DEVELOPMENT AND CALIBRATION OF A CUP ANEMOMETER FOR ATMOSPHERIC BOUNDARY LAYER FULL-SCALE MEASUREMENTS

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Abstract

Steady and turbulent flow calibration and performance of a cup anemometer specially developed for full-scale atmospheric boundary layer measurements is described. Potential sources of wind speed measurement error are quantified utilising laboratory and field calibrations.

Background

Rotating cup anemometers and vanes have long been the meteorologist's traditional tool for measuring wind velocity and atmospheric turbulence, today finding use in a wide range of research and operational applications. Desirable properties of any field cup anemometer include a linear calibration over a suitable operating wind speed range, low starting speed, high frequency gust response and a robust/weatherproof construction. A 3-Cup anemometer and vane was developed at the University of Sydney, Department of Civil Engineering, to meet these criteria for the purposes of full-scale turbulence measurement program conducted on free-standing lattice towers. The following outlines the steady and turbulent flow calibration and performance of the subject cup anemometer.

Steady Flow Calibration and Performance

The relationship between cup rotational frequency and the mean wind speed was established in a low turbulence aeronautical wind tunnel incorporating a strobe light. The strobe beam was directed towards the rotating cups with surrounding ambient light levels reduced. Strobe frequency was then adjusted until the moving cups appeared stationary. Each cup was marked differently to prevent confusion from visual aliasing. Resistance and capacitance of the anemometer's frequency to voltage tachometer was then adjusted to produce a 0-5 V range corresponding to 0-50 m/s wind speed.

Output voltage from the anemometer was then calibrated against wind speed using a pitot static tube connected to a Betz Manometer in the same wind tunnel flow. At wind speeds greater than a threshold start-up speed of 1 m/s, a direct linear relationship of the form $y = Ax + B$ was found. Non linearity at sub 1 m/s wind speeds is caused by friction/inertia of the cup rotor and the inability of the anemometer's frequency to voltage tachometer to convert low frequency pulses into a steady voltage.

Turbulent Flow Calibration and Performance

Wyngaard [1] used a crude axially symmetric model of a cup anemoneter to numerically derive an approximation for the aerodynamic torque 'T' on a cup anemometer rotor in turbulent flow. From this investigation, Wyngaard demonstrated a cup anemometer responds more quickly to an increase in wind speed than to an equivalent decrease, causing the cups to overspin. The mean value of a rotating cup anemometer reading in turbulent flow will then be erroneously higher than the true value of mean wind speed.

Wyngaard also demonstrated a cup anemometer can be modelled as a linear first order system with a time response constant 'τ' inversely proportional to mean wind speed U.

$$\tau = L/U \qquad (1)$$

Experimentally the response time τ of a cup anemometer is obtained by allowing the cups to accelerate from rest to their equilibrium speed in steady flow. The appropriate response time is then deduced as the time required for the cups to reach (1-1/e) of their final speed. This procedure was followed to produce the acceleration curves of Figure 1 giving a response length L ~ 2.8 m for the subject anemometer. This value is indicative of good frequency response despite the robust and weatherproof make of the subject anemometer.

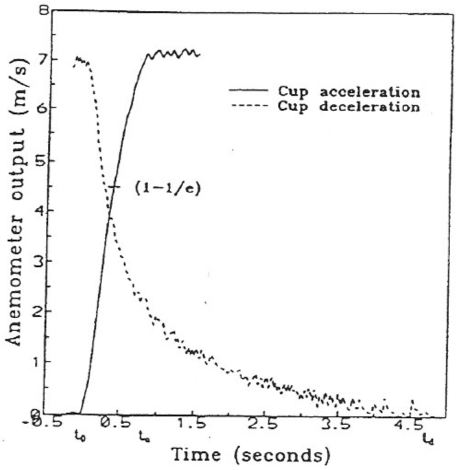

Figure 1 Cup anemometer response to a 7 m/s step increase and decrease in wind speed.

