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TWO-YEARS-WORTH OF TURBULENCE DATA RECORDED BY A SONIC-ANEMOMETER-BASED DATA ACQUISITION SYSTEM

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1. INTRODUCTION

It has become increasingly important that studies in wind energy, diffusion, and air-sea interaction are supported by high quality, remote measurements of atmospheric turbulence where such data must reliably accumulate over long periods. As a result, much emphasis has been placed on the development of durable fast-response meteorological instrumentation during recent years. In this paper we describe a new, commercially available, omni-directional sonic anemometer/thermometer. Based on wind tunnel tests an extensive calibration procedure for the sonic is reported. Finally, field data collected over a two-year period from a horizontally homogeneous site in the western part of Denmark are described as both instrument validation and as an illustration of the utility of the sonic for providing long-term high quality data.

2. THE SONIC ANEMOMETER/THERMOMETER

The three-dimensional sonic system in question is a Kaijo Denki model DAT-300 with an omni-directional sensor (TR-61B); see Fig. 1. The sensor consists of three pairs of acoustic transducers, each with a length of 80 mm and a diameter of 20 mm. The sound path for each pair of transducers is inclined 45° to the vertical and has a length of 20 cm.

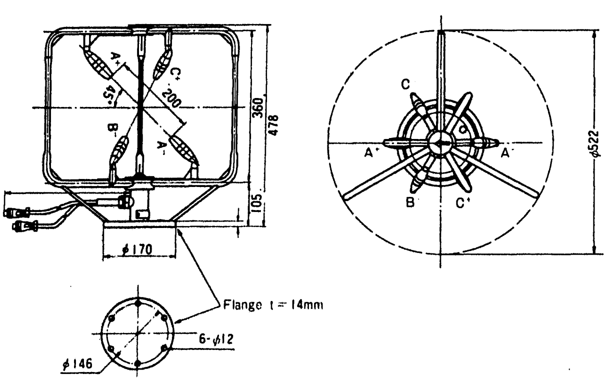

Fig. 1. The Kaijo Denki TR-61B probe head. Left and right in the figure correspond to north and south, respectively.

Calibration of the sonic was performed in the wind tunnel of the Danish Maritime Institute. During the calibration controlled wind speeds were allowable over the range of 3 to 20 m/s and turbulence levels were artificially screened to low levels.

2.1 Sonic Internal Flow Distortion

Because the sonic probe is designed to be stationary in the field with a varying wind vector, the distortion of the flow speed and direction (induced by the transducers and their supporting rods) was examined under controlled wind tunnel conditions. The sonic was systematically rotated 360° in the horizontal and through the range of +5° to -5° in the vertical. The main characteristics of the flow deformation for horizontal, laminar conditions are depicted in Fig. 2 (a, b, c). It appears that the speed-up factor (defined as the ratio of the sonic-measured wind speed to the true wind speed) is roughly 1.00 when averaged over azimuth, even though a systematic variation of one-degree factors on the order of 10% was observed. With reference also to Fig. 1, the supporting rods reduce the wind speed considerably, whereas the flow speeds up when directed unobstructed towards the transducers. The wind vector was found to be tilted upwards an average of about 1° for all azimuth directions; and both the tilt and horizontal deflection curves depend strongly on the geometry of the sensor.

The sonic response to an inclined flow (non-horizontal wind vector) was investigated for both different flow directions and flow speeds by tilting the probe head in the tunnel. An example of the tilting of the wind vector for three characteristic azimuth angles is shown in Fig. 3.

The sonic-derived wind vector is distorted most when the flow is in the direction of the sound paths. The flow is also significantly tilted for flow past the supporting rods and between sound paths. Considering the three-dimensional geometry of the probe head, the angular response is relatively complicated. The overall effect of the wind vector tilting originating in the sonic probe head was found to be a reduction of the vertical wind speed component on the order of 10%.

