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Wind Measurements for Wind Energy Applications—A Review

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SYNOPSIS A review is given of the error sources and uncertainties in cup and sonic anemometry. In both cases the effects of the tower, boom and other mounting arrangements, as well as the siting of the anemometer, should be considered carefully. Cup anemometer measurements are inherently biased due to the turbulent nature of the wind, but these errors can be neglected in many applications if a well-designed, fast-responding anemometer is used. The response characteristics of sonic anemometers are fairly complicated. Based on wind tunnel investigations and field comparisons some of the associated errors are identified and their magnitude assessed.

1 INTRODUCTION

Wind measurements are an important input in any wind energy application—determination of the wind climate and establishing the power curve of the wind turbine being the most obvious tasks. The accuracy of these measurements is crucial because the energy density and wind turbine power output are proportional to the cube of the mean wind speed. Further, the instruments used must be robust and reliably accumulate data over extended periods of unattended operation.

Most wind measurements are performed using simple mechanical devices, like the traditional cup anemometer. The behaviour of these is fairly well understood and the sources of error well known—but, alas, often neglected. A brief review of these error sources is given below, with emphasis on the importance of proper mounting and calibration of the anemometer.

The high price of solid-state wind sensors has until recently prohibited their wide-spread use in the wind energy community. Today, however, it has become feasible in large-scale projects—and certainly at wind turbine test centers—to deploy eg ultrasonic anemometers. These have a number of advantages over mechanical anemometers and further provide measurements of eg turbulence, air temperature and atmospheric stability. However, they also introduce new sources of error which are less-well known. Based on wind tunnel investigations and field comparisons of a number of commercially available sonic anemometers, some of these errors are identified and their magnitude assessed.

2 CUP ANEMOMETRY

The sources of error in cup anemometry include the effects of the tower, the boom and other mounting arrangements, the anemometer design, the turbulent characteristics of the flow and the calibration procedure. Evidently, proper maintenance of the anemometer is also important. In some cases, special problems arise due to eg icing of the cup rotor or deterioration of the mechanical parts of the anemometer at sites close to the sea.

2.1 Tower, boom and clamp effects

The tower or mast on which the cup anemometer is mounted interferes with the flow and therefore introduces errors in the measured wind speed and direction. For boom-mounted instruments this leads to a reduction in the wind speed measured downwind of the tower, as well as a smaller reduction in the wind speed measured on the upwind side. Since full 360°-coverage is often desirable in wind energy applications, two or more anemometers must be then be operated at each level. The width of the downwind sector angle in which the measurements are disturbed (typically ± 30–45°) is a function of the distance between the anemometer and the tower. However, no simple relationships exist because of the great variety of mast geometries. The distance should be at least 1.5 tower diameters (Kaimal and Finnigan, 1994), but preferably 3 or more. If only one level of measurement is needed, the tower effect can be avoided by mounting the anemometer on a slender pole on top of the tower, about 3 or more tower diameters above the tower.

The boom and other mounting arrangements may also be the source of quite large errors in the measured mean wind speed. A wind tunnel study of the effect of various boom and clamp arrangements was reported by Pedersen et al. (1991). Long-term measurements in the atmosphere have been carried out at Risø National Laboratory (G. Jensen, pers. comm.), an example is shown in Fig. 1.

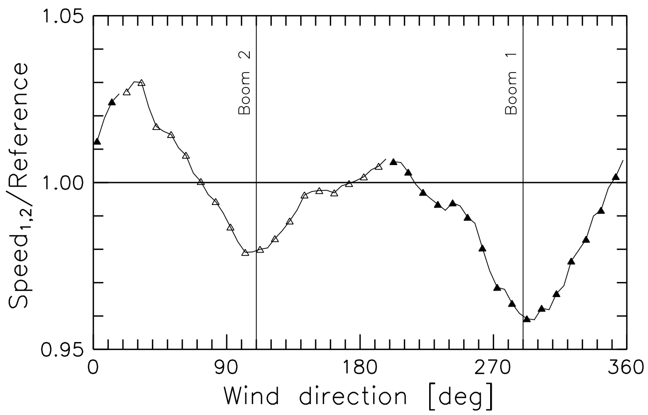

Figure 1: The influence of tower, boom and clamps on the measured mean wind speed. Data for two cup anemometers, mounted on opposite (upwind) sides of a tower, are shown.

The graph shows the ratio of the wind speed measured by two boom-mounted anemometers and the wind speed from an anemometer mounted on top of the tower, presumably outside the region of disturbed flow. The distance from the horizontal cup rotor plane to the circular boom is 5.5 boom diameters. The mean ratio is not the same for the two anemometers because they are mounted at different distances from the mast. However, the combined tower, boom and clamp effect for both anemometers is roughly the same, about 5 per cent. The analysis suggests that about half of this is due to flow-blocking by the mast and the other half is due to the boom and clamp—ie somewhat less than was found in the wind tunnel by Pedersen et al. (1991). The boom effect becomes smaller with increasing distance between the rotor and the boom ($\varnothing = 50$ mm) and vanishes at a distance of about 12 boom diameters. Consequently, the cup anemometers operated by Risø have now all been mounted on extension poles.

