the point of measurement is sufficiently low
- in reviewing flow disturbance, it should be recognised that horizontally sheared flow can be a particular problem
- it is important when deploying anemometers to ensure that the installation is ‘clean’ ie that there are no sources of local flow disturbance such as guy wires, loose cabling, connector boxes etc
- to ensure good signal integrity and availability, it is important when mounting a wind monitoring campaign to design against the effects of lightning, precipitation and low temperatures
- careful planning of data recovery and screening is important in ensuring high success in data capture.

APPENDIX 1

ALTERNATIVE TYPES OF ANEMOMETER

The main text unequivocally recommends the cup anemometer as being the preferred instrument for long term recording of mean wind speeds during site assessments or wind turbine performance evaluations.

Nevertheless cup anemometers are not a meteorological panacea, and should additional measurements of wind structure be required, then other types of instrument may well be preferable.

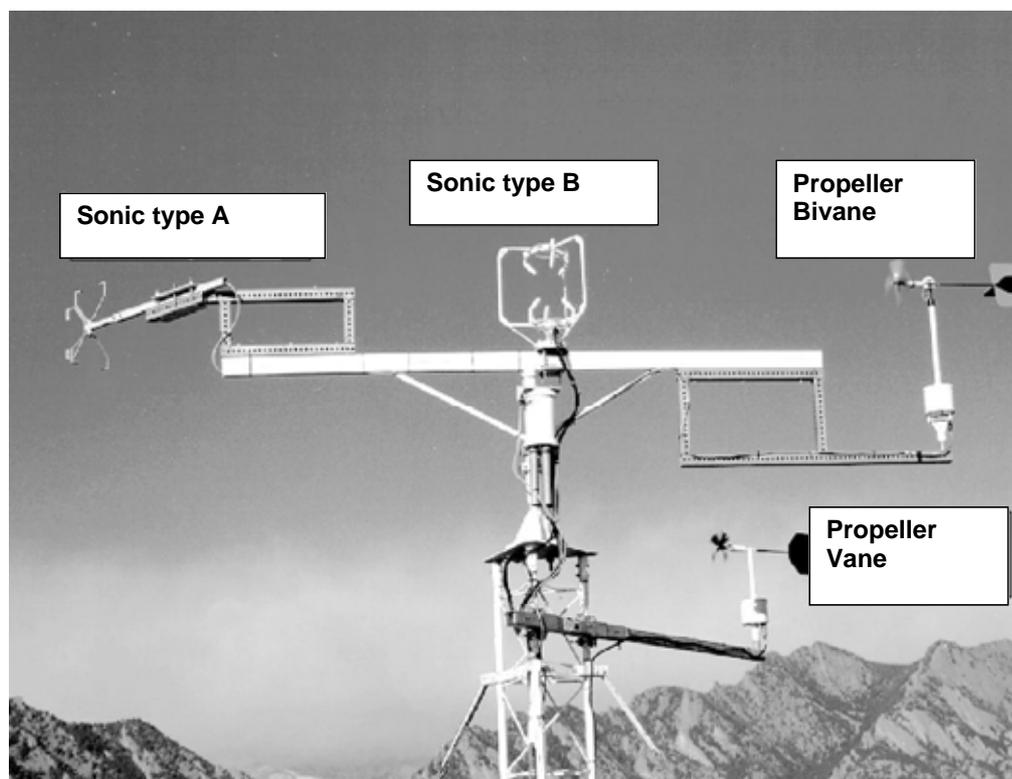
In this appendix, a number of different types of anemometer are described and assessed, in the context both of mean wind speed measurement and of detailed investigation of turbulent structure.

The appendix is not exhaustive, and certain types of instrument not in common use for wind energy applications are not examined (this includes laser Doppler (LDA), swinging plate and pressure tapping type instruments).

‘Alternative’ anemometry can be classified as mechanical, acoustic or thermal depending upon the working principle. Here, in the first category, the assessment is confined to propeller type devices, including helicoid propeller, propeller-vane, propeller-bivane and three-axis propeller devices. Within the acoustic category, both sonic and SODAR anemometers are reviewed.

For each type of instrument an overview of the principle of operation is given followed by a list of advantages and disadvantages.

The figure below shows a selection of sonic and propeller instruments.



PROPELLER TYPE ANEMOMETRY

Overview and Principle of Operation

Originally invented in the 1880's the helicoid propeller anemometer was resurrected as the *Aerovane* in the 1940's and has seen extensive use in a wide variety of environments including marine. In the 1960's propeller-vane and propeller-bivane anemometers based on the helicoid concept were developed for turbulence measurements.

The design of the helicoid propeller is such that the rate of rotation (above the effects of bearing friction) is linearly proportional to the wind speed. For example, the original four-bladed Gill propeller was designed to have a pitch (rotation) of 360° for one foot (0.305 metres) of air passage. The propeller has a nominal cosine response to the incident angle of the wind vector. This means the propeller responds primarily to that portion of the wind vector that is parallel to the rotor axis.

For making actual measurements of horizontal wind speed, and unlike the cup anemometer, a tail vane is needed to keep the propeller facing into the wind (the propeller vane anemometer).

To measure total wind speed, a second degree of freedom (pitching) can be added (the propeller bivane).

Note that these instruments can notionally be used to measure wind speed or wind vector.

