# PROPELLER ANEMOMETERS AS SENSORS OF ATMOSPHERIC TURBULENCE

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**Abstract.** Even though propeller anemometers are found to give outputs which deviate from the desired cosine relationship by an amount which varies with wind speed, their overall performance is consistent with many atmospheric requirements. Their output per unit wind speed is a function of angle of attack, such that when used as sensors of the vertical or horizontal cross-wind components in the atmosphere, calibration factors may differ by as much as 30% from those obtained in a normal wind-tunnel calibration procedure (in which wind velocity is parallel to the anemometer shaft). These characteristics are sufficiently important that great care should be taken in using these devices in *u-v-w* orthogonal arrays.

For use in eddy-correlation equipment, it appears that it is best to vane-mount the horizontal sensor to ensure that the appropriate calibration factor is employed.

The response lengths of propeller anemometers also vary with angle of attack. Near $\theta=0°$, the axially-referred response length appears to depend linearly on $\cos\theta$, but near $\theta=90°$ a dependence on $\cos^{1/2}\theta$ fits the data. No strong effect of wind speed is found.

Due to their limited response characteristics, these anemometers give rise to underestimates of the Reynolds stress measured near the surface. The extent of the loss is about 8 % when anemometers in good condition are employed at a height of 5m. Operation at a greater height would allow this error to be reduced. After exposure in the atmosphere for some time, the anemometers tend to respond more slowly and greater losses (of the order 25 %) can occur. Some improvement in performance is possible by the choice of a suitable spatial separation of the sensors.

## 1. Introduction

Estimation of the Reynolds stress, $\tau$, is basic to many micrometeorological studies. Of the various methods for obtaining $\tau$, the eddy correlation technique has achieved greatest popularity. This method is, however, subject to errors due to sensor tilt and the resulting cross-contamination of horizontal and vertical wind components (Kaimal and Haugen, 1969). An underestimation of the flux necessarily results if the sensor response is inadequate, even if the technique is correctly applied. Tilt error may be minimised by careful alignment of the sensing head and by proper analysis of the data (Dyer *et al.*, 1970), but often some compromise is necessary as far as sensor performance is concerned.

Given sensors of sufficiently fast response, and of sufficiently small physical size, it is possible in principle to reduce the loss of flux due to sensor inadequacies to a negligible level. To achieve this, it is required that the wind sensors respond fully to all velocity fluctuations in the flux-carrying range, i.e., up to at least 1 Hz in moderate wind speeds near the surface.

Eddy-correlation equipment employing helicoid propeller anemometers has been used in recent field work conducted by C.S.I.R.O. It has been recognised that the reliance upon these relatively slow sensors places strict limits on the flexibility of this equipment, and it is also conceded that some loss of flux must result. The present purpose is to expand on comments made in earlier descriptions of our techniques and equipment. This is necessitated by a recent study (Camp *et al.*, 1970) which has cast some doubt concerning the performance characteristics of propeller anemometers in general.

In a time response study of various types of anemometers, Camp *et al.* investigated the overall performance of a propeller anemometer identical to those used by us.* The four blades are sectors of a helicoid, forming a propeller about 23 cm in diameter of about 30 cm pitch. (In passing, it should be noted that this is in contrast to the usual 'vane' type of anemometer which employs plane blades.) Camp *et al.* report that propeller anemometers do not follow a cosine law near $\theta = 90°$ (where the angle of attack, $\theta$, is defined as 0° when the anemometer is facing into the wind, 90° when the axis is normal to the wind flow, and 180° when the wind blows along the anemometer shaft onto the propeller blades). Since this is precisely the attitude in which such anemometers are commonly employed as vertical component (w) sensors, there is an obvious need for some comment. Their interpretation of response lengths also appears anomalous (see Clink, 1971).

The equipment and techniques in conjunction with which propeller anemometers are used by us are described in Dyer *et al.* (1967) and in Hicks (1970).

## 2. Cosine Response

Figure 1 represents a careful calibration of a propeller anemometer, as a function of angle of attack, and obtained at two wind speeds. The results are normalised to unity at $\theta = 0°$.

Studies made in 1965 (K. M. King, private communication) showed the importance of using a shaft extension beyond the plane of the propeller blades (see Dyer *et al*, 1967). Without such an extension, the geometry of the sensor is sufficiently asymmetrical to cause an offset near $\theta = 90°$. This aspect will be discussed later, but at this time it is sufficient to recognise that the data reported here were obtained using such a shaft extension.

In Figure 1, it is obvious that not only are different results obtained according to the wind speed used, but also that agreement with the ideal cosine response is not found in general. These aspects are better illustrated in Table I, where the results of three calibrations (at 1.18, 3.28 and 7.98 m s$^{-1}$) are shown. In the tabulation, anemometer outputs are first normalised to the value obtained at $\theta = 0°$ and are then divided by cos $\theta$, so that for a perfect cosine response, each tabulated number should be unity. The listed values require little discussion, but some features should be emphasised:

(1) In general, lower values of $V/V_0 \cos\theta$ (where $V$ is the measured output and $V_0$ is that when the angle of attack $\theta = 0°$) are found near $\theta = 90°$.

(2) For most values of $\theta$, $V/V_0 \cos\theta$ increases with wind speed.

* Supplied by R. M. Young Co., Ann Arbor, Michigan, U.S.A.

