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CORRECTING MEASUREMENTS FROM A CUP ANEMOMETER AND WIND VANE

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ABSTRACT

Cup anemometers and wind vanes do not respond perfectly to wind speed and direction changes, as both instruments exhibit finite time constants. Some form of correction is therefore necessary if actual or instantaneous wind speed and direction is required. This paper presents a method to infer these from filters based on the instrument's dynamic step responses.

Following a series of step response experiments, carried out on a cup anemometer and wind vane used for wind turbine research, the responses were categorised by fitting equations of motion. As the wind vane's frequency response was an order of magnitude faster than the turbine's yaw movements, only a simple smoothing correction was applied to wind direction measurements. However, as the anemometer time constant was similar to the turbine, more complex corrections were needed for wind speed, and this was accomplished through a state space system approach. The resulting discrete time estimator was applied to anemometer measurements with corrections proving reasonably small, and found generally not to influence turbine parameters appreciably. For specific cases corrections may however be more important.

INTRODUCTION

According to Eggleston and Stoddard (1987), it is difficult to predict the flow through a turbine rotor in the field as spatial fluctuations are generally large between measurement point and rotor plane. This view is compounded if the instruments also exhibit non-zero time constants, τ; then the original measurements exhibit errors whose size depend largely on the time scale of interest, the frequency, ω, and amplitude, ΔU_∞, of the fluctuations. This paper presents methods used to deal with these errors and used to predict actual instantaneous wind speed, U_∞, and direction, θ_W, from measurements taken during wind turbine research.

During 1994-95 a prototype 5kW horizontal axis wind turbine was field tested at the University of Newcastle, Clausen et. al (1992). A meteorological station was included at the testing site in accordance with recognised turbine testing standards, Frandsen and Pederson (1990). This station consisted of a Synchrotac 710 series cup anemometer and wind vane, shown in Figure 1, which were attached one metre apart on an arm centred on top of a mast, and about two rotor diameters from and level with the axis of the turbine, which was about 10m above the local ground level.

These instruments cannot respond perfectly to changes in U_∞ and θ_W, so to estimate errors in measurements the dynamic response of each was tested in a wind tunnel; later, as testing requirements of the turbine required instantaneous measurements, the dynamic responses were used to predict actual U_∞ and θ_W.

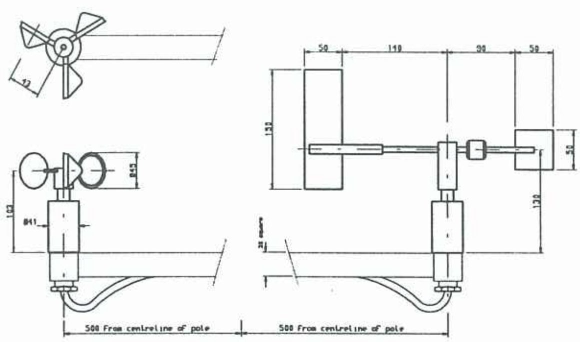

FIGURE 1. Anemometer and wind vane. Dimensions in mm.

DYNAMIC TESTS

Cup anemometers and wind vanes are typically tested by recording their responses to known wind changes, usually a simple step change, and then fitting to a dynamic equation, Ebert & Wood (1994) and Wyngaard (1981). Wind vanes usually show a damped second order response, and are categorised by damping ratio, ζ, and sometimes damped natural frequency, ω_d. Our wind vane was tested in the open working section of a wind tunnel by yawing the vane to an angle, θ_0, releasing it, and recording the response. The tunnel velocity, U_0, was kept constant, and voltages from the wind vanes potentiometer were read and stored digitally using a 12 bit analog to digital board and a personal computer. Categorised responses are shown in Figure 2 in terms of ζ and ω_d. The vane showed an almost constant ζ of about 0.25, and ω_d varied linearly with wind speed; these results are typical for wind vanes and compared favourably with a range of commercial vanes tested by Finkelstein (1980).