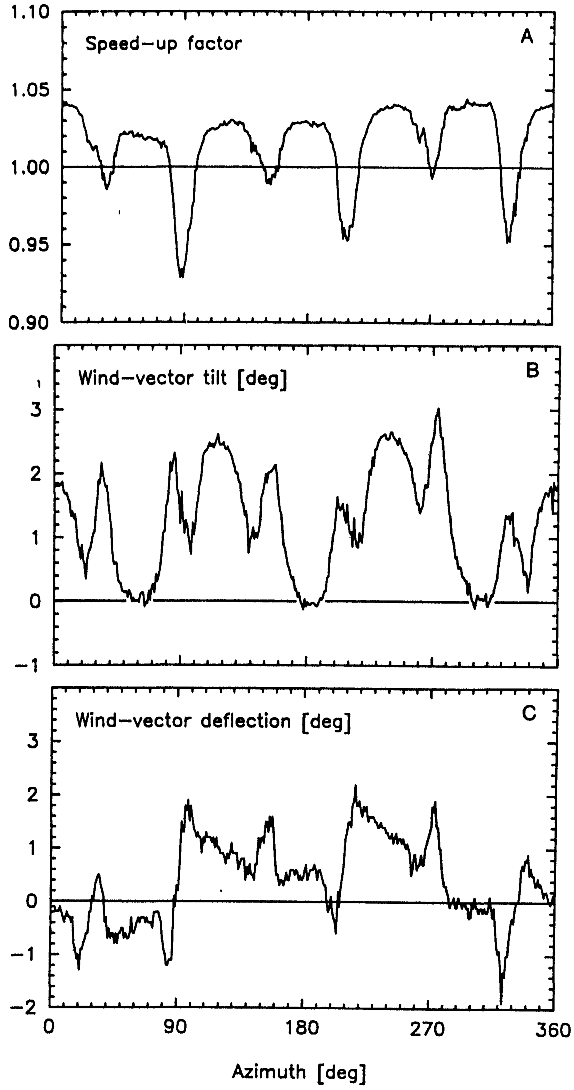

Fig. 2. The sonic response to a laminar, horizontal flow of 10 ms^{-1} for different azimuth angles in a wind tunnel. The resolution in azimuth is 1^o . a) Speed-up factor = $\bar{u}_{sonic}/\bar{u}_{true}$. b) Positive tilt indicates upward tilt of the wind vector. c) Positive deflection indicates clockwise deflection of the wind vector.

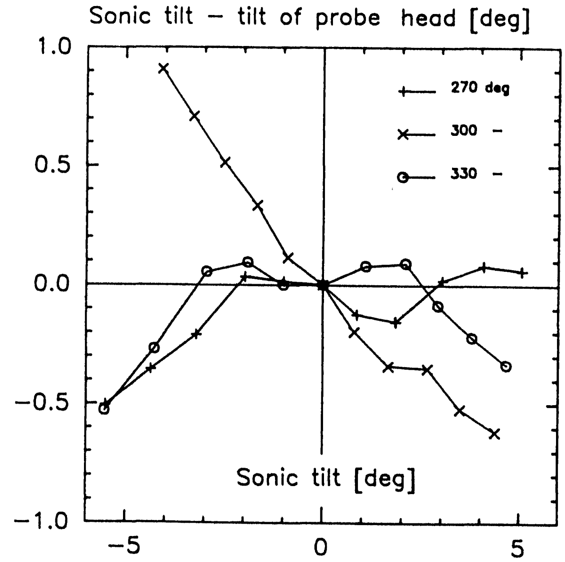

Fig. 3. The tilting of the flow induced by the sonic probe as a function of flow inclination. "Sonic tilt" is the actual flow tilt measured by the sonic less the flow tilt measured by the sonic for horizontal flow.

2.2 External Alignment

The sonic anemometer provides the user with measurements of the wind-vector components u_f, v_f, w_f, obtained in a three-dimensional fixed Cartesian coordinate system, the x-axis of which conventionally points in the easterly, the y-axis in the northerly, and the z-axis in the vertical direction. The desired turbulence statistics, however, in terms of the covariance matrix of the fluctuating velocity components u', v', w', are commonly referred to a Cartesian coordinate system, the x-axis of which is aligned in the mean wind direction whereas the mean cross- and vertical wind components are zero. We shall refer to this coordinate system as externally aligned.