The total wind vector may also be measured by a fixed, orthogonal array of three helicoid anemometers. To achieve accurate results, a post-measurement, empirical correction procedure must be applied to account for the deviation from the true cosine sensitivity about each axis and for the flow interaction effects from the instrument support arms.

Advantages

The helicoid propeller anemometer, when used in conjunction with an orienting vane, provides both wind speed and direction information in a single unit. In theory the propeller anemometer should not require wind tunnel calibration. In practice, however, such calibrations should be performed on a regular basis to establish the low-wind speed performance and to detect increased drag from bearing wear. Though not usually important in wind energy applications, the very low starting speed (particularly with photo-electronic signal generation) caused by the relatively high level of aerodynamic torque, is sometimes an advantage over more expensive cup anemometers exhibiting the same characteristics. Over-speeding errors are generally not considered to be a major problem with propeller anemometers but there is some evidence that they do indeed exist. Experience has shown that the propeller anemometer is a reasonable sensor for measurement of turbulence, at least for establishing minimal characteristics such as turbulence intensity and horizontal wind speed standard deviation.

Disadvantages

A particular disadvantage of the propeller vane is related to its inability in a real turbulent dynamic wind to track changing wind directions perfectly. This inertial effect can result in directional overshoots that can place the rotor off the wind axis resulting in a lower wind speed reading. This is particularly true in low wind speeds under unstable flow conditions when the

azimuthal wind direction is changing rapidly in response to the passage of large, convective eddies. Low values of the tail-damping coefficient (often used in instruments designed to withstand very high wind speeds) can also lead to low readings arising from off-axis behaviour. Horizontal off-axis errors tend to be much less severe at high wind speeds because of the substantial tail aerodynamic damping available. Off-axis flows in the vertical direction can also be responsible for errors in wind speed measurements. This is particularly true for propeller-vane anemometers installed on sloping terrain or near abrupt topographical features which can sustain either a steady vertical component or frequent, large vertical velocity excursions.

The measurement of the total wind vector can be accomplished by either the propeller-bivane or the 3-axis, orthogonal array of propeller anemometers. Measurements in strong, gusty winds with a propeller-bivane have shown that the precessional or gyroscopic motions associated with a rapidly accelerating rotor cause the propeller axis to swing in the direction of rotation and away from the true wind vector orientation. These excursions are often amplified by the under-damped azimuth and elevation angle responses causing a combination of horizontal and vertical off-axis speed errors. Such responses often lead to both high and low total wind speed readings (depending on conditions) and overstated values of standard deviation. The chief problem with the 3-axis, orthogonal array as a sensing system for the total wind speed is associated with the application of the off-axis and support arm shadowing corrections, which has considerable inherent uncertainty. A contributor to this uncertainty is the fact that the dynamic response of a helicoid propeller to wind speed changes decreases when the angle between the flow and axis increases. For example when the angle with respect to the rotor axis reaches 85 degrees, its distant constant has tripled.

An additional effect that has been noted with propeller anemometers in highly turbulent conditions is associated with stalling of the blades. This can occur when a rapid rise in wind speed occurs to which the rotor cannot respond.

The use of propeller anemometers for power performance measurements especially within a multi-row wind farm is strongly not recommended. Experiences using such equipment in a densely populated wind farm have revealed horizontal wind speed errors that exceeded 25% under certain atmospheric flow conditions.

ACOUSTIC (SONIC) ANEMOMETERS

Overview and Principle of Operation

The modern sonic anemometer has been developed primarily as a tool in atmospheric boundary layer turbulence research. Being non-mechanical in operation, it overcomes many of the problems associated with cup and propeller anemometers and flow direction vanes particularly with regard to dynamic response characteristics which are so important in turbulence research. These advantages come at a high price in terms of complexity and therefore cost. A 3-axis sonic anemometer can provide a very high resolution measurement of the three-dimensional wind vector. However flow distortions caused by the structure of the instrument can translate into significant errors in the direction and magnitude of the measured wind vector.

The sonic anemometer operates on the principle of precisely measuring the time it takes an ultra-high frequency acoustic pulse (typically 100 kHz) to traverse a known path length in the direction of the wind and opposed to it. The relationship between the transit-time difference Δt and the air velocity V_d is

$$\Delta t = \frac{2d}{a^2} V_d$$

where a is the sound velocity and d is the path length. A knowledge of the air temperature T and the relationship $a^2 = kRT$ where k is the ratio of specific heats and R the gas constant allows the wind velocity to be expressed in terms of the transit-time difference Δt . Modern sonic anemometers can measure these transit time differences with sufficient resolution to achieve velocity sensitivities as low as 0.5 cm/s.

Advantages

The sonic anemometer, like the helicoid propeller, is a fundamental principle instrument. In its purest form it does not exhibit the non-linearities and other errors associated with its mechanical brethren. Its chief attributes are its resolution and precision (and not necessarily the accuracy) with which it can measure the total wind vector. It has the capability of providing excellent measurements of incident flow angles when properly utilised.

The sonic anemometer is ideally suited to measurement of turbulent structure.

Disadvantages

Sonic anemometers are not well suited to definition of mean wind speed as required for site assessment or power performance evaluation.