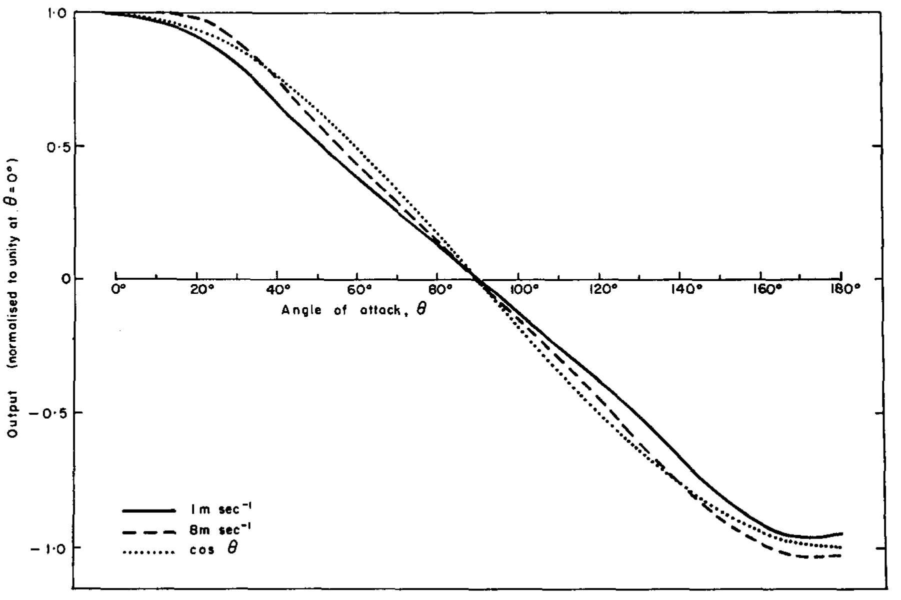


Fig. 1. A comparison between propeller anemometer output and the ideal cosine form for two velocities, 1 and 8 m $s^{-1}$ (approx.). For simplicity of presentation, anemometer stalling near 90° is not shown.

TABLE I

Experimentally determined values of $V/V_0$ cos $\theta$ obtained in a wind tunnel using a helicoid propeller. The angle $\theta$ is defined as 0° when the propeller is facing directly into the wind.

| $\theta$ | Wind-speed (m $s^{-1}$) | | | $\theta$ | Wind-speed (m $s^{-1}$) | | |
|---|---|---|---|---|---|---|---|
| | 1.18 | 3.28 | 7.98 | | 1.18 | 3.28 | 7.98 |
| 0 | 1.00 | 1.00 | 1.00 | 180 | 0.95 | 0.94 | 1.03 |
| 10 | 0.99 | 0.99 | 1.01 | 170 | 0.98 | 0.97 | 1.05 |
| 20 | 0.97 | 0.98 | 1.05 | 160 | 0.97 | 0.97 | 1.05 |
| 30 | 0.94 | 0.97 | 1.03 | 150 | 0.93 | 0.96 | 1.03 |
| 40 | 0.87 | 0.91 | 0.97 | 140 | 0.86 | 0.91 | 1.00 |
| 50 | 0.81 | 0.83 | 0.91 | 130 | 0.79 | 0.85 | 0.95 |
| 60 | 0.76 | 0.80 | 0.87 | 120 | 0.74 | 0.78 | 0.90 |
| 65 | 0.76 | 0.79 | 0.88 | 115 | 0.75 | 0.80 | 0.90 |
| 70 | 0.72 | 0.78 | 0.83 | 110 | 0.70 | 0.78 | 0.88 |
| 75 | 0.66 | 0.76 | 0.84 | 105 | 0.66 | 0.77 | 0.88 |
| 80 | 0.68 | 0.78 | 0.86 | 100 | 0.67 | 0.80 | 0.92 |
| 85 | – | 0.79 | 0.80 | 95 | – | 0.94 | 1.04 |

(3) Interference by the anemometer shaft and mounting assembly is evident at all wind speeds near $\theta = 180°$, in that values of $V/V_0$ cos $\theta$ do not tend to unity.

The values listed in Table I are accurate to about 1% of $V_0$, this being the net error resulting from inaccuracy of measurement of the anemometer output and the error involved in setting the angle of attack in the wind tunnel.

From the point of view of vertical component measurement, the table shows that the calibration of a propeller anemometer of this type is different from that obtained in the conventional manner (which would give merely $V_0$ in the present terminology). In fact, the anemometer output per m $s^{-1}$ of normal wind component drops by about 30% in light winds as $\theta$ tends to 90°.

When anemometers of this type are employed in orthogonal arrays to detect the $u$, $v$ and $w$ wind components ($u$ along the mean wind, $v$ crosswind and $w$ vertical), care should be taken to apply the appropriate calibration. That this calibration is itself a small function of the wind speed is evident from the data.

## 3. Measuring the Vertical Component of the Wind

Figure 1 and Table I show that over a considerable range centred on $\theta = 90°$, the response is nearly proportional to cos $\theta$ but that the constant of proportionality is less than unity and is a function of wind speed. Table II gives the results of a regression of anemometer output (in mV) on the product $U \cos\theta$ where $U$ is the wind-tunnel velocity, constrained to angles of attack from 60° to 120° (in 5° steps) and for the three velocities listed in Table I. The correlation coefficients obtained are all greater than 0.999, an indication of the excellent linearity of these devices near $\theta = 90°$.