To calculate the externally aligned quantities from the measurements in the fixed coordinate system, we first rotate the frame of reference around the z-axis of the probe head an angle $\theta = \tan^{-1}(\bar{v}_f/\bar{u}_f)$, thereby aligning the x-axis with the mean wind direction in the xy-plane of the probe head. In this turned coordinate system the mean wind speed becomes $\bar{u}_{xy}$, whereas the corresponding cross-wind component $\bar{v}_{xy}$ equals zero. Subsequently, we rotate around the y-axis an angle, ϕ, such that $\phi = \tan^{-1} (\bar{w}_f/\bar{u}_{xy})$, thereby obtaining that also $\bar{w}$ in the realigned system becomes zero.

Following these rotations, the covariance matrix $\underline{\underline{\tilde{C}}}$ of the aligned wind components, u', v', w', relate to the covariance matrix $\underline{\underline{C}}$ of the fixed-frame unaligned wind components, u_f, v_f, w_f, according to

$$\underline{\underline{\tilde{C}}} = \underline{\underline{M}}\ \underline{\underline{C}}\ \underline{\underline{M}}^T \qquad (1)$$

Here, $\underline{\underline{M}} = \underline{\underline{B}}\ \underline{\underline{A}}$, where $\underline{\underline{B}}$ and $\underline{\underline{A}}$ are unit matrices for right-handed coordinate rotation around the y- and z-axes, respectively.

The alignment procedure, as well as the wind-tunnel-derived calibration curves (Fig. 2), are coded into the data acquisition system and provide real-time calculations of the turbulent energies ($\overline{u'^2}$, $\overline{v'^2}$, $\overline{w'^2}$), shear stresses ($\overline{u'w'}$, $\overline{v'w'}$), and a sound-virtual temperature-based heat flux ($\overline{w'T_s'}$).

3. FIELD RESULTS

3.1 Experimental Set-up

The sonic-anemometer system was employed from February 1983 to February 1985 in a field experiment in western Jutland, Denmark. The sonic probe was mounted at a height of 5.5 m on a 24-meter meteorological mast. Further, the mast contained fast-responding cup-anemometers at heights of 3.0, 9.9 and 23.8 m, wind vanes at 9.9 and 23.8 m, and pt-500 temperature sensors at 2.0 and 22.9 m. The temperature sensors gave the absolute temperature as well as the temperature difference between the two levels. The mean relative humidity (at screen height) and short-wave incoming radiation were measured for prolonged periods. The mast was in successful operation for about two years. In this period the sonic anemometer system operated continuously for about 85% of the time, giving consecutive 20-min averages of mean wind speed and direction, wind vector tilt, temperature and variances and covariances of u', v', w' and T_s' (sound-virtual temperature). The sampling rate was 1 Hz. The profile instrumentation had a corresponding efficiency of more than 95%. The basic data set thus consists of more than 40,000 20-min values from each sensor.

The mast was situated in an agricultural area, mainly with corn fields. The area is extremely flat and devoid of buildings and vegetation other than the crops. The results presented below were obtained in a 135-degree sector around SW where the surface is rather horizontal and homogeneous.

3.2 Results from the Sonic-Anemometer

Figure 4 (a,b) shows the ratio of standard deviation of the vertical wind velocity fluctuations and the friction velocity as a function of surface layer stability in terms of z/L, where z is the height (5.5 m) and L is the Monin-Obukhov length. The measurements are shown as mean values of σ_w/u_* in logarithmically equidistant classes of z/L, and the standard deviation in each class is indicated by bars. The data are compared with relations suggested by Merry and Panofsky (1976) and Panofsky and Dutton (1984). In the unstable regime the measurements agree rather well with both relations though the data points are shifted slightly towards lower values of σ_w/u_*. On the stable side (Fig. 4b) σ_w/u_* is seen to be more or less constant to a z/L of about 1-2 (L ~ 3-5 m), as suggested by Panofsky and Dutton (1984). For very stable conditions the scatter increases, but the data indicate an increasing ratio.

The ratios σ_u/u_*, σ_v/u_* and σ_w/u_* for near neutral stability were found to be 2.56, 1.83, and 1.15, respectively. These values are within 10% of the average values given in Panofsky and Dutton (1984, Table 7.1): 2.39, 1.92, and 1.25.