The most obvious disadvantage of using sonic anemometry is inherent cost, but there are also technical reasons. Firstly, sonic anemometer accuracy is not always particularly good, although dynamic response is excellent. Also the presence of precipitation can prevent operation. Additionally, the geometry of the sensing heads used by current sonic anemometers induce a degree of flow distortion which can produce wind speed errors.

ACOUSTIC (SODAR) ANEMOMETERS

Overview and Principle of Operation

Although they both rely upon acoustic principles, SODAR anemometers differ greatly from sonic anemometers in the spatial scale of their measurement. Sonic anemometers study wind structure by employing acoustic principles between closely spaced transmitters and receivers, whereas SODAR instruments look at larger scale structures using a combined transmitter/receiver and remote back-scattering.

The SODAR (sound detection and ranging) technique is based on scattering of short, directional, narrow beamed sound pulses. The pulses are emitted from a ground based acoustic antenna. Sound scattering occurs where there are small-scale fluctuations in the acoustic refractive index field. These are caused by inhomogeneities in the temperature field, which in turn moves with the atmospheric wind. The central frequency of the back-scattered signal differs from that of the emitted pulse due to the Doppler effect. The antenna can detect the frequency shift, which is directly dependent upon the wind speed along the sound propagation path. By using more than one antenna, each orientated in a different direction, the three dimensional wind vector can be derived. The frequency of the received sound signal can be allocated to a height according to the

propagation time. It is thus possible to obtain a vertical wind profile measured simultaneously at different heights.

To cover an altitude range of 20 up to 150 metres, as is of interest for large wind energy applications, so called mini-SODARs can be used. These have an operating frequency of 4 to 6 kHz (i.e. are in the audible range) and can provide continuous profile information with moderate resolution in space (between five and ten metres) and time (every second).

The typical uncertainty in measurement of wind speed using SODAR is about 2 to 4%. This can be reduced if cross-comparison is made with a parallel, low level meteorological mast.

Advantages

The major advantages of SODAR relate to its ability to define wind profiles and to look at higher elevation wind speeds. These can be prohibitively expensive to monitor using mast mounted meteorological instruments. The cost of meteorological masts increases non-linearly with height and therefore SODAR is of clear relevance to MW scale turbines.

SODAR systems are also highly portable making it inexpensive to conduct short-term campaign investigations.

Meteorological mast installations may require planning permits from the local government authority. SODAR requires no such permissions.

Being a remote sensing tool, SODAR does not disturb the flow in the way that a met mast does.

Disadvantages

SODAR systems are not yet in widespread use for wind energy applications. They are not cost effective for smaller turbines and the choice of suppliers is limited. Being portable makes SODAR systems vulnerable to theft and being ground based, the antennae can be readily damaged. SODAR therefore is not well suited to long-term, unattended data collection.

Although portable, SODAR requires a stable platform. SODAR systems may be very useful in the context of the offshore MW turbine market, however they could not simply be mounted on floating vessels.

The fact that SODAR systems operate in the audible range may in some instances be a disadvantage.

APPENDIX 2

CUP ANEMOMETER EQUATIONS OF MOTION

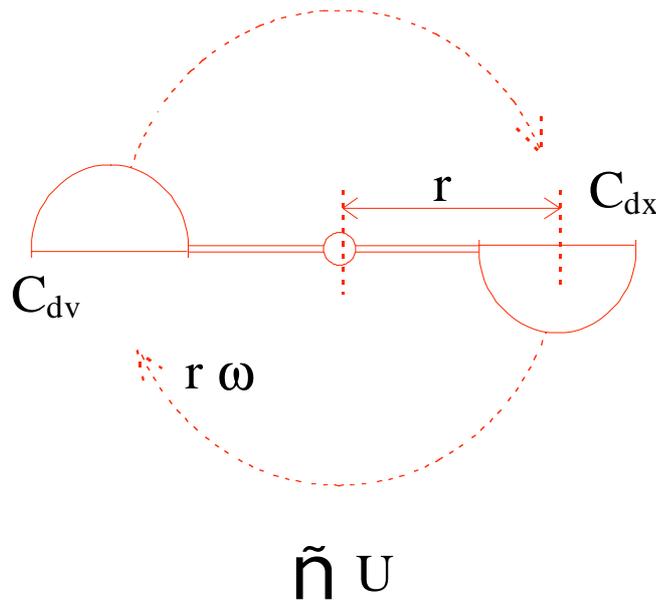
This appendix is designed to present the more important aspects of cup anemometer behaviour in a mathematical context and in particular to support certain sections of the main text.

In analysing the behaviour of the cup anemometer, it is helpful to look at aerodynamic, inertial and frictional effects, and a suitable starting point is the aerodynamic element.

Although most cup anemometers have three cups so as to give a low torque ripple, it is more convenient analytically to look at a two cup arrangement. In looking at gross effects, this is perfectly justifiable. The analysis can be regarded as looking at one of the three cups and looking at the aerodynamic effect averaged over a complete rotation.

General Aerodynamic Balance

Consider a cup anemometer rotating at speed ω in a free wind speed U :



The instantaneous aerodynamic torque on the rotor, M_A , is given by:

$$M_A = \frac{1}{2} r \rho A C_{dv} (U - r\omega)^2 - \frac{1}{2} r \rho A C_{dx} (U + r\omega)^2$$

where A is the frontal area of the anemometer, ρ is the air density and C_{dv} and C_{dx} are the drag coefficients for the concave and convex faces of the anemometer cup.