2.2 Cup anemometer design

Any treatment of the design considerations of cup anemometers is outside the scope of this paper. A modern, sturdy, light-weight, fast-responding cup anemometer should be used. The distance constant, ie the column of air corresponding to 63% recovery time for a step change in wind speed, should preferably be about a few meters. An example of such an anemometer is the Risø–70 model described by Busch et al. (1980) and Kristensen (1993).

2.3 Biases caused by turbulence

The errors in cup anemometry caused by the turbulent nature of the wind have been treated by many authors in the past, and will not be treated in detail here. A thorough review of cup anemometer dynamics has recently been given by Kristensen (1993).

Kristensen discusses four types of overspeeding: i) u-bias or 'overspeeding' causing too high measured wind speeds because the cup anemometer responds more quickly to an increase in the wind than to a decrease of the same magnitude; ii) v-bias or the so-called DP-error (data processing 'error') which accounts for the fact that the cup anemometer is not a vector instrument, but measures the mean of the total horizontal wind speed; iii) w-bias and iv) stress-bias which are equal to zero only if the anemometer has an ideal cosine response.

The four biases mentioned above are proportional to $(\sigma_u/U)^2$, $(\sigma_v/U)^2$, $(\sigma_w/U)^2$ and $\langle uw\rangle/U^2$, respectively. The errors associated with these biases (ie i, iii and iv) are in most cases of the order of 1% or less and can be neglected in most applications (Kristensen, 1993). The v-bias (of order 10%) should be taken into account when comparing cup- and sonic-measured mean wind speeds.

2.4 Calibration of cup anemometers

Cup anemometers should be maintained and calibrated on a regular basis to ensure accuracy in the mean wind speed measurements. It is usually recommended to perform the calibration in a wind tunnel, over the range of wind speeds that are of interest. However, since wind tunnel work is expensive and time-consuming—or a wind tunnel is simply not readily available—this is often not done. An alternative may be to intercompare cup anemometers in the atmosphere—a technique we have used with success at Risø, see Figs. 2 and 3.

The intercomparison of several anemometers with a reference anemometer can conveniently be done on a mast and boom set-up made for the purpose and erected at a reasonably homogeneous site. Great care should be taken to avoid mast and boom effects, and anemometer positions should be switched to ensure that all positions are equally well suited. Even though only winds in a narrow sector can be used, a reasonable range of wind speeds is often obtained in one or a few weeks (in Denmark, at least . . .).

2.5 Siting of anemometers

The improper siting of a well-calibrated and properly mounted anemometer can easily render the measurements useless. Hence, if wind measurements are not made at the exact point of interest, eg at hub height at the site of a wind turbine, some effort should go into siting the anemometer. The effects of topography on a number of possible sites may be estimated using numerical models, eg the WAsP models described by Troen and Petersen (1989) and Mortensen et al. (1993a, 1993b).

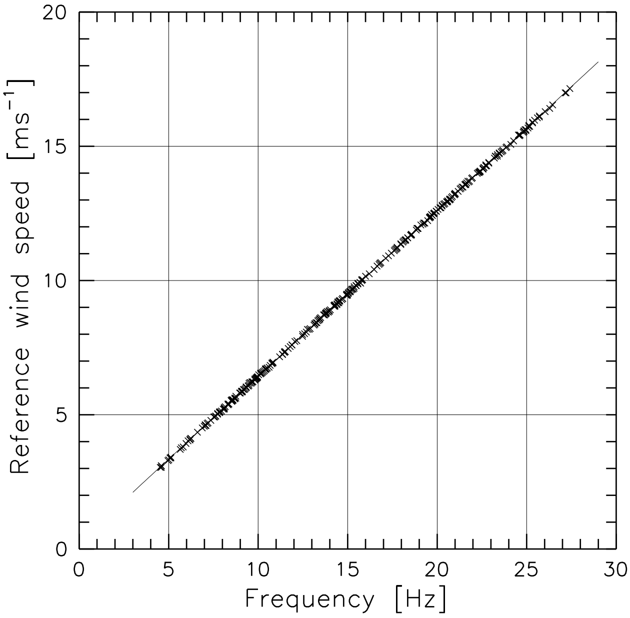

Figure 2: Intercomparison of two cup anemometers under atmospheric conditions. Output frequency (x) of test cup anemometer versus reference wind speed (y). The calibration reads: $U = 0.6167 \times F + 0.26$.