3.3 Results from Sonic and Profile Instrumentation

Figure 5 compares the 20-min averaged wind speed at 5.5 m, measured by the sonic anemometer, with the corresponding wind speed derived from the profile instrumentation. The agreement between sonic- and profile-derived wind speeds is seen to be excellent. Furthermore, the ratio of profile and sonic wind speeds has been analysed as a function of time, wind direction, wind speed and stability. These investigations showed that i) no drift in calibration of the sonic system could be discerned during 19 months of operation, ii) the correction of the sonic horizontal wind speeds (Fig. 2a) effectively removes any variation with wind direction of the ratio $\overline{u}_{cup}/\overline{u}_{sonic}$, iii) the mean overspeeding correction of the cup-anemometers amounts to about 1% and, when

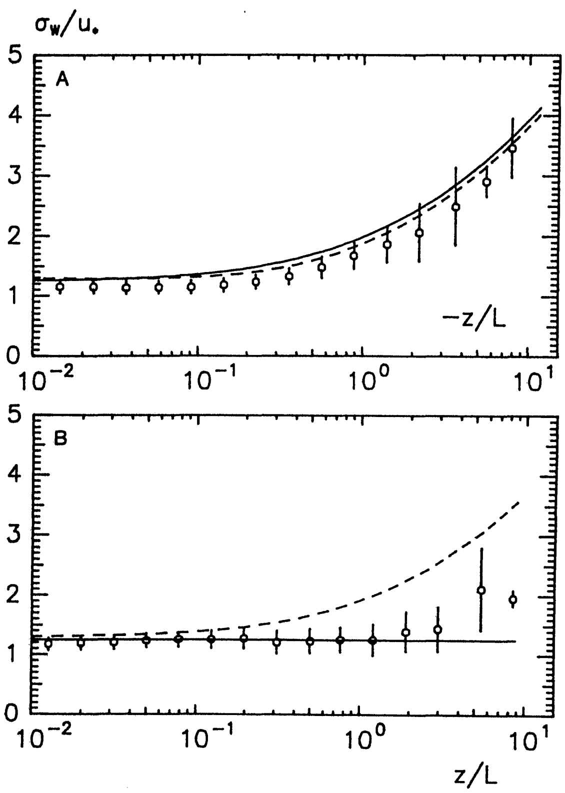

Fig. 4. σ_w/u_* as function of z/L for unstable (a) and stable (b) conditions. The curves are from Merry & Panofsky (1976) (dashed) and Panofsky & Dutton (1984) (full line).

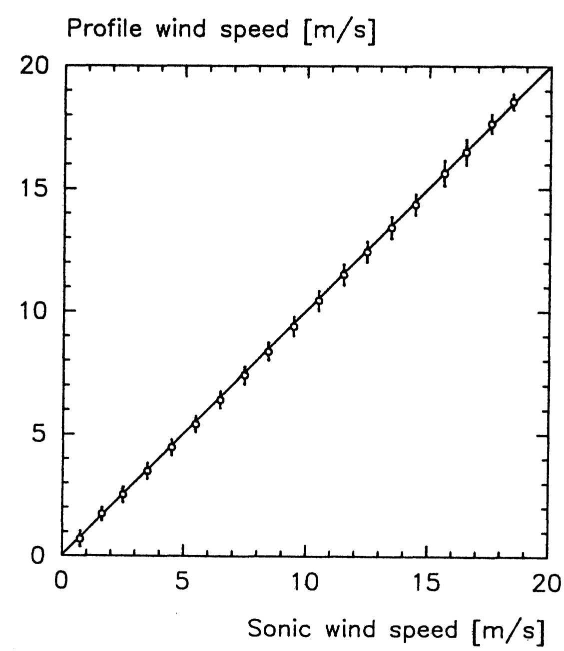

Fig. 5. Profile-derived versus sonic wind speeds at 5.5 m a.g.l. Standard deviation of each 1 m/s-class indicated.

applied, makes the ratio practically invariant with wind speed and stability.