In the steady state, there is perfect torque balance ($M_A=0$), and the equation reduces to:

$$C_{dv} (U - r\omega)^2 = C_{dx} (U + r\omega)^2$$

defining λ and μ as the speed and drag ratios respectively:

$$\lambda = \frac{r\omega}{U}; \mu = \frac{C_{dv}}{C_{dx}}$$

allows further re-expression in a quadratic form which has the solution:

$$\lambda = \frac{\mu + 1}{\mu - 1} - \sqrt{\left(\frac{\mu + 1}{\mu - 1}\right)^2 - 1}$$

Typical values of C_{dv} and C_{dx} are 1.4 and 0.4 respectively, giving a value of μ of 3.5. The above equation predicts that the consequential speed ratio λ will be 0.303, ie the rotor will rotate at approximately one third of the wind speed. Note that this solution also serves to confirm the theoretically linear sensitivity of the cup anemometer to wind speed. It furthermore confirms that the speed ratio depends solely on the drag characteristics of the cup (not the size) and that rotational speed is inversely related to rotor radius.

Aerodynamic Balance in Sheared Flow

In section 5.4 it was stated that a uniform horizontal shear across the face of the cup anemometer rotor would not be averaged out arithmetically by the anemometer.

To demonstrate this, consider the previous figure but with the left hand cup with concave face windward seeing wind of $U(1+\varepsilon)$ and with right hand cup with convex face to windward seeing a wind speed of $U(1-\varepsilon)$. The steady state aerodynamic equation of motion this time

$$C_{dv}(U(1+\varepsilon)-r\omega)^2 = C_{dx}(U(1-\varepsilon)+r\omega)^2$$

The quadratic solution this time is:

$$\lambda = \frac{(1+\varepsilon)\mu + (1-\varepsilon)}{\mu - 1} - \sqrt{\left(\frac{(1+\varepsilon)\mu + (1-\varepsilon)}{\mu - 1}\right)^2 - \left(\frac{(1+\varepsilon)^2\mu - (1-\varepsilon)^2}{\mu - 1}\right)}$$

A value of ε of 0.2% yields a λ of 0.305 which is 0.7% higher than the previous value which related to the zero shear condition.

Distance Constant

In the absence of friction, the rotor inertial force will balance the aerodynamic torque:

$$I\alpha = M_A$$

The first equation in this appendix suggests that this dynamic relationship can be re-expressed in the general form:

$$\frac{d\omega}{dt} = -a\omega + bu^2 + c\omega^2$$

where a , b and c are constants which depend purely upon the aerodynamic, geometrical and inertial characteristics of the rotor.

The final term, numerically, will always be of minor significance and can be dropped in order to obtain a solution.

The responsiveness of a cup anemometer is conveniently described by its behaviour following a step change in wind speed.

Assume that at time $t < 0$, the wind speed is u_0 and that the anemometer has reached a steady state rotational speed ω_0 of $(b/a)u_0$. At time $t = 0$, the wind speed undergoes a step change Δu to u_1 .

The analytical solution to the reduced dynamic equation of motion is then:

$$\omega = \frac{b}{a} \left[u_0 + \Delta u \left\{ 1 - \exp\left(-\frac{t}{\tau}\right) \right\} \right]$$

where τ is equivalent to $I/(a.u_1)$ and describes the time taken for the anemometer to respond to $(1 - (1/e))$ or 63.2% of the change in wind speed.

τ is clearly dependent upon the ‘target’ wind speed and cannot therefore be regarded as being an instrument constant. The coefficient I/a however is fixed and is termed the anemometer distance constant, this being equivalent to the length of air stream which passes the anemometer during the time taken for it to respond to 63.2% of the step change.

Cup anemometers for use in wind energy applications should have a value of I/a of about 2.0 to 3.5 metres.

The above solution and definition of distance constant imply that a cup anemometer will be more responsive to turbulence at higher wind speeds.

In practice, an anemometer cannot be expected to have a fixed distance constant. The above derivation ignored an aerodynamic term which can be of significance (ignoring it has given rise to a solution which is clearly wrong if the wind speed drops to zero - the anemometer is predicted to carry on rotating at its initial speed) and also ignored all frictional effects. The distance constant should therefore be regarded as an approximate relative indicator of an anemometer’s responsiveness.

Frictional Effects

At the beginning of the appendix, an expression was given for the aerodynamic torque developed by a cup anemometer.

In drawing up a more complete equation of motion, mechanical friction should also be included:

$$I\dot{\omega} = M_A - M_F$$

where I is the rotor inertia and the frictional torque, M_F , in general form is given by:

$$M_F = F_0 + F_1\omega + F_2\omega^2$$

where F_0 , F_1 and F_2 are termed the static, dynamic and parabolic friction coefficients respectively.

The new dynamic equation of motion is

$$\frac{d\omega}{dt} = \frac{\omega^2}{I} \left[\frac{1}{2} \rho A r^3 (C_{dv} - C_{dx}) - F_2 \right] - \frac{\omega}{I} \left[\rho A r^2 U (C_{dv} + C_{dx}) + F_1 \right] + \frac{1}{I} \left[\frac{1}{2} \rho A r U^2 (C_{dv} - C_{dx}) - F_0 \right]$$

which in comparison with the earlier aerodynamic based version is seen to have modified coefficients for each right hand side term.

