6th Australasian Hydraulics and
Fluid Mechanics Conference
Adelaide, Australia, 5-9 December 1977

Field Measurements of the Characteristics of a Rural Boundary Layer Near the Ground: Part II — Data Processing

R. FLAY
Graduate Student, Department of Mechanical Engineering, University of Canterbury, N.Z.
and
D. LINDLEY
Senior Lecturer, Department of Mechanical Engineering, University of Canterbury, N.Z.

SUMMARY Some problems associated with the processing of data taken from orthogonal arrays of propeller anemometers, used in a field experiment to measure the characteristics of a rural boundary layer close to the ground are discussed. Errors associated with the characteristics of the sensors and with data retrieval and processing have been investigated and some preliminary results are presented. The results confirm that correction for the non-cosine response characteristic of the sensor is essential and that trend removal, sensor frequency response, data sampling rate and record length are important considerations if precision is to be ensured.

1 INTRODUCTION

The frequency and non-cosine response limitations of the Gill type [Gill, (1975)] of propeller anemometer when used in orthogonal arrays for the measurement of wind structure are well known [Horst (1972)].

In the experiment described in Part I of this paper a similar design of anemometer, but having a digital output was used for measurements of velocity, turbulence intensity, average wind direction, power spectral densities, correlation functions and Reynold's stresses. Figure numbers quoted in this paper refer to Figures in Part I.

All these parameters are subject to several possible errors including those investigated by Horst. The errors to be investigated in this work are those due to:-

digitisation of the signal, non-cosine response of the sensor, short and long term changes in wind properties during the recording period, frequency response limitations of the sensor, and effect of record length.

Some general features of the software to calculate wind structure parameters and preliminary results of the error analyses are presented in this paper.

2 THE DATA RECORD

Propeller anemometers rotate at a speed approximately proportional to $V\cos\theta$ where V is the impinging wind velocity and θ the angle it makes with the rotational axis of the anemometer. Hence if three such anemometers are used in an orthogonal array, the actual wind vector as it varies with time can be measured.

In the present anemometer design, each propeller drives a shaft mounted disc containing 32 slots. The disc rotates between two light emitting diodes and photo-receivers, which give both speed and direction of rotation. The square waves from these diodes drive an 8-bit counter, 1 bit used to give the direction of rotation, and the other 7 bits to give the speed of rotation. The counters are allowed to count for a period of time (which is switch selectable) which is determined primarily by a consideration of the mean wind speed, and which is selected prior to a data recording. The time periods are 1/8, 1/16, 1/32, 1/64, 1/128 seconds.

The counters for each array are scanned sequentially, the contents stored in a buffer-formatter and the counter reset to zero. The scanning frequencies corresponding to the counting time periods above are respectively 7.5, 15, 30, 60, 120 H_z. When the buffer is full, the contents of the buffer are written onto 7 track magnetic tape on a Kennedy 8107 tape deck in blocks of 512 six-bit words.

The data on the 7 track tape is later "processed" on a Burrough's B6718 computer.

3 PRE-PROCESSING

3.1 Reformatting, running mean, first difference test

In the first pass of the data, the data is read off the 7 track magnetic tape, reformatted into records of 256 data from each anemometer, put into blocks of 768, and written to a computer library tape. The records are written in sequence to the tape in the order anemometer 1, anemometer 2,..., anemometer N, anemometer 1, ... etc. During this pass of the data a running mean is calculated and consecutive data from each anemometer compared. The running mean is used to detect trends in the data and compare with observations made in the field during recording. The difference test is used to check for outliers.

The difference test is used to see whether the difference between consecutive data is larger than that which could be expected from the characteristics of the instrument. The anemometer has a certain amount of inertia and the propeller has known lift-drag characteristics so that assuming a maximum possible sharp edged gust impinges on the instrument it will accelerate an amount which can be calculated. If the acceleration of the instrument is greater than could be expected, a simple but effective correction technique is to replace the outlier by the mean of the preceding value and the next value. Outliers are usually caused by hardware faults and occur very infrequently in practice.

Providing the data after the above test appears to have very few or no outliers, and the trends in the means are as expected, the data recording is assumed to be a good one and more detailed analysis is performed.

3.2 Probability density, stationarity check

Wind velocity fluctuations over a period of between 10 minutes and one hour are often assumed to have a Gaussian distribution. However, measurements in the lower 30 m of the boundary layer indicate the more frequent occurrence of gusts and lulls than is represented by a Gaussian distribution [ESDU (1974)].

Thus the velocity data can be plotted as a probability distribution and compared with the Gaussian distribution. A χ 'Goodness of Fit Test' is often used to see if the data varies significantly from a Gaussian distribution. Large deviations may mean malfunctioning sensors or the bad choice of wind conditions for the experiment.

An additional test on the data to check its reliability is an examination of its stationarity. A good non-parametric test which is easy to apply is that called the 'Run Test' [Bendat and Piersol (1971)]. It can be used to check if the mean and variance calculated over short time periods when the data stream is broken up into separate blocks show variations other than those due to expected sampling variations.

If it appears that the wind velocity contains a trend, i.e. a frequency component with a period greater than the record length, then this should be removed before further processing takes place. This is necessary as these trends will tend to cause large distortions in the subsequent processing of correlation and spectral quantities. In particular, trends in the data distort the estimation of low frequency spectral content.