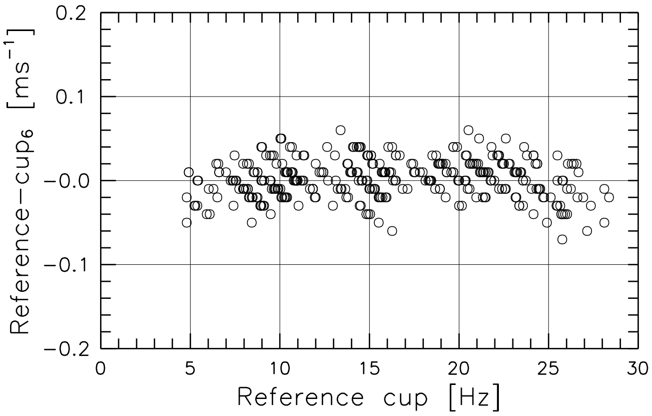

Figure 3: The difference between the calibrated wind speed and the reference wind speed as a function of the frequency output of the reference anemometer. The standard deviation of the differences is 0.023 ms^{-1} and the mean temperature of the runs 6.0°C.

3 SONIC ANEMOMETRY

The sonic anemometer measures the wind speed from the flight times of ultrasonic sound pulses traveling across a fixed sound path. It has no moving parts and therefore none of the response problems associated with eg the cup anemometer. By the same token, it requires very little maintenance. The wind speed measured along a sound path, S_ℓ, is a function of the path length and travel times only: $S_\ell = (\ell/2)(1/t_1 - 1/t_2)$, and does not depend on atmospheric conditions like pressure, air temperature, humidity, etc.

Until recently, cost and ease-of-operation were major obstacles to the application of sonic anemometers in wind energy studies. However, most sonics are now fairly easy to operate and a number of systems have become available at reasonable prices. Furthermore, one sonic anemometer substitutes for a cup anemometer, a wind vane and a temperature sensor, including booms, clamps, cabling, radiation screen etc.

Another major concern, inherent in sonic anemometry, is the fact that the probe head itself distorts the flow—the effect of which can only be evaluated accurately by a comprehensive wind tunnel investigation. The transducer shadow effect is a particularly simple case of flow distortion and a well-known source of error in sonics with horizontal sound paths. Less well known are the errors associated with inaccuracies in probe head geometry and the temperature sensitivity of the sound transducers. Finally, specific details in the design of a given probe head may give rise to errors.

3.1 Sonic probe geometry

The probe head geometry enters in the transformation of the wind speed components measured along the sound paths into the Cartesian components of a conventional (x, y, z) coordinate system. Using the design angles of the probe, inaccuracies in the manufacturing of the probe head will thus translate into errors in the transformed wind components.

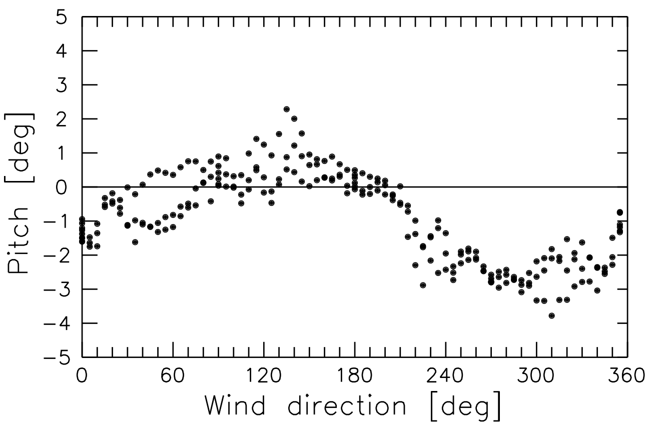

Figure 4: Apparent pitch of the wind vector for horizontal flow in a wind tunnel (Solent research model).

The errors in the horizontal wind speed components are likely to be negligible, whereas the vertical component—and higher order statistics—may suffer quite severely; an example is shown in Fig. 4. These and other alignment errors may be alleviated if the turbulence statistics are transformed into a coordinate system aligned with the mean flow, but the solution to the problem is to measure accurately the probe angles and path lengths and use these in the calculation of the wind components.

3.2 Transducer shadow effect

One of the well-known errors in sonic anemometry is the transducer shadow effect, ie the underestimation of the wind components measured along the acoustic paths due to velocity deficits in the wakes of the transducers (Kaimal, 1979). For a given flow speed the shadow effect is a function of the angle θ between the flow vector and the sonic path, see Fig 5.