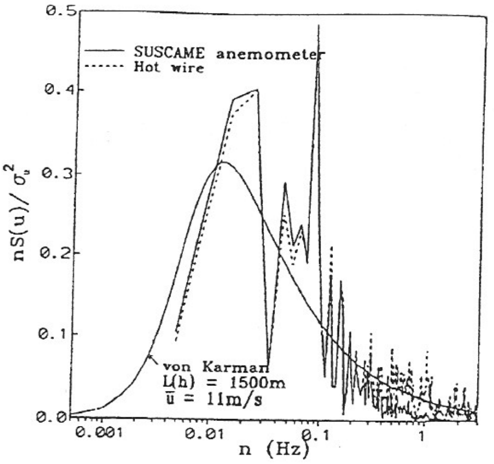

Figure 2 Cup anemometer and hot wire anemometer synthetic turbulence spectra.

The acceleration test was reversed to illustrate the overspinning tendencies of the cup anemometer as recognised by Wyngaard. Figure 1 reveals the time t_d' required for the anemometer to decelerate from equilibrium velocity to rest is greater than the time t_a' taken to accelerate over the same wind speed range, leading to an overspin error. The initial rates of cup acceleration and deceleration are observed to be similar suggesting overspin error will be minimal at low amplitudes of wind speed fluctuation.

Attempts in the past to numerically quantify the magnitude of overspin error have been met with only reasonable success, failing to realise the natural disorder of atmospheric turbulence, e.g. Kaganov and Yaglom [2] and Ramachandrian [3]. A better estimation of overspin error in turbulent flow can be found by comparing the wind speed as measured by a cup anemometer with a more accurate low inertia sensor. Izumi and Barad [4] compared the output from a standard cup anemometer with that of a low inertia sonic anemometer and hot wire anemometer, all placed within immediate vicinity at a height of 6m over flat terrain. Mean over spinning of the cups was found to be around 15%. This was found to be in contrast with the latter findings of Hyson [5], demonstrating overspin error at a height of 1.5 m was of the order 0.5-3%. Discrepancy between these results probably stems from variations in site conditions and maintaining laboratory calibrations of the low inertia sensors in the field.

To overcome these limitations, a laboratory investigation was devised to experimentally establish the degree of overspin for the subject anemometer in turbulent flow conditions. A vertically aligned hot-wire anemometer (lowpass filtered at 3 Hz) and the subject cup anemometer were both immersed in a 310 mm diameter jet stream generated by a 15 kW fan. Airflow inside the jet was almost steady and uniform with a turbulence intensity of just 1% measured by the hot wire. A von Karman [6] turbulence spectrum similar to that expected at the lattice tower site was then replicated synthetically. Artificial low frequency turbulence was generated by slowly varying the fan speed of the jet in time with a pre-recorded full-scale wind velocity trace. High frequency turbulence was generated by manually passing a semi-porous batten intermittently through the jet upstream of both anemometers. A power spectral analysis was then performed upon the wind speed records from both anemometer. The correct 'recipe' of each velocity fluctuation was found through a trial and error process until the hot wire turbulence spectrum closely resembled an expected idealised von-Karman spectrum, as illustrated in Figure 2.

210 second samples of this synthetic turbulence were recorded and analysed to obtain the mean wind speed of each anemometer. Immediately following this, the mean wind speed U of each anemometer was measured in steady flow. Jet speed was adjusted until the hot-wire mean speed under artificial turbulence matched that under steady flow. At this flow rate, the degree of cup anemometer overspin could be determined from the ratio of mean wind speed measured by the cup anemometer under turbulent and steady flow. The whole procedure was repeated 5 times in succession to eliminate any possible hot wire drift errors. Overspin error was measured to be low at approximately 0.1% under simulated category 2 terrain at 60 m. This result is not surprising since the bulk of the energy contained within the wind turbulence spectrum under these conditions is at low frequencies, well within the frequency response of the anemometer cups. Experimentally varying the frequency composition of synthetic turbulence demonstrated overspin error becomes increasingly significant as the proportion of high frequency turbulence is increased towards the upper limit of anemometer frequency response.

From Figure2 it is evident the subject cup anemometer frequency response begins to diminish beyond 0.5 Hz (mean wind speed = 11 m/s). This observation has been quantified by Davenport [7] using an anemometer admittance function, also demonstrating frequency response will improve with increasing mean wind speed.