TABLE II

Results of regressions of anemometer output (in mV) on $U \cos \theta$ (where $U$ is wind tunnel velocity) for $60° \leq \theta \leq 120°$ and for 5° increments in $\theta$.

| | | | |
|---|---|---|---|
| Wind speed (m $s^{-1}$) | 1.18 | 3.28 | 7.98 |
| Correlation coefficient | 0.9991 | 0.9998 | 0.9998 |
| Slope (mV/m $s^{-1}$) | 40.6 ±0.6 | 44.1 ±0.3 | 45.7 ±0.3 |
| and as % of 0° calibration | 72.0 | 78.2 | 81.0 |
| Error at ±10° from $\theta = 90°$ ($E = 5.2$ %) | −7.4 % | −0.6 % | 1.5 % |
| ±20° ($E = 2.5$ %) | −3.3 % | −1.4 % | −2.4 % |
| ±30° ($E = 1.5$ %) | 2.7 % | 0.4 % | 0.3 % |
| Apparent updraft at $\theta = 90°$ (cm $s^{-1}$) | | | |
| (a) without shaft extension | 1.2 | 4.8 | 16.7 |
| (b) with shaft extension | −0.3 | 0.6 | 6.3 |

As has been already indicated, the slopes are found to be significantly less than the calibration figure obtained holding $\theta$ at 0° (56.4 mV/m $s^{-1}$). Also, the slopes obtained at the three wind speeds are significantly different, as the tabulated standard errors indicate. The errors between the measured values and the predicted outputs from each regression line are listed at three angles, corresponding to ±10°, 20°, and 30° from $\theta = 90°$. These errors must be compared with the accuracy with which the angles of attack could be pre-set in the present determination. This is estimated to be 0.5°, resulting in the uncertainties listed as E in the table. At 1.18 m $s^{-1}$, each of the three error estimates is greater than that attributable to the angle uncertainty, and consequently there is reason to suspect that this type of propeller anemometer does not perform well at such low velocities. However, at the higher speeds, the error estimates are all small. It appears that the anemometer functions well as a $w$ sensor provided the wind speed is above about 2 m $s^{-1}$.

The difference found in calibration coefficients (the slopes of Table II) is such that a value of, say, 45 mV/m $s^{-1}$ could be applied at all wind speeds between 2 and 10 m $s^{-1}$ provided that errors of the order of 5% in $w$ can be tolerated, and that the wind does not deviate from the horizontal by more than 30°.

## 4. The Effect of a Shaft Extension

In the above discussion, it has been assumed that a shaft extension beyond the plane of the propeller is always employed. Data show that the use of such an extension improves the geometry of the device to an extent readily visible in simple experiments. Consider, for example, a propeller anemometer set at some angle $\theta$. Without altering this angle, outputs can be measured with and without a shaft extension. Such outputs can be interpreted as apparent updrafts through the propeller caused by the asymmetry of the device. Table II includes the results of this type of investigation, carried out at the same wind speeds as used previously.

It is clear that the magnitude of the updraft caused by asymmetry will be greatest at high wind speeds when the propeller is mounted with axis vertical. The offsets quoted in the table support a wind speed dependence. In conditions of 8 m $s^{-1}$, a 16.7 cm $s^{-1}$ updraft through the propeller is reduced to 6.3 cm $s^{-1}$ by the addition of the shaft extension supplied for this purpose by the manufacturer. At lower speeds, a correspondingly smaller effect is found. Estimates of the extent of the dependence on $\theta$ are difficult to derive, and the present data cannot be used in this manner.

The starting characteristics of all mechanical wind sensors are controlled, to a large extent, by friction and sticking. Typically, there is a threshold velocity below which the anemometer will not rotate. Wind tunnel tests show that for $\theta = 0°$, the propeller anemometers used here are non-linear below about 1 m $s^{-1}$, with a threshold velocity of the order 25 cm $s^{-1}$. This aspect is of little importance in the atmospheric $u$-context, since such low wind speeds are most uncommon. However, a second threshold exists in the region $\theta = 90°$, as is evident in the data of Table I for the lowest wind-speed case. In a wind-tunnel speed of 1.18 m $s^{-1}$, no rotation is seen when the angle of attack is between approximately 80° and 100°.

In such conditions, another general feature of propeller anemometer performance becomes obvious: the tendency for the blades to orient themselves in the mean flow to minimise drag. A recorder trace of the anemometer output contains a sinusoidal component of four times the propeller revolution frequency. Thus there are three aspects of anemometer threshold relevant to the case of $w$-measurement: friction, mechanical sticking and propeller pulsing. For any angle of attack near 90°, it follows that the threshold velocity is determined by the driving torque being sufficient to overcome mechanical effects and to maintain rotation of the sensor. In this regard, the situation is similar to that of a normal cup anemometer in light winds.

Table I suggests that the threshold angle of attack approaches 90° as the wind speed increases, as must be expected from the above torque considerations. In atmospheric applications such as that discussed below, a 'dead zone' of less than $\pm 2°$ about $\theta = 90°$ seems likely. The net effect of this on measurements of atmospheric turbulence is difficult to estimate, since any error which might result must arise from a situation of intermittent turbulence. The time-domain traces presented by McDonald (1972), for example, show that in unstable conditions, vertical velocities are rarely zero, and that propeller anemometers continually fluctuate through zero with negligible 'dead zone' effect. In the following discussion, such effects are consequently neglected, with the reservation that the situation in stable conditions might well be different.