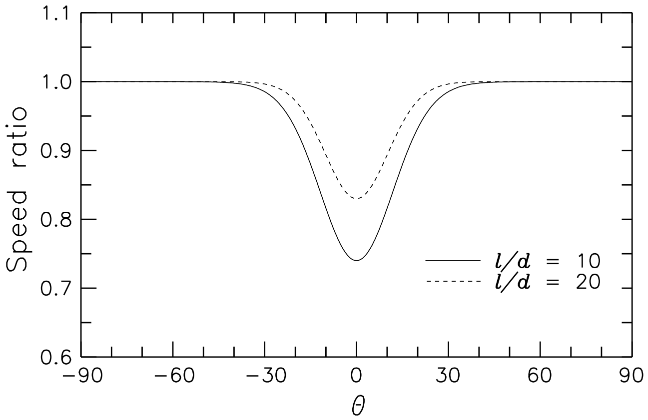

Figure 5: Attenuation of the flow speed along a single sonic path caused by the transducer shadow effect. Parameterization of Kaijo Denki type transducers according to Wyngaard and Zhang (1985).

The transducer shadow effect is particularly important in sonic probes with horizontal sound paths, eg the ATI k-probe or the Kaijo Denki TR-61A, where it may be corrected for by the anemometer software (Applied Technologies, 1991). In other probe heads the sound paths are inclined 45° to the horizontal and the transducer shadow effects will therefore in general be small.

3.3 Array flow distortion

The so-called omni-directional probe heads, like the Kaijo Denki TR-61B or the Solent 1012/R2, were designed to be mounted on top of a mast for 360°-coverage; but, as a consequence, suffer from flow distortion by the bulk of the array, support struts, etc. The array flow distortion can only

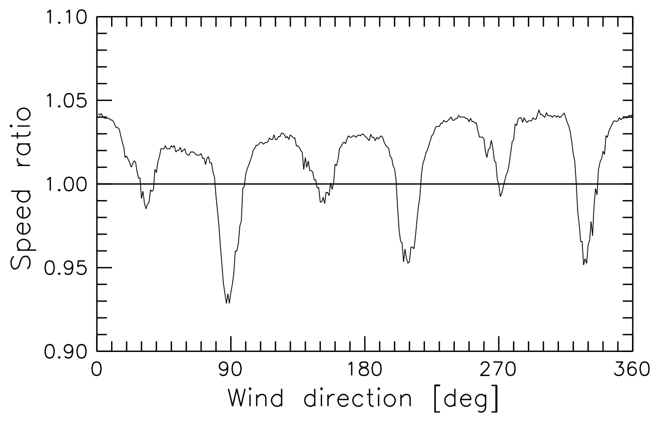

Figure 6: Array flow distortion of the Kaijo Denki TR-61B probe for horizontal, near-laminar flow in a wind tunnel (Mortensen, 1994).

be determined in detail in a wind tunnel investigation, turning the probe around a vertical and (preferably) a horizontal axis. For the Solent 1012/R2 probes (research model) this has been done by the manufacturer for horizontal flow and the measured distortion is built into the anemometer software for on-line correction. For most other omni-directional probes similar measurements must be carried out by the user, see eg Mortensen (1994).

3.4 Temperature sensitivity of transducers

The wind speeds measured by sonic anemometers are in principle independent of pressure, air temperature, humidity etc. However, temperature variations may cause small variations in the properties of transducers and electronics, whereby the time-of-flight of the sound pulse becomes a function of not only the flow speed, but also ambient temperature. This effect can be assessed in an environmental chamber at zero wind speed, an example is given in Fig. 7.

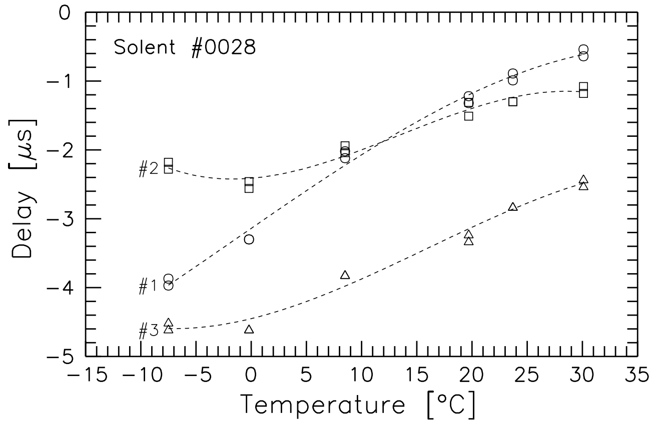

Figure 7: Temperature sensitivity of the time-of-flight measurements along the three paths of a Solent sonic.

This temperature sensitivity will affect both the wind speed and temperature output of the sonic: the maximum errors in horizontal wind speed and absolute temperature (over the range of -10°C to $+30$°C), corresponding to the delay variations depicted in Fig. 7, are 2% and 5 K, respectively—and well within the manufacturers specification (Gill Instruments, 1990). Once the delay variations have been determined, these can of course be programmed into the anemometer or data analysis software.