Flow distortion induced by supporting structures

Reliable measurement of wind speeds and directions in the atmospheric boundary layer can only be achieved if the structure supporting the anemometer does not distort the local flow field. Supporting anemometer booms and tower structures present a potential source of anemometer flow distortion.

Boom distortion

Pedersen, Hansen, Oye, Brinch and Fabian [8] have demonstrated the proximity of rotating cups to their supporting anemometer booms can give rise to an unacceptable dependence of measured wind speed upon wind direction. A wind tunnel calibration was performed upon the subject anemometer to investigate boom interference further. The cup anemometer and boom were mounted upon a retort stand and placed at mid tunnel height. Initially the boom was positioned perpendicular to tunnel flow and then progressively rotated horizontally in 10° increments by 90°. Anemometer wind speed at each angle was then normalised to the wind speed in the initial boom position and a reference manometer to obtain the plot in Figure 3. It is seen mean wind speed will vary by about 5% depending upon wind yaw angle.

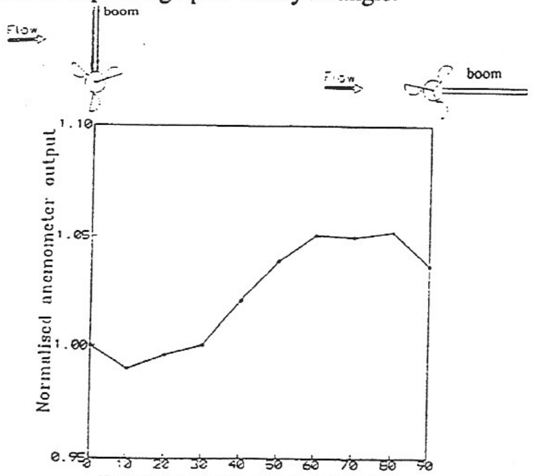

Figure 3 Normalised anemometer output for varying horizontal boom angle

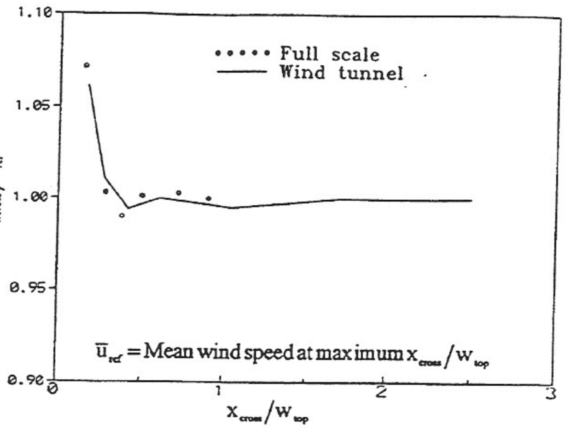

Figure 4a Anemometer mean wind speed distortion versus distance from tower face. Boom perpendicular to cross-wind face.

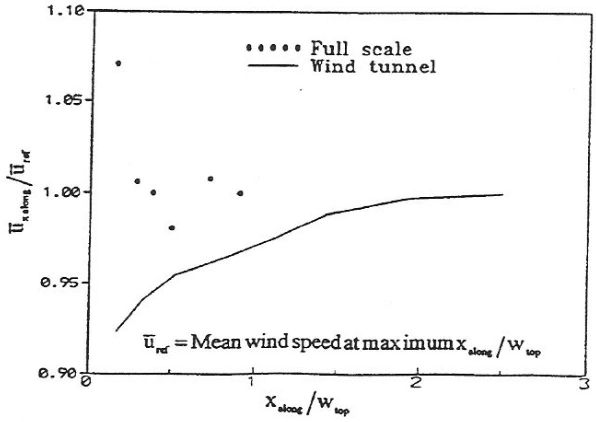

Figure 4b Anemometer mean wind speed distortion versus distance from tower face. Boom perpendicular to windward face.