The more important effect of friction relates to steady state sensitivity, which can be investigated by setting the left hand side of the above equation to zero.

It is quickly seen that a linear relationship between rotational speed, ω , and wind speed, U , no longer exists.

Further investigation of the mathematics shows that friction serves to:

- introduce an offset into the calibration
- alter the general linear gain from the zero friction case, and
- introduce a non-linearity.

APPENDIX 3

CALIBRATION PROCEDURES AND RECOMMENDATIONS

Ideally where an anemometer is calibrated should not affect the calibration results. Experience of inter-comparison exercises demonstrates that this is not so and points towards the need for quality assurance, traceability, objective assessment of uncertainty and recognised procedures.

This appendix is based upon a procedure that has been established and implemented by the MEASNET grouping of wind turbine testing organisations¹⁶.

Anemometers must be individually calibrated in a wind tunnel of adequate quality run by a qualified organisation to recognised procedures.

The Calibrating Institution

The calibrating institution should be able to demonstrate its competence to calibrate anemometers.

Within Europe this can be shown by formal accreditation to EN45001.

In other countries or in the absence of EN45001, the institution should be able at least to demonstrate:

- traceability of all instrumentation to national standards
- procedures to control instrumentation
- consistency of calibrations obtained in the wind tunnel with those produced by other competent organisations
- repeatability of results for different operators and for different occasions
- formal training qualification requirements for operators

The Wind Tunnel

Although the availability of an objective assessment of uncertainty is more important in the selection of a tunnel than the potential for high accuracy, a number of requirements should be placed on the tunnel:

- it should have a working range of at least 4 m/s up to 16 m/s
- the axial turbulence intensity of the flow should be less than 2%
- the mean flow profile should be uniform to within 0.2% (i.e. standard deviation of all points in the working cross section should be below this value); the difference between mean wind speeds at the positions corresponding to the 'convex cup' and 'concave cup' 'face to the wind'
- it should have a blockage ratio (the ratio of the frontal area of the anemometer and associated mountings to the total working cross-section of the tunnel) no more than 0.1 for open and 0.05 for closed section tunnels

Wind Tunnel Calibration

The wind speed seen by an anemometer during calibration cannot be measured directly. Thus the wind tunnel must be 'calibrated'. This involves correlating conditions at a reference position

with those at the position to be occupied by the anemometer rotor during anemometer calibration. Calibration should encompass the following principles and procedures:

- the reference position should be chosen so as to be close to the anemometer position but not so close that mutual flow disturbance effects are experienced (this can subsequently be checked by moving the anemometer into and away from its calibration position and checking that no flow changes are seen at the reference position)
- if possible, more than one reference position should be chosen, and an average reference value established
- calibration should be carried out using pitot tubes and the rig calibration established for dynamic pressure, not wind speed
- specific procedures should be put in place to set the position and alignment of the pitot tubes (the uncertainty in alignment should be no more than 1°)
- calibration should be carried out for rig settings which approximately correspond to those to be used for anemometer calibration
- readings should be averaged over 30 seconds and data should be collected both for rising and falling wind speeds
- automatic digital data acquisition is to be preferred and a sampling rate of at least 10 Hz should be used
- normal good practice in data sampling should be adopted e.g. use of anti-aliasing filters and amplification to ensure full use of the data systems conversion range
- to reduce uncertainty, the rig calibration should be repeated with the pitot tube and pressure measurement systems interchanged between reference position and anemometer position
- in processing the results the data should be subjected to a two parameter linear regression of anemometer position conditions on reference position conditions
- only the slope of the regression should be used subsequently since the offset will relate to instrument zeroing conditions specific to the rig calibration test
- the calibration should be supported by an assessment of uncertainty in accordance with ISO principles (due to swapping of systems, many type B uncertainty sources can be neglected and type A should dominate)
- the calibration should be re-established after any alteration or service to the tunnel
- the wind tunnel calibration should undergo a gross check prior to every contract calibration, this being done by an abbreviated calibration of a reference anemometer kept specifically for the purpose
- calibrations of the reference anemometer obtained during different atmospheric conditions should be used to demonstrate repeatability - the maximum difference between calibrations at 10 m/s should be no more than 0.5%
- an up-to-date facility report should be maintained which records details of the rig and its calibration

Anemometer Calibration

Recognised, written procedures should exist for the calibration of anemometers, and these should include the following aspects:

- prior to the calibration, the overall integrity of the facility should be verified by carrying out a comparative check calibration of a reference anemometer kept by the institute specifically for that purpose