3.5 Speed sensitivity

In some cases, the flow distortion by a sonic probe—or part of the distortion—has been shown to depend on flow speed as well. As an example, Fig. 8 shows speed ratio differences at three different flow speeds in a wind tunnel for the Kaijo Denki TR-61B as a function of wind direction (Mortensen, 1994).

For this probe it was found that the flow response could be described as the combination, or sum, of two distinct parts. The array flow distortion (Fig. 6)—which reflects strongly the geometry of the sensor head—seems to be largely independent of flow speed. However, this is superimposed with

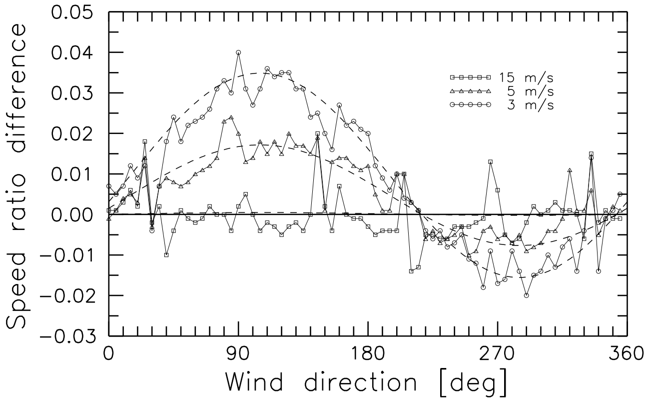

Figure 8: Flow speed sensitivity of the horizontal wind speed measured with a Kaijo Denki TR-61B probe (Mortensen, 1994).

the cyclic, speed-dependent variation illustrated above. This part is a 360°-modulation of the speed ratios and is probably due to the specific mounting of the signal and power cables below the base of the TR-61B probe head. These cables are attached to a point at 0°, ie at right angles to the direction where the speed dependency has its maximum amplitude. The effect of the cables diminishes with increasing flow speed and becomes insignificant at speeds greater than $\approx 10\,\mathrm{ms}^{-1}$. The design of the TR-61B probe has since been changed to eliminate this effect (Yoshiki Ito, pers.comm.).

3.6 Calibration of sonics

The response characteristics of a sonic anemometer can only be determined in detail by investigations in a suitable wind tunnel. Since the response is a function of probe geometry, flow angle-of-attack in both the horizontal (wind direction) and vertical (pitch) and, possibly, flow speed and ambient temperature, such investigations tend to become fairly extensive. Furthermore, wind tunnel investigations are by no means trivial to carry out and different results may be obtained with the same type of anemometer under different experimental conditions. An example of this is shown in

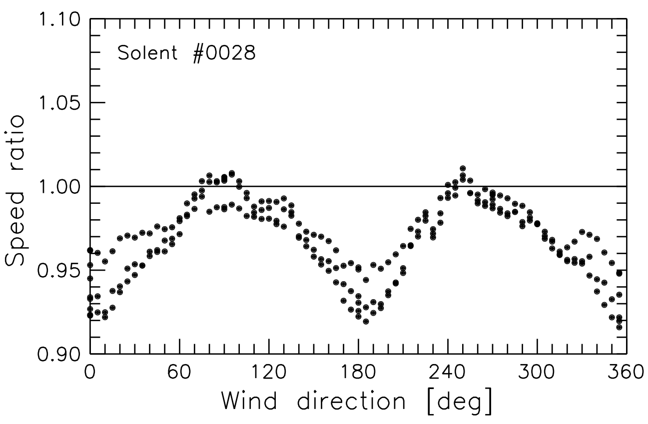

Figure 9: Ratios of calibrated (manufacturers calibration) horizontal wind speed and wind tunnel speed as a function of wind direction for Solent sonic #28.

Fig. 9, where the ratio of calibrated sonic wind speed and wind tunnel speed in two test runs at Risø are plotted as a function of wind direction relative to the probe. The sonic output has been corrected for flow distortion employing the built-in correction tables and, ideally, the speed ratios should then be close to 1. This is clearly not the case and too small mean wind speeds would be expected in the atmosphere, see below.

3.7 Field intercomparison of sonics

This section presents some preliminary results of a field intercomparison of four state-of-the-art wind sensors: three ultrasonic anemometers and a propeller/vane anemometer. The sonic anemometers are manufactured by Kaijo Denki Ltd. (mod. DAT-300/TR-61A), Gill Instruments Ltd. (mod. 1012R2), and Applied Technologies Inc. (mod. SWS-211/3K). The propeller anemometer is a modified R.M. Young (mod. 35005) Gill-type propeller vane (Michaelis, 1991).