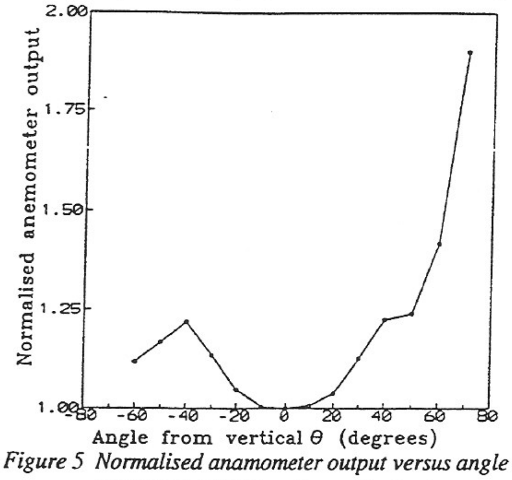

Figure 5 Normalised anamometer output versus angle of anemometer tilt from the vertical axis

Tower distortion

Lattice towers are often utilised for full scale atmospheric turbulence measurements since their porosity represents minimal degradation to free stream flow. Wieringa [9] attempted to quantify the degree of flow distortion induced by a supporting lattice tower during the 1968 Kansas atmospheric surface layer experiment, using a potential flow numerical model to estimate a wind speed decreased of 6% one tower width upstream of the tower. This conclusion was later met with some debate by Wyngaard et al [10], and [11]. In a separate investigation, Gill et al [12] found flow stagnation would not exceed 2% for a low solidity tower.

A full scale calibration was conducted to estimate the degree of wind speed distortion induced by the Prospect Tower [13]. Two anemometers were utilised for this test, one as a reference, while the other was moved to various positions around the 60 m level of the tower. Several 60 second samples of wind speed from both anemometers were simultaneously recorded at each location. The ratio of variable to reference mean wind speeds was then calculated and plotted against normalised distance from the tower in Figure 4. Only reference wind speeds between 7-8 m/s and normal to the southern face of the tower were analysed.

This calibration was repeated using a 1:33 scale boundary layer wind tunnel simulation, this time using linearised hot wire sensors for wind speed measurements, the results of which are superimposed upon the full scale results of Figure4. Good agreement is found between full-scale and wind tunnel results when the flow is perpendicular to the boom, both tests indicating tower induced distortion will be negligible at a distance $x_{cross}/w_{top} > 0.5$. When the anemometer is upstream of the tower, the wind tunnel results indicate a 5 % decrease in mean wind speed for values $x_{cross}/w_{top} = 0.5$.

Further sources of cup anemometer error

While cup anemometers respond primarily to the wind component in the cup plane, there exists an additional instability under vertical wind fluctuations. A lift force under vertical flow exists due to the 'negative lift slope' of the hemispherical cups. Most cup anemometers then display sensitivity to the wind velocity component perpendicular to the rotating plane known as the 'normal velocity sensitivity'.

Experimentally this was detected by placing a reference hot wire probe and the subject anemometer in a wind tunnel of steady velocity and rotating the subject anemometer axis away from the vertical by varying angles θ. The ratio of measured speed to the speed in the cup plane $U\cos\theta$ is plotted against θ in Figure 5. An error of approximately 10% can be seen at angles θ of 30°. Some asymmetry exists at greater angles due to the anemometer housing. In conditions of real boundary layer flow over flat terrain, the mean vertical component of wind speed is zero. Kaganov and Yaglom [2] have shown the vertical sensitivity error induced by the fluctuating vertical component of turbulence in these conditions will be negligible.

Rainfall influence upon anemometer response is another potential source of error. Dentler [14] has demonstrated rainfall influence diminishes with increasing wind speed; at a wind speed of 15 m/s and a torrential rainfall rate of 100 mm/h, the decrease in cup speed relative to the wind speed is only 1%.

Conclusions

Steady and turbulent flow calibration and performance of a cup anemometer specially developed for full-scale atmospheric boundary layer measurements, conducted on lattice towers, have been described. Potential sources of wind speed measurement error have been quantified utilising laboratory and field calibrations including cup rotor overspin in turbulent flow, flow distortion by supporting structures and normal velocity sensitivity. Supporting anemometer booms and tower structures were found to present the greatest potential source of wind speed error for the subject anemometer.

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