## 5. Orthogonal Arrays of Propeller Anemometers

Table I shows that the output of this type of anemometer (per unit wind speed) deviates systematically from the ideal cosine law. For $\theta$ near 90°, the appropriate calibration factor is about 20% lower than that normally quoted ($\theta = 0°$) at moderate wind speeds. This has an obvious relevance to the atmospheric $u$-$v$-$w$ context, in which a fixed orthogonal set of these anemometers is sometimes used. The following points are clear:

(1) For the $w$ component, good data will result provided the corresponding anemometer is calibrated as in Table II, by varying $\theta$ from, say, 60° to 120° in a wind tunnel at various wind speeds. The calibration so obtained will be different from that appropriate in other contexts.

(2) For the $u$ and $v$ components, accurate information will be obtained only if the wind is along either of the anemometer axes, allowing the use of the $\theta = 0°$ calibration. If, however, the wind is at an angle of 45°, then both the $u$ and $v$ anemometers will underestimate the wind velocity, possibly by as much as 15% if complete reliance is placed on a $\theta = 0°$ calibration technique. It follows that the calibration factors to be applied to the horizontal anemometers of an orthogonal array cannot be specified to the accuracy which is usually required (unless corrections are continuously applied on the basis of estimates of $\theta$ from the $u$-$v$ outputs). It is for this reason that vanes are often employed to orient a propeller anemometer into the mean wind, allowing the $\theta = 0°$ calibration factor to be applied with confidence.

## 6. Propeller Anemometer Response Characteristics

For the present purposes, the response times are obtained by allowing an anemometer to accelerate from rest to its equilibrium angular velocity in conditions of constant wind speed. The appropriate time constant is then deduced as the time required for the anemometer to reach $(1 - 1/e)$ of its final speed.

Figure 2a illustrates the acceleration response of propeller anemometers in wind speeds of about 4 m s$^{-1}$ and for various angles of attack, $\theta$. To allow the data to be presented in the one diagram, time is scaled according to the response time ($T$)

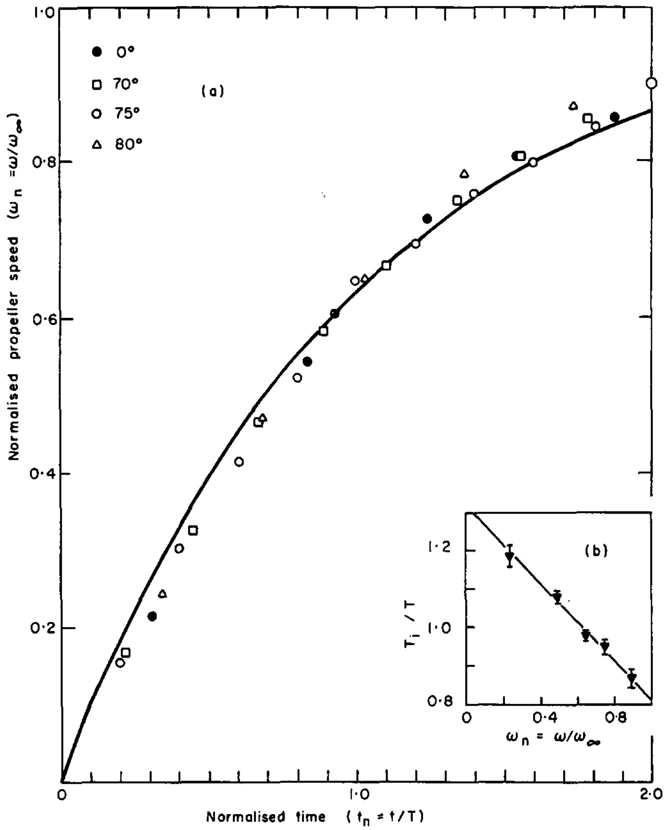


Fig. 2. (a) The response of a propeller anemometer allowed to accelerate from rest up to an equilibrium speed of rotation $\omega_\infty$ as a function of time scaled according to the response time ($T$) calculated in the usual manner as the interval required for $\omega$ to reach 63.2 % of $\omega_\infty$, Four different cases are shown, corresponding to angles of attack $\theta$ ranging from 0° to 80°. The line drawn represents a purely exponential response. (b) The variation of effective proportional response time ($T_i/T$) with anemometer speed, plotted non-dimensionally.

appropriate in each case ($t_n = t/T$) and anemometer outputs are normalised to unity at the equilibrium velocity ($\omega_n = \omega/\omega_\infty$). The line drawn is the ideal exponential response characteristic,

$$\omega_n = 1 - \exp(t_n). \tag{1}$$

It is seen that the four cases presented in Figure 2a consistently differ from the ideal characteristic, falling below the curve when $t_n < 1$ and above the curve otherwise.