Cup anemometers under small fluctuations usually exhibit a linear first order response, with $\tau \propto U_0$. Non-linearities however cause them to respond faster to increases than decreases in U_0, causing overspeeding or "overrunning". Wyngaard details a number of general dynamic equations, but we chose the method of Hyson (1972) primarily because of its simple experimental method. Hyson derived an equation of motion for a cup anemometer with negligible bearing friction by equating Newton's first law with an aerodynamic cup force, and expressed this as,

$$\frac{1}{u_c}\frac{du_c}{dt} \approx -\frac{\rho a^2 \pi r^2 \sqrt{\alpha\beta}}{I}\left[\frac{u_c}{U_o} - \left(\frac{u_c}{U_o}\right)_{eq.}\right] \quad (1)$$

where I is the moment of inertia, ρ the air density, r the cup centre radius, a the cup radius, and u_c the rotational speed in m/s; the subscript *eq.* represents a point at equilibrium. The constant $\sqrt{\alpha\beta}$ can be found by subjecting the anemometer to step speed increases and decreases and measuring the response. For our anemometer this was done in the open working section of a wind tunnel by opening or closing the tunnel entrance. One step increase or decrease was one experiment, with anemometer output read with the same data acquisition system as used for the wind vane with sampling started before the step, and proceeding until anemometer equilibrium was reached. For all experiments the tunnel response time was better than 0.3s which was generally an order of magnitude faster than the anemometer.

A number of experiments were conducted including step increases from $u_c = 0$, some initial u_c, and step decreases,

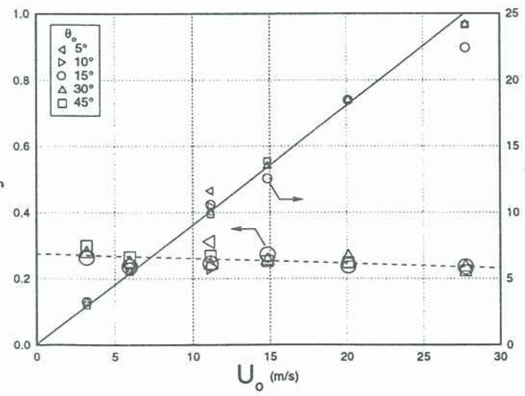

FIGURE 2. Wind vane dynamic response as damping ratio (ζ) and damped natural frequency (ω_d) for varying wind speed (U_o). Large symbols are ζ, small symbols ω_d, and lines are least squares fit for each. Data taken using various angle of release (θ_o) given in the figure.

and the measured accelerations are shown in Figure 3 as a function of the departure from equilibrium of u_c/U_0; here the relationship between u_c and U_0 at equilibrium was found by applying a small reflective strip to one cup and measuring reflected light pulses from a hand held emitter and counter, with u_c found to vary linearly with U_0. The straight line fitting the data in Figure 3 is given by;

$$\frac{1}{u_c}\frac{du_c}{dt} \approx -0.219\left[\frac{u_c}{U_o} - \left(\frac{u_c}{U_o}\right)_{eq.}\right] \quad (2)$$

Integrating (2) results in an equation of motion;

$$\frac{du_c}{dt} = -0.219 u_c U_o + 0.057 U_o^2 + 0.0046 \quad (3)$$

Equating (1) and (2) gives $\sqrt{\alpha\beta} \approx 0.714$, which compares with 3.4 for Hyson's test anemometer which physically was quite different to our instrument. Using Hyson's definitions for τ and distance constant, D, gave, for our instrument, $\tau = 4.56/U_0$ seconds and D = 4.56m which correlated reasonably well with values found in experiment and defined more conventionally. By comparison, Hyson's anemometer gave $\tau = 1.42/U_0$ seconds and D = 1.42m and hence our instrument responded considerably more slowly.