- prior to carrying out a calibration, the anemometer should be run for approximately 5 minutes
- for anemometers to be used for wind turbine power performance evaluation a calibration range of 4 to 16 m/s should be adopted with 1 m/s spacing, a sequence of 4, 6, 8, 10, 12, 14, 16, 15, 13, 11, 9, 7, 5 m/s being suggested
- for analogue and high rate pulse output anemometers the output should be sampled at 1 Hz or faster
- for low rate pulse output instruments a totalised count can alternatively be established
- each point should be established over a minimum of 30 seconds - for low resolution instruments (e.g. 1 pulse per revolution), this duration should be increased to ensure that the uncertainty component resulting from resolution does not become significant
- before collecting data at each wind speed conditions should be allowed to stabilise for at least 1 minute - stability can be assumed should successive 30 second wind speed averages be within 0.05 m/s of one another
- to infer wind speed values from rig calibration corrected readings of dynamic pressure, air density must be known - this must be based upon measurement of temperature, pressure and humidity, not upon assumption; details of relevant equations are given in Appendix 4
- the calibration test should be supported by a thorough assessment of uncertainty (see also Appendix 4)
- in assessing the quality of the calibration and/or the quality of the anemometer a two parameter linear regression of derived wind tunnel wind speed on anemometer output should be conducted; should the correlation coefficient be less than 0.99995, then the calibration should be repeated - if the resulting second correlation coefficient still be less than 0.99995 then the anemometer is likely to be inherently non-linear due to excessive friction or aerodynamic design and should not be used
- the calibration test results should be thoroughly recorded in any test certificate.

APPENDIX 4

ANEMOMETER CALIBRATION UNCERTAINTY ASSESSMENT

This appendix is based upon uncertainty principles outlined in the ISO Guide to the Expression of Uncertainty in Measurement⁴. The reader is urged to gain familiarity with this document.

A summary of uncertainty theory together with a numerically worked example for anemometer calibration based upon the applied theory given below can be obtained elsewhere¹.

When carrying out an anemometer calibration, the measurand is the mean wind speed ‘seen by’ the anemometer during definition of a calibration point. This value cannot be measured directly.

Typically, the mean wind speed is related to measurements of dynamic pressure, temperature and barometric pressure and is evaluated as:

$$\bar{v} = k_f \frac{1}{n} \sum_{k=1}^n v_k = k_f \frac{1}{n} \sum_{k=1}^n \left(\frac{2k_c p_k R T_k}{C_h B_k k_\rho} \right)^{\frac{1}{2}}$$

where:

- v_k is the value of wind speed for sample number k [m/s]
- k_f is a flow correction factor which *inter alia* may take account of
 - wind tunnel blockage (Maskell’s factor)
 - horizontal wind shear
 - global corrections obtained by cross checking against a quality, reference tunnel
- p_k is the pressure measured by a reference pitot static tube [Pa]
- k_c is a correction factor relating the pitot-tube position to the anemometer position, this being derived by wind tunnel calibration tests
- R is the gas constant for dry air 287.1 [J/KgK]
- T_k is the temperature [K] for sample k
- C_h is the head coefficient of the pitot tube
- B_k is the barometric pressure. [Pa] for sample k
- k_ρ is a factor which corrects the density term (B_k/RT_k) for humidity effects

The factor, k_ρ , which corrects the air density for humidity effects, is given by

$$k_\rho = \left(1 + \frac{\varphi_k P_w}{B_k} \left(\frac{R_A}{R_w} - 1 \right) \right) \approx \left(1 - 0.378 \left(\frac{\varphi_k P_w}{B_k} \right) \right)$$

Where

- φ_k is the value of relative humidity for sample k [-]
- P_w is the vapour pressure for the prevailing temperature [Pa]
- R_w is the gas constant for water vapour (=461.50) [J/kgK]

P_w can be approximated by the empirical polynomial equation

$$P_w = 0.51t^3 + 0.89t^2 + 48.3t + 604$$

where t is in $[C^\circ]$

During a calibration, k_r is unlikely to change appreciably and can be evaluated using the mean values of B , ϕ , and T .

In practice, the measured quantities will be measured indirectly where the chain will consist of the elements shown in the table below.

Table *Typical measurement chain*

input	physical parameter	x_k
conversion	transducer, with quoted sensitivity	gain $1/K_{x,t}$
link	low level voltage	$x_k/K_{x,t}$
conversion	signal conditioning with applied gain	gain $1/K_{x,s}$
link	high level voltage	$x_k/K_{x,t} K_{x,s}$
conversion	data sampling with discrete quantisation	gain $1/K_{x,d}$
output	bit representation	$V_{x,k} = x_k/K_{x,t} K_{x,s} K_{x,d}$

Each conversion has an associated factor, so that:

$$x_k = (K_{x,t} K_{x,s} K_{x,d}) V_{x,k}$$

where

x_k is the value of the physical parameter corresponding to input

$V_{x,k}$ the bit representation of the k 'th sample of x .

K is a transformation factor

x,t is the subscript corresponding to the transducer transformation

x,s is the subscript corresponding to the signal conditioning transformation

x,d is the subscript corresponding to the digital data sampling transformation.

Taking these conversion expressions and inserting them into the physical parameter relationship gives:

$$\bar{v} = k_f \frac{1}{n} \sum_{k=1}^n \left(\frac{2k_c (K_{p,t} K_{p,s} K_{p,d}) R(K_{T,t} K_{T,s} K_{T,d}) V_{p,k}}{C_h (K_{B,t} K_{B,s} K_{B,d}) k_\rho} \right)^{\frac{1}{2}}$$

or

$$\bar{v} = k_f \left(\frac{2k_c (K_{p,t} K_{p,s} K_{p,d}) R(K_{T,t} K_{T,s} K_{T,d})}{C_h (K_{B,t} K_{B,s} K_{B,d}) k_\rho} \right)^{\frac{1}{2}} \frac{1}{n} \sum_{k=1}^n \left(\frac{V_{p,k} V_{T,k}}{V_{B,k}} \right)^{\frac{1}{2}}$$

Each of the coefficients on the left hand side of the summation sign has associated uncertainty.