In Figure 2b, the same data are presented somewhat differently. Rather than determining the response time in the manner above, each individual data point is used to deduce an estimate of the time constant ($T_i$) from Equation (1). These values are then normalised according to the overall values ($T$) obtained above, and averaged in groups of $\omega_n$. Consequently, Figure 2b shows that such anemometers as are used here accelerate more slowly from rest than would be expected on simple exponential grounds. The straight line drawn in the diagram is an adequate representation of the data, and suggests that the time required for a propeller to respond to sudden increases in wind speed increases with the magnitude of the fluctuation. If such fluctuations are small, then the figures imply that the response times obtained in the present way might well be overestimated. Thus, in the later context of atmospheric turbulence, the response time obtained here may be up to 20% different from those actually effective. Considering the probable magnitudes of fluctuations $u'$ in a mean wind $\bar{u}$ ($|u'/\bar{u}|$ probably not greater than about 30%), it seems likely that the present values may be overestimates.

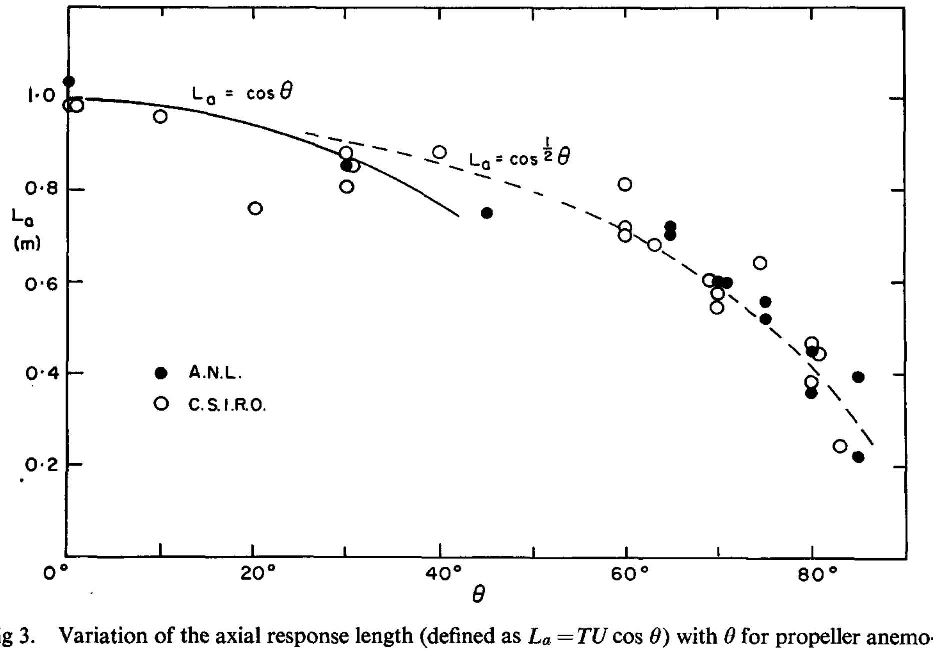


Fig 3. Variation of the axial response length (defined as $L_a = TU \cos\theta$) with $\theta$ for propeller anemometers. Data obtained in Australia and in the U.S.A. are plotted separately.

In passing, it is worthwhile to mention that the line of Figure 2b indeed indicates equality of the individually calculated response time $T_i$ and the overall mean value $T$ when the normalised anemometer output is $\omega_n = 0.632$, as is required by the methods adopted in the presentation.

Clink (1971) suggests that Camp *et al.* (1970) have incorrectly reported the response lengths of their propeller anemometers. The data obtained in wind-tunnel testing at C.S.I.R.O. and at Argonne National Laboratory, U.S.A., confirm Clink's viewpoint. Figure 3 presents the results obtained using a number of anemometers. Each plotted point represents the average of several measurements made with a single instrument.

The response length plotted in the diagram is defined by

$$L_a = TU\cos\theta, \tag{2}$$

where the subscript $a$ is used to identify this as referring to the axial velocity component. $U$ is the wind tunnel velocity, and $T$ is the measured time constant (as above). To obtain the conventional response length $L = UT$ from the data of Figure 3, it is thus necessary to divide the reported values by $\cos\theta$.

Insofar as a propeller anemometer resolves wind velocity and responds to changes in the axial component of the driving force, Figure 3 is a fair physical representation of its performance. It is seen that the axial response length decreases as $\theta \sim 90°$, in the same way as indicated by Camp *et al.* (Figure 3), even though these authors claim that their 'distance constants' are calculated with respect to wind speed in the tunnel. In fact, the response length as calculated in either manner is far from constant with angle of attack (although our data support near-constancy with wind speed) and hence the present preference for the terminology 'response length'.

It is of interest to recall that Figure 1 and Table I indicate that our type of propeller anemometer operates in different modes depending on whether $\theta$ is sufficiently near 90° or not. The critical angle between the two regimes seems to be about 50°. In Figure 3, two corresponding response-length relationships are indicated. Near 90°, the data suggest that $L_a$ is proportional to $\cos^{1/2}\theta$, while near $\theta = 0°$ the data tend to support a proportionality with $\cos\theta$ (i.e., a constant response length referred to wind-tunnel velocity).

A dependence of response length on wind speed is apparent in Figure 3 of Camp *et al.* Data obtained at C.S.I.R.O. do not support this, possibly because the effect is hidden by errors involved in the determination of the time constant. Since a small variation of calibration factor with wind speed is evident near $\theta = 90°$ (see Table II), we might expect a similar change in response in this situation. Such a small effect would not be seen in the present data.

## 7. The Effect of Friction

When wind velocity increases, a propeller anemometer accelerates until friction is exactly balanced by the residual driving torque. If friction were negligible, the propellers used here would rotate at their designed minimum-drag rate, being one revolution for about every 30 cm of wind run. The instruments as reported so far typically gave equilibrium rotation rates approximately 98% of this value, verifying that friction is usually small.