Equation (3) was integrated numerically to calculate anemometer responses to sinusoidal wind speed fluctuations expressed as $U_o(t) = \overline{U_o} + \Delta U_o \sin(\omega t)$ for a range of mean wind speeds $\overline{U_o}$, ω, and ΔU_0. Integration was performed using a fourth order Runge-Kutta scheme, and responses expressed as the percentage deviation from

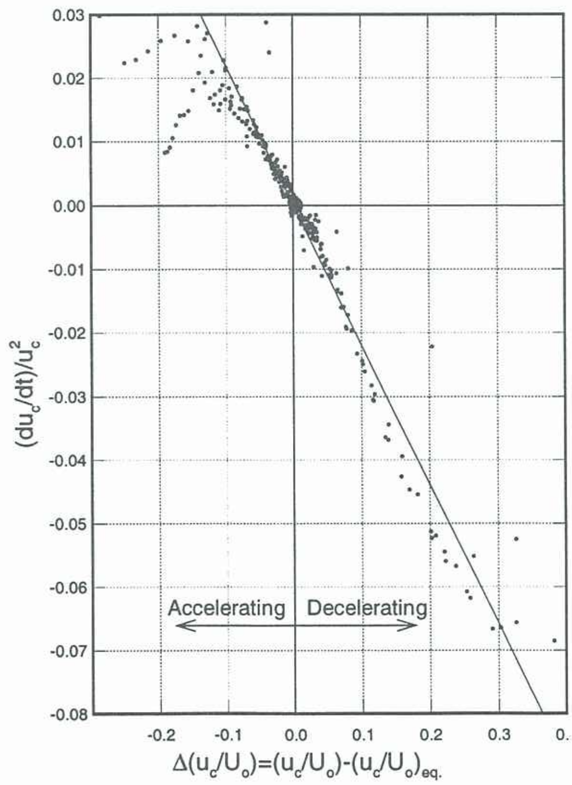

FIGURE 3. Anemometer acceleration results. Points are from experiment, line is equation (1) with $\sqrt{\alpha\beta} = 0.714$.

$\overline{U_o}$ of the anemometer over a number of cycles; this of course is simply the overrun and results are shown in Figure 4. For all combinations the overrun was positive, indicating that the anemometer speeds up faster than it slows down; a direct result of the non-linearity in Equation (3).

The absolute values of overrun are similar to those of Hyson, but exhibit maximum values at much lower ω, presumably due to the slower response. Using atmospheric hot-wire tests Hyson estimated the overrun of his instrument at about 1%. No similar tests were performed on our anemometer. However, as responses to discreet frequencies were somewhat worse than his, a higher error was expected.

DYNAMIC CORRECTIONS

As the vane's frequency response was found to be orders of magnitude faster than that exhibited by the turbine in yaw, no corrections were applied to θ_W except to remove higher frequencies to which the vane could not respond adequately. To prevent phase shift associated with filtering a simple smoothing function was used for this, which was designed to approximate the filtering affects of a Butterworth second order filter.

The anemometer τ was, however, of order of the turbines, and therefore fluctuations to which the turbine could respond were not adequately known. As the instantaneous performance of the turbine was under examination, more sophisticated corrections were necessary, and these were applied using a state space control system approach as described by Dorf (1986). Initially, a linear transfer function model, G_m, was sought with response characteristics similar to those found in the dynamic tests. For simplicity, G_m was determined directly from observed data rather than linearisation of Equation (3). Inversion of G_m then would produce an estimator which, given the anemometer output, could estimate the actual instantaneous input U_∞.