The intercomparison was carried out in 1992 during the STORM Fronts Experiment Systems Test (STORM-FEST 92). In this experiment, NCAR's ASTER (Atmosphere-Surface Turbulent Exchange Research) facility was deployed for $2\,^1\!/_2$ months near Sabetha, Kansas. The ASTER facility (Semmer and Martin, 1991) was used for data acquisition and processing. The wind sensors were all mounted approx. 4 meters above ground level. The horizontal distances between the sonic sensors were approx. 5 meters, and the distance from the propeller mast to the nearest sonic mast approx. 10 m. To avoid flow distortion and shelter effects originating in the masts and ASTER trailers, only wind directions in a 180° sector are analyzed. The data reported here were collected on five days with predominantly northerly winds, Julian Day 55, 56, 58, 69, and 70. Furthermore, only observations with complete data coverage are used. This leaves 1252 5-minute observations for the five days in question.

The mean wind speeds measured by the three sonic anemometers are compared to the mean speed measured by the propeller anemometer in Figs. 10–12. The slope (a) and offset (b) of the least-squares fit shown in each graph with a dashed line is given in Tab. 1.

The Kaijo Denki and propeller mean wind speeds compare very well (Fig. 10), with a slope of 0.995 and an offset of 0.040 ms^{-1}. The sonic data are not corrected for transducer shadow effects or array flow distortion; however, since most of the measurements were obtained in a fairly narrow sector these effects are presumably small.

The relationship between Solent and propeller wind speeds (Fig. 11) is also linear, but with a slope of 0.962 and an offset of 0.057 ms^{-1} the sonic seems to underestimate the mean wind speed by about 4%. In this case the sonic measurements are corrected for flow distortion by the built-in correction tables. These account for the directional variation of the flow distortion, but leaves an offset of about 4%.

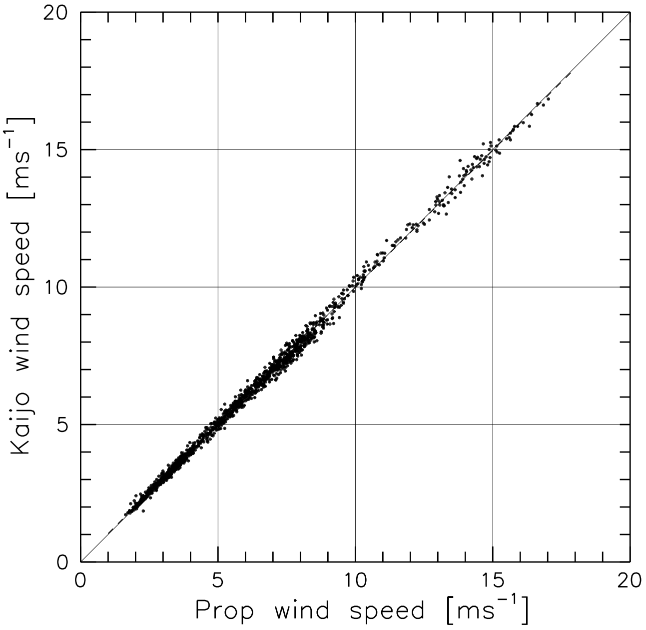

Figure 10: Comparison of mean wind speeds measured with a Kaijo Denki TR-61A probe head and a propeller anemometer.

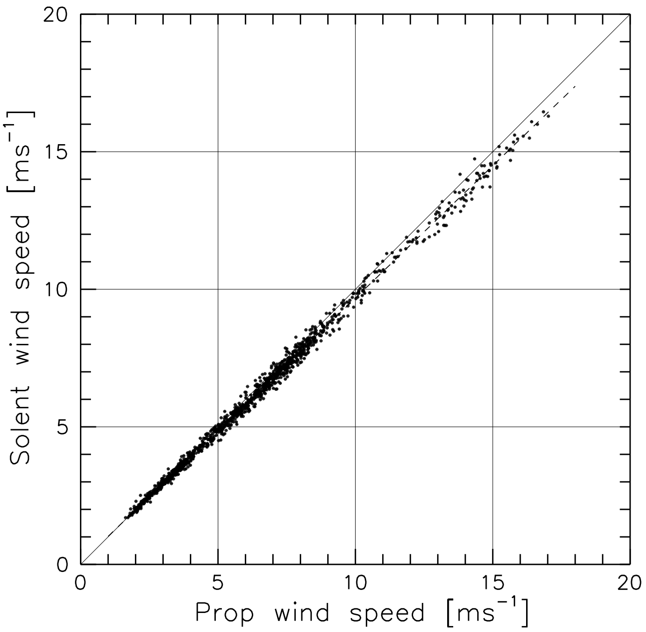

Figure 11: Comparison of mean wind speeds measured with a Solent 1012R2 probe head and a propeller anemometer.

Incidentally, a reduced mean wind speed is to be expected if this particular probe behaves in the same way as probe #0028, see Fig. 9. The reason(s) for the discrepancies shown in Figs. 9 and 11 are not yet fully understood, but seems to be related to the fact that the calibration done by the manufacturer is carried out at a different flow speed and temperature than the data reported here.