The problem reduces to one of estimating the value of the contributory uncertainties, and

deciding on how to amalgamate them, taking into account their degree of correlation. All these uncertainties will be of type B.

The right hand side of the expression relates to the derivation of a statistical mean, and the mean value will have associated type A uncertainty. This uncertainty, s_A is derived as follows:

$$s_A(\bar{v}) = k_f \left(\frac{2k_c (K_{p,t} K_{p,s} K_{p,d}) R(K_{T,t} K_{T,s} K_{T,d})}{C_h (K_{B,t} K_{B,s} K_{B,d}) k_p} \right)^{\frac{1}{2}} s(\bar{v})$$

where

$$s^2(\bar{v}) = \frac{1}{n} \frac{1}{n-1} \sum_{k=1}^n \left(\left(\frac{V_{p,k} V_{T,k}}{V_{B,k}} \right)^{\frac{1}{2}} - \bar{v} \right)^2$$

and

$$\bar{v} = \frac{1}{n} \sum_{k=1}^n \left(\frac{V_{p,k} V_{T,k}}{V_{B,k}} \right)^{\frac{1}{2}}$$

Returning to type B errors and referring to the expanded expression for mean wind speed, the sensitivity factors for the numerator coefficients are easily derived by partial differentiation and these equate to half the derived mean wind speed divided by the coefficient value, eg:

$$\frac{\partial \bar{v}}{\partial k_c} = \frac{1}{2} \frac{\bar{v}}{k_c}$$

The only exception is for k_f which not being within the square root does not have the half factor:

$$\frac{\partial \bar{v}}{\partial k_f} = \frac{\bar{v}}{k_f}$$

The sensitivity factors for the denominator coefficients are similar, but have a negative sign, eg

$$\frac{\partial \bar{v}}{\partial C_h} = -\frac{1}{2} \frac{\bar{v}}{C_h}$$

Most of the uncertainty sources of type B can be regarded as being fully independent (correlation coefficient, $r=0$). One exception is the digital data system conversion uncertainty which, leaving aside the quantisation component, is likely to be fully correlated across all three data channels. Another exception is the humidity correction factor k_r which has a functional dependency on temperature and barometric pressure. Treating them as fully uncorrelated however, is conservative and will typically introduce very slight overall overestimation of uncertainty.

Defining, the type B uncertainty sources as follows:

$u_{p,t}$ standard uncertainty in conversion factor $K_{p,t}$

$u_{p,s}$ standard uncertainty in conversion factor $K_{p,s}$

.....and similarly for all the other $K_{subscript}$ conversion factors. Additionally, defining:

- u_f standard uncertainty in tunnel correction factor k_f
- u_t standard uncertainty in wind tunnel calibration coefficient k_c
- u_h standard uncertainty in pitot tube head coefficient C_h
- u_r standard uncertainty in humidity correction to density, k_r

allows the combined uncertainty, $u_{c,B}$ of the category B errors to be expressed as:

$$u_{c,B}^2(\bar{v}) = c_f^2 u_f^2 + c_t^2 u_t^2 + c_{p,t}^2 u_{p,t}^2 + c_{p,s}^2 u_{p,s}^2 + c_{p,d}^2 u_{p,d}^2 + c_{T,t}^2 u_{T,t}^2 + c_{T,s}^2 u_{T,s}^2 + c_{T,d}^2 u_{T,d}^2 + c_h^2 u_h^2 + c_{B,t}^2 u_{B,t}^2 + c_{B,s}^2 u_{B,s}^2 + c_{B,d}^2 u_{B,d}^2 + c_\rho^2 u_\rho^2$$

where the sensitivity factors, c , have subscripts which follow the same pattern as those for the uncertainty sources to which they refer.

Thereafter, the total combined uncertainty can be evaluated as:

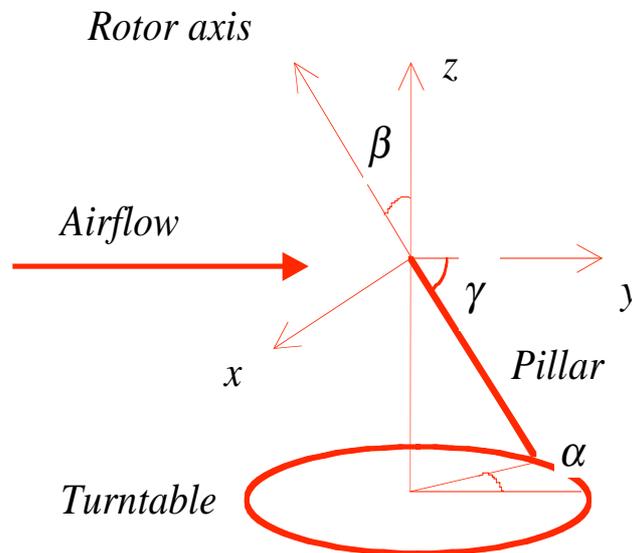
$$u_c^2(\bar{v}) = u_{c,B}^2(\bar{v}) + s_A^2(\bar{v})$$

APPENDIX 5

CATEGORISING VERTICAL SENSITIVITY

To establish the vertical sensitivity of a cup anemometer, the experimental requirement is to pitch the rotor about a lateral axis forwards and backwards whilst keeping the centre of the rotor fixed in space.