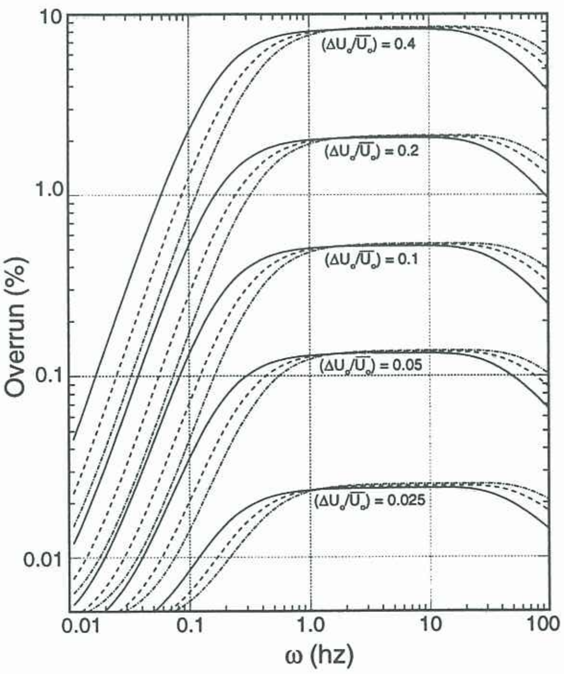

Figure 4. Percentage overrun for varying ω, $\overline{U_o}$, and ΔU_o from integration of Equation (3). For $\overline{U_o}$; 5m/s(———); 7.5m/s (- - - -); 10m/s (-·-·-·-). Values of ΔU_o are defined in the figure.

Experimental responses suggested a model of form $G_m(s) = (Xs+1)/((Ys+1)(Zs+1))$, where s is the Laplace variable, and X, Y and Z are pole and zero time constants. To compensate for anemometer non-linearities, two transfer function models were used, one modelling the response to step increases in U_o, and one to decreases. Discrete time versions of these are shown in Figure 5 together with actual anemometer output, U_A, and the response as predicted by Equation (3); in this figure U_A is non-dimensionalised with the final tunnel speed $U_{o,f}$. The predicted response from both Equation (1) and discrete time versions of $G_m(s)$ are reasonable in the figure, though the slight initial delay in anemometer and discrete versions, a result of the time constant of the tunnel, were not predicted by the equation. Note also the wavering anemometer response, which was believed to be caused by a slight imbalance in the cups.

As the model transfer functions were strictly proper, that is, as they had more poles than zeros like most physical systems, the exact inversions were non-causal and highly noise sensitive. As an alternative, a band limited inversion, $G_e(s) = (Ys+1)((Zs+1)/(Zs+1)(\beta_1 s+1)(\beta_2 s+1))$, was used; β_1 and β_2 are tuning coefficients which determine the compromise between estimator response time and noise amplification, and can effectively be used to filter out higher frequencies.

A state space representation of both estimators, or set of coupled linear differential equations describing the state of the system in the time domain, was found through a state space conversion. As there is only one input, the measured wind speed $U_{\infty,m}$, and one output, the approximated actual wind speed U_∞, and as both estimators are third order, the system state differential equations and output equations can be expressed respectively as;

$$\frac{d}{dt}x = Ax + BU_{\infty,m}(t) \qquad (4a)$$

and,

$$U_\infty(t) = Cx \qquad (5a)$$

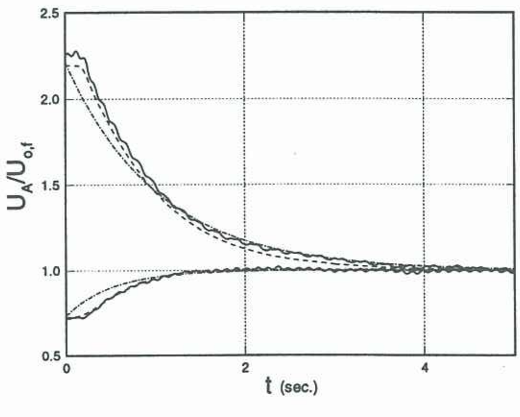

FIGURE 5. Actual and predicted anemometer response to step increase (bottom data) and step decrease (top data). Lines are; U_A (———); discrete version of G_m (---------); Equation (3) (-·-·-·-·-).

where $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$. x_1 and x_2 are state variables, and A, B and C are matrices dependent on $G_e(s)$ which were conveniently found using the transfer function to state space conversion provided by Matlab software.