As an example of the application of the sonic anemometer system, we will finally present a climatological investigation of the flux-profile relationship for momentum. The dimensionless gradient of wind speed in the surface layer, Φ_M, is by definition given as

$$\Phi_M = k \frac{z}{u_*} \frac{\partial \overline{u}}{\partial z} \qquad (2)$$

where k is the von Kármán constant, u_* is the friction velocity and $\partial \overline{u}/\partial z$ is the gradient of mean wind speed at height z. $\partial \overline{u}/\partial z$ was found by differentiating mathematical expressions fitted to the wind-speed profile. The friction velocity is obtained directly from the sonic anemometer as $\sqrt[4]{(\langle u'w'\rangle)^2+(\langle v'w'\rangle)^2}$. Prescribing a value of unity for $\Phi_M(0)$ at neutral conditions leads to a von Kármán constant of 0.375, which is used in the following. Figure 6 shows the dimensionless wind speed gradient as a function of atmospheric stability in terms of the gradient Richardson number. Again, the number of observations allows us to present the data in logarithmically equidistant classes of stability. The standard deviation in each class is given by bars. The Richardson number was chosen as scaling parameter because it turned out to be a better statistic for describing Φ_M in the unstable regime (Mortensen, 1985). Also shown is a Businger-Dyer-like representation of Φ_M for unstable conditions

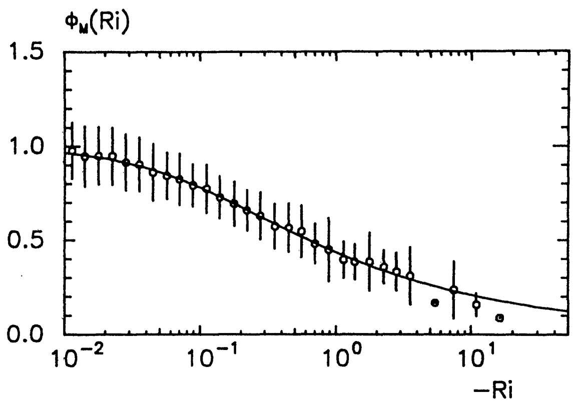

Fig. 6. The dimensionless gradient of wind speed as a function of gradient Richardson number for unstable conditions.

$$\Phi_M(Ri) = (1 - a \cdot Ri)^n \quad ; \quad Ri < 0 \qquad (3)$$

In our case the value of 12 for a and an exponent of -1/3 yields good agreement with the measurements. The result of a similar analysis in the stable regime is shown in Fig. 7. For Richardson numbers less than 0.15 the measurements are described well by a relation of the form:

$$\Phi_M(Ri) = (1 - b \cdot Ri)^{-1}; \quad 0 < Ri < 0.15 \qquad (4)$$

A value of 4.5 was used for b in Fig. 7.

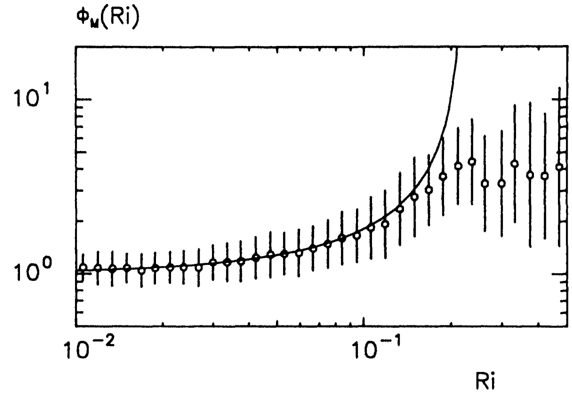

Fig. 7. As Fig. 6, but for stable conditions.

4. CONCLUSION

The described sonic-anemometer and data acquisition system have proven a very sturdy and reliable turbulence instrument for unattended operation over prolonged periods. This is true for the above-mentioned field experiment and also for several air-sea interaction, diffusion and wind engineering studies, in which the system has been employed under a wide range of meteorological conditions.

We presently believe that the greatest uncertainty in the turbulence statistics obtained with the system is associated with the vertical angular response of the sensor, i.e. the suppression of the vertical wind velocity component. Further investigations will be conducted to resolve this difficulty in more detail. The generally good agreement between our observations and previously established relationships is encouraging to this continued effort.

5. ACKNOWLEDGEMENTS

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