Consequently, the data presented above apply only to sensors in good condition. It has been found that extensive field use, especially in dusty environments, causes increased loading on the propellers themselves (greater friction) which results in larger response times than would normally be found. An anemometer exposed for six weeks at Tsimlyansk, U.S.S.R., was found to have a response length of 2.2 m at $\theta = 0°$ and 1.3 m at $\theta = 80°$ (axially referred as in Figure 3). Both values are much greater than those commonly accepted. After cleansing, the same anemometer gave respective lengths of 1.36 m and 0.42 m, in closer agreement with Figure 3.

## 8. The Measurement of Reynolds Stress

It is conventional to consider a sensor as a simple analog R–C circuit having a time constant $T$ responding to an imposed fluctuation $\sin(\omega t)$. It is easily shown that this gives rise to an output $[\sin(\omega t) - \omega T \cos(\omega t)]/Z$ where $Z = (1 + \omega^2 T^2)$. In the present case, the outputs from two such sensors are multiplied together, and the resultant output is integrated. This leads to an effective transfer function:

$$A_{1,2}(\omega) = \frac{1}{Z_1 Z_2}(1 + \omega^2 T_1 T_2), \tag{3}$$

where the two sensors are allowed to have different responses to signals initially in phase. The case of a phase difference between the two signals is treated later. In the present case, we are concerned with propeller anemometers which have distance constants of about 1 m (appropriate to the horizontal velocity) and about 2.5 m (for the vertical component, estimated from Figure 3 as the most likely value in normal atmospheric conditions, and referred to the horizontal component). It has already been shown (in Section 6) that the electrical analog to the present sensors introduces errors of less than 20% in $T$.

In Table III, values of the transfer function are listed: (a) for matched sensors of response length 1 m; (b) for matched sensors of response length 2.5 m; and (c) for

TABLE III

The effect of sensor response lengths $L_1 = 1$m and $L_2 = 2.5$m on atmospheric sinusoidal fluctuations of frequency $f$. The tabulated values are these of the transfer function $A_{1,2}$ relevant to Reynolds stress measurement employing these sensors. The atmospheric signals are assumed to be in phase. Five cases are listed: (a) using matched sensors of response length 1 m, (b) using matched sensors of response length 2.5 m, (c) using one sensor of 1-m response length and one of 2.5-m response length, (d) as in (c) but allowing the slower sensor to be located 40cm upwind of the faster, and (e) as in (d) but with the sensors interchanged. For purposes of the calculation, a wind speed of 5m s$^{-1}$ at a height of 5m is assumed.

| $f$(Hz) | Transfer functions | | | | |
|---|---|---|---|---|---|
| | (a) | (b) | (c) | (d) | (e) |
| 0.01 | 1.000 | 0.999 | 0.999 | 0.999 | 0.999 |
| 0.02 | 0.999 | 0.996 | 0.997 | 0.998 | 0.997 |
| 0.05 | 0.996 | 0.976 | 0.982 | 0.984 | 0.979 |
| 0.10 | 0.984 | 0.910 | 0.931 | 0.939 | 0.922 |
| 0 20 | 0 940 | 0.717 | 0.781 | 0.803 | 0.752 |
| 0.50 | 0.717 | 0.289 | 0.411 | 0.447 | 0.350 |
| 1.00 | 0.386 | 0.092 | 0.176 | 0.187 | 0.122 |
| 2.00 | 0.136 | 0.025 | 0.057 | 0.041 | 0.020 |
| 5.00 | 0.025 | 0.004 | 0.010 | −0.007 | − 0.009 |
| 10.00 | 0.006 | 0.001 | 0.003 | 0.001 | 0.001 |

one of each. Ideally the values obtained should be unity over the entire flux-carrying range, which extends to a frequency of about 2 Hz in normal conditions near the surface. It is seen that the best performance is obtained with the faster matched sensors, as must be expected. However, it is clearly better to employ a faster sensor than to match both at the slower response. This is in contrast to the commonly held belief that in all such situations, sensor responses should be matched, and is a direct result of the faster sensor allowing a greater passage of signal even though some of this is out of phase with that derived from the slower.

At first thought, we might expect that the transfer coefficients listed in column (c) of Table III are those applicable to the measurement of Reynolds stress using propeller anemometers, as suggested in Hicks (1970), where the horizontal anemometer is vane-orientated into the wind. However, it has been assumed that both anemometers are physically located at the same place, which is not possible.

The effect of a spatial separation of the sensors may be examined by considering the phase error which results. Instead of both sensors responding to imposed signals $\sin(\omega t)$, it is now necessary to consider one of these being phase lagged by an amount $\varepsilon = \omega d/\bar{u}$, where $d$ is the upwind separation. A modified form of equation (3) results:

$$A_{1,2}(\omega, \varepsilon) = \frac{1}{Z_1 Z_2}\left[(1 + \omega^2 T_1 T_2)\cos\varepsilon - \omega(T_2 - T_1)\sin\varepsilon\right], \tag{4}$$

where it is assumed that sensor 2 is the slower and that the faster sensor is upwind of it.

In Table III, columns (d) and (e) give the results of this consideration. Not surprisingly, some difference is found, and it appears that an improvement in overall performance can be obtained by arranging the sensors in such a way that the faster sensor is always downwind of the slower. The value of $d$ used in the calculation is 40 cm, which is physically reasonable.