This can be achieved using a pitching rig, but a more elegant and controllable arrangement can be obtained by mounting the anemometer on an inclined pillar, set at an angle β , which in turn is mounted on a turntable which can be rotated through an angle α . The resulting angle, γ , as shown in the diagram below represents the angle which the incident flow makes with the pillar and rotor axis (a value of 90° would represent flow in the plane of the rotor).



γ is related to α and β by the relationship:

$$\gamma = \frac{\pi}{2} - \tan^{-1} \left(\frac{\cos \alpha \cdot \sin \beta}{\sqrt{\sin^2 \alpha + \cos^2 \alpha \cdot \cos^2 \beta}} \right)$$

The advantage of this experimental approach is that by having a relatively small but accurately set β and a relatively large and adjustable α , very good definition of vertical sensitivity can be established in the important -15° to $+15^\circ$ range. In fact, if β is set to 15° , then γ will vary ostensibly sinusoidally from -15° to $+15^\circ$ as α rotates through 360° .

APPENDIX 6

CATEGORISING MECHANICAL FRICTION

The frictional coefficients of a cup anemometer can be estimated experimentally by studying how the anemometer slows down from a starting speed in the absence of rotor aerodynamic effects¹⁷.

The suggested procedure involves replacing the rotor with a disc of similar inertia and mass as the rotor and tilting the anemometer slightly (about 10°) to simulate the aerodynamic thrust which would result in an 8 m/s wind.

When spun, the rotor will slow down at a rate dependent upon the mechanical friction of the bearings and the aerodynamic friction on the disc (which can be approximated by $-0.616\pi\rho r^4 (v\omega^3)^{1/2}$ where ρ , air density is approximately 0.00123 g/cm³ and ν , the kinematic viscosity of air is 0.144 cm²/s).

The equation of motion for the disc can then be expressed as:

$$\tau_{mech}(\omega_i) = I\alpha_i + f_{aero}\omega_i^{3/2}$$

where τ_{mech} is the unknown bearing friction, I is the disc inertia, and the third term is the aerodynamic friction as calculated above. ω_i and α_i are the sampled rotor speed and derived deceleration respectively.

Having calculated the mechanical friction, polynomial curve fitting techniques can be used to obtain the optimum values for the static, dynamic and parabolic friction coefficients described in appendix 2:

$$\tau_{mech}(\omega_i) = -(F_0 + F_1\omega_i + F_2\omega_i^2)$$

The temperature sensitivity of the coefficients can be examined by cooling the anemometer in a refrigerator or cold room.

The likely effect on calibration linearity can be assessed using the equations in Appendix 2.

APPENDIX 7

DETERMINING DISTANCE CONSTANTS

As demonstrated mathematically in Appendix 2, the cup anemometer distance constant is a useful but only approximate measure of responsiveness.

Because the theory which justifies the existence of a distance constant is a major simplification of reality, it is unrealistic to suppose that distance constants will be consistent if evaluated in different wind conditions.

To ensure intercomparability and repeatability, there is therefore a need to have a uniform method of evaluation¹⁸. This appendix suggests such a method.

Experimental Requirements:

The aim of the test is to identify how the anemometer responds to a step change in wind speed. To simulate the step change, the anemometer should be held stationary in a wind tunnel whose air flow is approximately 8 m/s.

The anemometer should be released and its output logged.

The output should be sampled at a rate of at least 30 Hz.

At this sampling rate, it should be recognised for pulse output anemometers (even of high rate design) that considerable and random resolution error can be expected. For analogue output instruments, considerable ripple in the signal is also very possible.

For low pulse rate instruments (eg one or two pulses per revolution), it is better to determine the time between successive pulses and to calculate the mean indicated speed within the period.

The experiment should be repeated at least five times.

Data Processing and Analysis

In analysing the data the aim is to curve fit the time series of anemometer output with the idealised behaviour described by the equation:

$$u_{ind}(t) = u_0 + \Delta u \left\{ 1 - \exp\left(-\frac{(t - t_0)}{\tau}\right) \right\}$$

$u_{ind}(t)$ is the time series of indicated wind speed, t_0 is the time of release of the anemometer and τ is the time constant for the response, which can be related to distance constant, l/a , by $l/a = \tau u_1$, where u_1 , the target wind speed is equivalent to $u_0 + \Delta u$ where u_0 is the initial wind speed and Δu is the magnitude of the step change.

In curve fitting the data, it is useful to re-express the formula in a linear manner that is suitable for two parameter linear curve fitting, the parameters being $-1/\tau$ and t_0/τ :

$$\ln\left(1 - \frac{u_{ind}(t) - u_0}{\Delta u}\right) = -\frac{1}{\tau}t + \frac{t_0}{\tau}$$

The left-hand side is readily calculated from the test data.

In carrying out the curve fitting regression analysis, it is important not to use all of the data since it will be seen not to be linear over its entire range. This is entirely due to the incompleteness of the theoretical model. In particular initial and terminal behaviour will be seen visually to deviate from the central linear portion. Only this linear portion should be curve fitted.

Data from each test should be analysed in turn and the resulting values of $1/a$ averaged to yield the distance constant to be quoted.

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