The ATI and propeller mean wind speeds compare very well (Fig. 12) for wind speeds less than approx. 9 ms^{-1}, but above this speed the scatter increases and the slope and

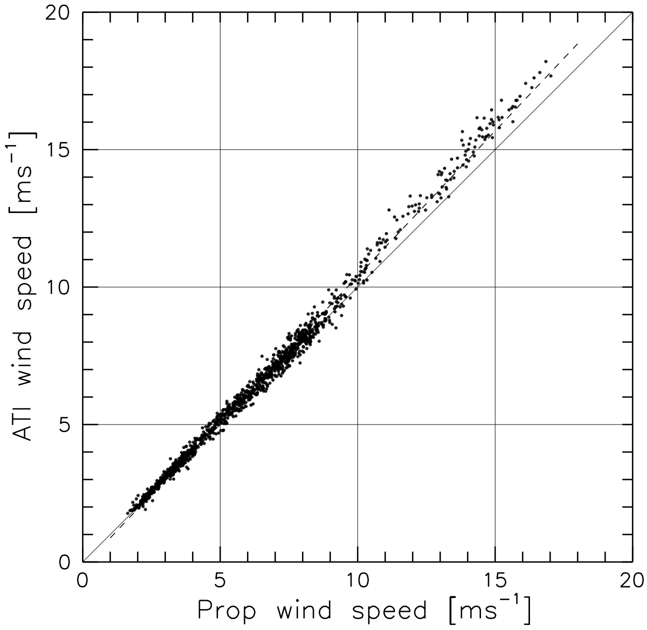

Figure 12: Comparison of mean wind speeds measured with an ATI SWS-211/3k probe head and a propeller anemometer.

offset become 1.124 and -0.838 ms^{-1}, respectively. Obviously, this particular instrument was malfunctioning at high wind speeds. This is confirmed by inspection of the raw time traces of wind speed, where it is apparent that spikes occur frequently in the data at high wind speeds—in particular in the u-component. The reason for this is not known, but it is likely to be a characteristic of this particular probe only. The data are corrected for transducer shadow effects by the anemometer software.

Among the reasons for using sonic anemometers is their ability to provide measurements of the turbulent wind and temperature fluctuations—and thereby the stress, heat flux and stability. As examples of this, Figs. 13–14 compare the stress measurements obtained by the three sonic anemometers. The stress is here represented by the friction velocity $u_* = \sqrt{\tau/\rho} = \sqrt{-\langle u'w' \rangle}$, where τ is the shear stress and ρ is air density. The Kaijo Denki is chosen as the 'independent' variable in both figures, since this instrument has the longest 'track record' and has been used for reference purposes in many investigations.

It is evident that the scatter, as well as the systematic differences between the probes, increase when we look at second and higher order statistics. The relationship between Solent and Kaijo Denki friction velocities (Fig. 13) is linear, but the Solent seems to underestimate u_* by about 13%. This is partly due to the underestimation of the u-component; but, more importantly, the Solent seems to also underestimate the vertical wind speed fluctuations (Tab. 1).

The ATI and Kaijo Denki compare well (Fig. 14) for small values of the friction velocity, but the comparison becomes meaningless at higher values of u_* because of the erroneous measurements mentioned above.

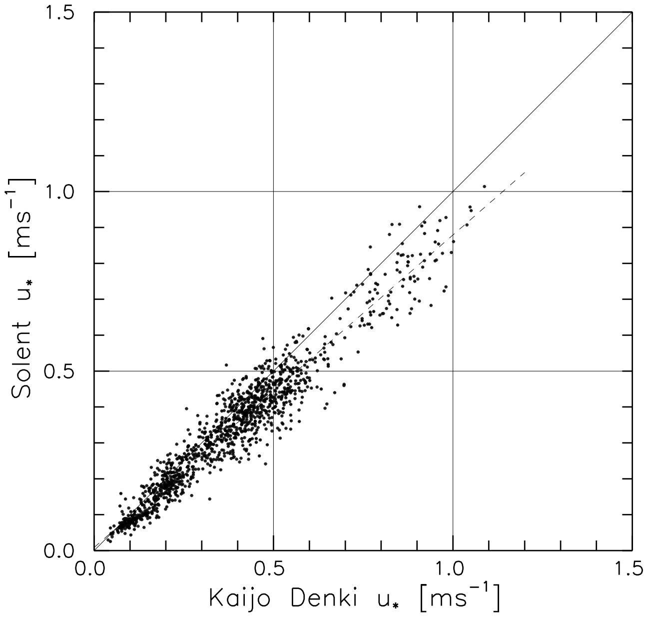

Figure 13: Comparison of friction velocities measured with the Solent and the Kaijo Denki sonic anemometers.