On the assumption that, to a first approximation, phase differences between $u$ and $w$ may be neglected (a point examined again later), we may apply the above formulae to estimate the efficiency of measurement of Reynolds stress by propeller anemometers on the basis of co-spectral data obtained by fast-response instrumentation.

In Figure 4, the co-spectral data of Miyake *et al.* (1970) are used as a basis for such a calculation. Three estimates of the co-spectra found after analysis of signals transmitted by propeller anemometers are shown, corresponding to; (a) response lengths of 1 m for the horizontal component and 2.5 m for the vertical (as in column (c) of Table III); (b) for response lengths matched at 2.5 m (column (b)) and (c) for the larger response lengths found after extended use of the anemometers (reported in Section 7 above). Integration under the four curves of the diagram yields the loss in Reynolds stress which must be expected from the use of sensors with such large time constants:

(1) Using sensors which are matched to the slowest response time, the loss of Reynolds stress amounts to 11.7%.

(2) Using the faster horizontal anemometer results in an improvement: 8.5% loss.

(3) After six weeks exposure in the field, frictional effects cause the loss to be increased to 25.4%.

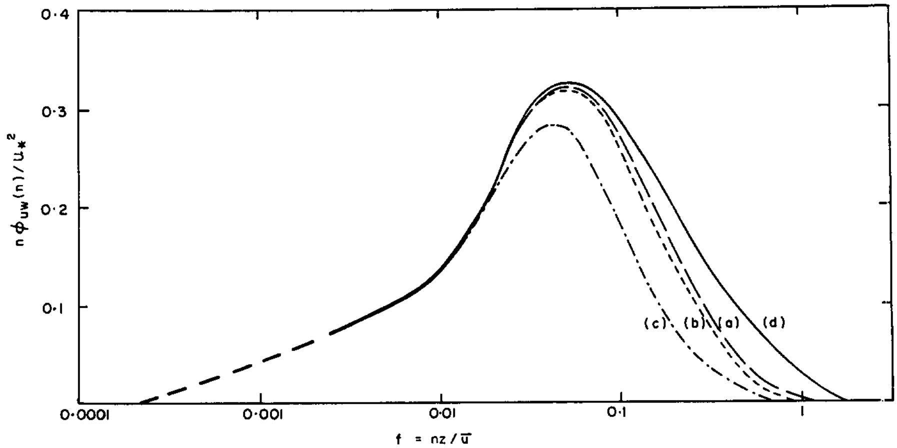


Fig. 4. The effect of limited high frequency performance of wind sensors on the $u-w$ covariance spectrum. The spectrum of Miyake *et al.* (1970) (curve d) is presumed to apply at a height of 5m in a 5m $s^{-1}$ wind speed. Then curve (a) shows the result of employing response lengths of 1 m for the horizontal component and 2.5m for the vertical, curve (b) assumes matched sensors of 2.5-m response length, and curve (c) is appropriate to the response lengths found after six weeks continual exposure of a particular pair of propeller anemometers.

It should be emphasized that the above estimates assume a wind speed of 5 m $s^{-1}$ and an operating height of 5 m. At greater heights, smaller losses will be found. Also, it is assumed that the atmospheric signals are in phase. In the present considerations, where different sensor response times are being considered, the natural phases of the atmospheric phenomena might well be important, and some discussion of the probable effects is in order.

## 9. The Effect of Out-of-Phase Components

The general behaviour of covariance equipment exposed in conditions of significant out-of-phase correlation between the signals of interest can be investigated in much the same way as above. Consider the case in which the second atmospheric signal lags the first by a phase angle $\delta$. Then, in the same way as Equation (3) was derived earlier, a different form of the effective transfer function is obtained:

$$A_{1,2}(\omega, \delta) = \frac{1}{Z_1 Z_2}\left[(1 + \omega^2 T_1 T_2) - (\omega T_2 - \omega T_1)\tan\delta\right]. \tag{5}$$

This equation may be further modified to take into account the spatial separation of sensors, but for the present it will be considered in its own right and the results obtained will be compared with those obtained previously from Equation (3).

Equation (5) shows that the effect of any phase difference is confined to the higher frequencies, since it appears in a term which also includes the frequency itself.

Figure 5 illustrates the phase lags between $u$ and $w$ found in moderately unstable conditions during an experiment at Edithvale (Victoria) in 1968. The plotted angles