For a small sampling interval Δt, (4a) and (5a) can be rewritten as,

$$x_{t+\Delta t} = x_t + \Delta t(Ax_t + BU_{\infty,m}(t))\ ;\ x_o = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_{t=0} \quad (4b)$$

and

$$U_\infty(t) = Cx_t \quad (5b)$$

The sequential nature of (4b) and (5b) make them very suitable to digital processing, and these were used for all dynamic corrections. An application to field data is shown in Figure 6 for an arbitrary 100s sample, with the step decrease based estimator showing the largest corrections due to the longer τ when decelerating. As a discontinuity in phase and gain between the two estimators prevented them from simply being used for times of acceleration and deceleration, an average of the two was thought reasonable and used for turbine evaluations; the average is also shown in the Figure. Generally corrections are small, and in all turbine field data, maximum corrections were typically of order of 10% in magnitude and less than 1 second in phase shift; these made only slight differences to turbine quantities being investigated. In specific cases however, for example where maximum gust is an issue, corrections may be of great importance and therefore more applicable.

The effects of smoothing for wind vane data for the same period are also shown in Figure 6, with the filtering effects clearly evident. Though a state space method was not used for our wind vane, there is no reason why one could not be applied using the same techniques as for the anemometer.

CONCLUSIONS

A reasonably simple method to predict the actual wind speed and direction through measurements made by a cup anemometer and wind vane exhibiting non-zero time constants has been presented. Corrections made to field data taken by the authors for wind turbine research were however generally small, though in specific cases they may be of more importance.

It should also be noted that errors associated with the finite distance between measuring point and the point of interest were not included in the preceeding analysis. For our wind turbine research a spatial correction of this sort was also applied, and is detailed in Ebert (1995).

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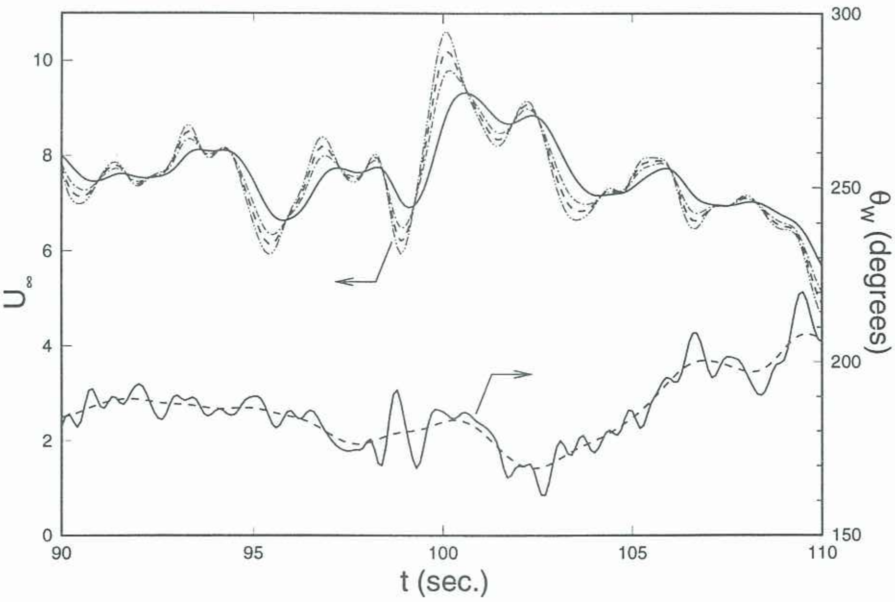

Figure 3. Corrections to field measured meteorological data. Top data is wind speed (U_o), bottom data is wind direction, (θ_w). For wind speed; actual anemometer data (———); estimator based on step increase (-·-·-·-·-); estimator based on step decrease (-···-···-); average of estimators (--------). For wind direction; actual wind vane data (———); wind vane data smoothed (-------).