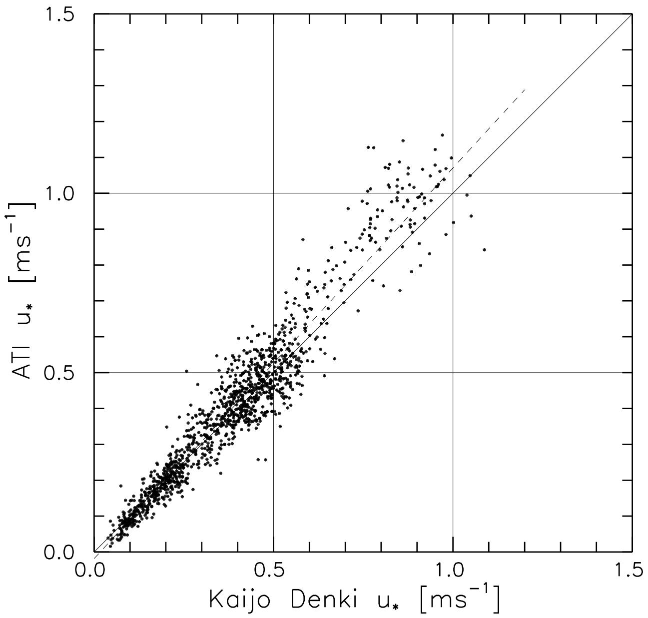

Figure 14: Comparison of friction velocities measured with the ATI and Kaijo Denki sonic anemometers.

The sonic intercomparison experiment, with respect to mean wind speed, friction velocity and the standard deviations of the velocity and temperature fluctuations, is summarized in Tab. 1.

4 CONCLUDING REMARKS

Cup anemometers will continue—for some time at least—to be the instrument of choice for measuring the mean wind speed in wind energy applications. They are truly omnidirectional sensors, robust, very easy to operate, and can—with regular maintenance and calibration, as well as attention to the details of mounting and siting—provide long-term, accurate measurements of the mean wind speed. The errors associated with the turbulent biases can in principle also be estimated and corrected for, but in many applications these may be neglected if a well-designed, fast-responding anemometer is used.

Table 1: Comparison of mean wind speeds, friction velocities, and velocity variances measured with a propeller and three different sonic anemometers.

	X	Y	a	b
Speed	Propeller	Kaijo Denki	0.995	0.040
	Propeller	Solent	0.962	0.057
	Propeller	ATI	1.057	-0.180
	< 9 ms^{-1}	ATI	1.005	0.077
	> 9 ms^{-1}	ATI	1.124	-0.838
u_*	Kaijo Denki	Solent	0.870	0.009
	Kaijo Denki	ATI	1.089	-0.019
	Solent	ATI	1.195	-0.010
σ_u	Kaijo Denki	Solent	0.946	0.011
	Kaijo Denki	ATI	1.182	-0.111
	Solent	ATI	1.241	-0.117
σ_v	Kaijo Denki	Solent	0.893	0.018
	Kaijo Denki	ATI	0.975	0.003
	Solent	ATI	1.090	-0.016
σ_w	Kaijo Denki	Solent	0.884	0.009
	Kaijo Denki	ATI	0.879	0.017
	Solent	ATI	0.988	0.011
σ_T	Kaijo Denki	Solent	0.864	0.067
	Kaijo Denki	ATI	0.967	-0.009
	Solent	ATI	1.096	-0.077

Sonic anemometers provide measurements of the turbulent wind and temperature fluctuations with a small temporal (20 Hz) and spatial resolution—from which the mean wind speeds and temperature, as well as the turbulence intensities, shear stress, heat flux and atmospheric stability can be derived. These atmospheric characteristics may be extremely important in wind energy and wind turbine studies, and sonic anemometers will therefore be deployed increasingly in these areas.

Cost and ease-of-operation are of less concern in sonic anemometry now, but the calibration—or rather determination of the flow response characteristics—of most sonic anemometers unfortunately still requires fairly comprehensive investigations by the user. The errors in sonic anemometry described above are all potentially quite serious and any sonic should preferably be tested with respect to these and other possible errors.

The field comparison described above gives an indication of the overall accuracy, or rather differences, that can be expected when deploying state-of-the-art sonic anemometers in the atmosphere under near-ideal experimental conditions—mounted and operated by a skilled crew. Typical numbers (Tab. 1) are: 5% in mean wind speed (U), 10–15% in friction velocity (u_*), 10% in the standard deviations of the longitudinal and transversal wind speed components (σ_u and σ_v), and 10–15% in the standard deviations of the vertical wind speed component (σ_w) and absolute temperature (σ_T). As more investigations of the flow response characteristics of specific sonic probes become available—and the results of these applied in the interpretation of sonic-measured data—these numbers should hopefully become smaller.

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Finally, the contributions of my colleagues at Risø, in particular R. Barthelmie, J. Højstrup, G. Jensen and L. Kristensen are gratefully acknowledged.

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