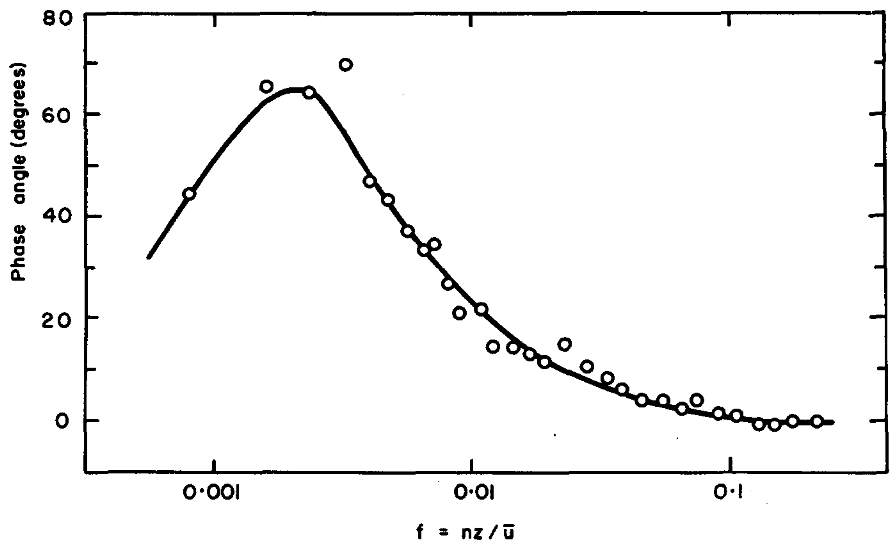


Fig. 5 The phase angle by which fluctuations in $u$ lag those in $w$ in moderately unstable conditions. These data were obtained at Edithvale (Victoria) during 1968, at a height of 4m in winds of about 5m $s^{-1}$

are those by which the horizontal wind velocity lagged the vertical, obtained from quadrature and co-spectral information analysed by fast-Fourier transform. It is seen that lags of the order of 45° were found at normalized frequencies of less than 0.01, but that as frequency increases, the atmospheric fluctuations tend to be in phase. Similar behaviour is implied by the co- and quadrature spectral data given by Cramer *et al.* (1962), and by Smith (1970).

It is possible to improve the overall performance of a covariance instrument employing sensors of different time constants by arranging the sensors in such a way that the faster corresponds to the signal which is lagged (as is shown by consideration of Equation (4)). In the case in which propeller anemometers are employed, the $w$-sensor is the slower and, as is seen in Figure 5, the horizontal velocity is the lagged signal. Consequently, an improvement in performance must be expected in general.

In the same way as before, Equation (5) can be used to construct a modified co-spectrum which predicts, upon integration, the loss in Reynolds stress which would be expected. Using, as previously, response lengths of 1 m for u and 2.5 m for $w$, the loss deduced in this way amounts to 6.6% which must be compared with the earlier estimate of 8.5% obtained using the same sensor characteristics but ignoring the quadrature component. It seems that an improvement will generally result from considerations of natural phase lags, but that the magnitude of this amounts to only about 2%.

The previous comments about the benefits of employing mis-matched sensors or carefully chosen physical separations are in no way diminished by the present considerations. It seems, in fact, theoretically possible to utilise the natural phase lag in the atmosphere to compensate, partly, for sensor inadequacies, in much the same manner as was discussed in the case of separated sensors. However, the obvious complexities of the general case as it is now postulated are such that the various ramifications are too numerous to itemize here. It appears preferable to consider each individual problem in its own right.

## 10. Conclusions

Careful calibration of propeller anemometers shows that these devices differ from the ideal cosine performance in a manner which is a function of wind speed, but which is of little significance in covariance applications. When used as sensors of cross-wind components, the appropriate calibration factors are up to 30% lower than those which should be employed when the anemometer faces into the mean wind. Consequently, for use in eddy-flux applications, the horizontal component anemometer should be vane-mounted, even though this introduces an error due to the use of wind speed rather than velocity resolved along the mean direction.

For angles of attack near zero, the anemometers appear to have a nearly constant response length, when this is referred to wind-tunnel velocity (or total wind speed in the free atmosphere). However, near $\theta = 90°$ a dependence on $\cos\theta$ is found, in such a way that the response length (referred to the axial wind component) appears to be proportional to $\cos^{1/2}\theta$. No large influence of wind speed is evident in the present data.

When employed in eddy-correlation equipment, propeller anemometers allow the Reynolds stress to be measured with a loss of about 8.5%, resulting from their inability to respond to sufficiently high frequencies, at heights of about 5 m in wind speeds of about 5 m $s^{-1}$. This is significantly better performance than would be obtained if the horizontal anemometer were altered to give matched response times, which would give a loss of about 12% in the measured stress. However, anemometers exposed for long periods tend to deteriorate in performance, eventually giving losses probably greater than 25%.

The above numbers are derived from considerations of atmospheric fluctuations in horizontal and vertical wind components, which are assumed to be in phase. When measurements of quadrature spectra are taken into account, an improvement of the order of 2% results.

There is evidence that the present estimates are of the correct order. Measurements of Reynolds stress and wind profiles in neutral stratification (Hicks, 1970) yielded a value of the von Karman constant $k = 0.41 \pm 0.025$. Increasing the stresses to allow for sensor inadequacies on the basis of the results quoted above would result in a value for $k$ still not significantly different from the commonly accepted value of 0.41. Also, comparison between co-spectra obtained using propeller anemometers and those from sonic techniques gave a stress loss of about 16% (Dyer and Hicks, 1972). This figure was obtained during the extensive field trial at Tsimlyansk, U.S.S.R., at the conclusion of which the degraded response lengths of Section 7 were measured.

Some overall improvement in Reynolds stress determination using propeller anemometers can be obtained by suitable physical location of the sensors. For example, if the faster sensor is located downwind, then a phase lag is introduced which tends to compensate that introduced by the slower anemometer.

In general, there seems no reason why propeller anemometers should not be used in the eddy flux context, provided their limited frequency capabilities are borne in mind and that losses of flux of the order of 8% are acceptable in normal operating conditions. Such losses may, of course, be reduced by operation at greater heights than the 5-m level considered here.

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