3.3 Trend removal

Another difficulty in analysing field measurements of wind structure is the choice of a mean velocity for the duration of the record. If a change in the weather pattern occurs during a recording, the mean will change and therefore the same mean may not be representative throughout the recording.

The simplest approach to calculate the mean wind speed is to average the velocity for the duration of the record and analyse the data as it fluctuates about this mean wind speed. A mean may also be fitted to the data which varies in a linear, parabolic or higher order way with time throughout the recording. This work has investigated the variation of the wind structure parameters using two types of trend (in the mean) removal from the data.

The two types of trend removal are linear and parabolic. Both have been fitted by least squares to the data stream and are defined such that if x(t) is the original data stream, then y(t) being the data with trend removal is

$y(t) = x(t) - a_o - a_1 t$ (linear; a_o, a_1 are constants)

$y(t) = x(t) - b_o - b_1 t - b_2 t^2$ (parabolic; b_o, b_1, b_2 are constants)

Higher order polynomials may also be fitted to the data with a consequent increase in computer time but have not been fitted to this data.

4 ANALYSIS PROCEDURES

4.1 Velocities, directions, turbulence intensities, Reynolds stresses

A computer program has been written which calculates the average velocity, wind direction, turbulence intensities in the x, y and z directions and Reynolds stresses. It calculates these for orthogonal arrays at different heights for the required record lengths and sampling frequencies, with or without correction for non-cosine response.

The program is organised so that the data stream is read sequentially and various summations accumulated. At the end of each integral number of 4.5 minutes of data, which corresponds to an integral number of tape records, the summations are used to calculate the above parameters. Since the anemometers will invariably be aligned in a direction such that the wind vector does not coincide with the anemometer axis, the summations are used to resolve the data into the longitudinal and lateral directions for that particular recording length and the parameters calculated.

When the end of the data stream is reached, the program returns to the beginning of the data stream and recalculates the parameters, this time using as input the average of two consecutive data samples. This process can be repeated as often as desired. The actual physical period for which the counters are allowed to count is fixed by the instrumentation so changes in the sampling frequency by this averaging technique are simulated in the software.

The output of this program is plotted in Figures 2, 3, 4 and 5 and show the effect of changes in three constraints - sampling frequency, length of recording and correction for non-cosine response.

A subroutine written by [Horst (1972)] and using correction factors for these particular anemometers has been used to correct for non-cosine response.

4.2 Spectral densities and correlation functions

The investigation has been limited so far to one-dimensional power spectral densities and autocorrelations. It has been assumed initially that results obtained for the one-dimensional power spectral densities and autocorrelation functions regarding recording and processing parameters would also apply to cross-spectral densities and cross-correlation functions.

The power spectral density was calculated by taking a discrete Fourier transform of the time series data. No taper to reduce leakage was applied to the time series data before taking the Fourier transform, although the effect of a cosine taper on the first and last 10% of the data is to be investigated [Brigham (1974)]. The square of the magnitude of the spectral components when multiplied by a scaling factor is the power spectral density. The scaling factor is required to convert the values calculated by the discrete Fourier transform to those values which would be calculated by the continuous Fourier transform for positive frequencies only.

The autocorrelation corresponding to the power spectral density was calculated by taking an

inverse Fourier transform of the power spectral density before it had been multiplied by the scaling factor.

If the time series data has been normalised by dividing by the r.m.s. and removing the mean, then the following will occur:

(i) the power spectral density will have an area under the curve equal to one;
(ii) the DC term of the spectra will be equal to zero;
(iii) the autocorrelation curve will have a correlation of one for a time lag of zero;
(iv) the autocorrelation curve will tend to a correlation of zero for long time lags providing there is no trend or periodicity in the data.

The input and output to the program has been made very flexible so that the data could on input

(i) be corrected for non-cosine response;
(ii) have various types of trends removed;
(iii) be sampled at various frequencies;
(iv) have various number of points

and on output the wind structure parameters plotted as:

(i) a function of height;
(ii) a function of type of trend removal;
(iii) a function of sampling frequency;
(iv) spectra versus either frequency in H_z or versus non-dimensionalised frequency $n\tilde{Z}/\bar{V}_{\tilde{Z}}$

to enable the effect of changes in any of the above to be observed easily.

5 EFFECT OF VARIOUS RECORDING CONSTRAINTS ON WIND STRUCTURE MEASUREMENTS

5.1 Correcting for non-cosine response

Propeller anemometers rotate more slowly than the ideal rotational speed which is proportional to $V\cos\theta$, where V is the wind velocity and θ the angle it makes with the anemometer axis. An assumption that the anemometers behave ideally will therefore produce an error, and the magnitude of the error is being investigated by comparing wind structure parameters which have been calculated from data streams both corrected and not corrected for the non-cosine response of the anemometers.

A correction procedure has been used, which finds θ and multiplies the actual rotational speed by a correction factor which is itself a function of θ. This brings the actual speed of the anemometer up to the speed it would rotate at if it behaved ideally. This speed is then linearly related to the wind speed by a calibration coefficient.

It has been observed that the effect of correcting for the non-cosine response of the anemometer is to increase the average velocity; this follows because the propeller will always underestimate the wind velocity unless the wind vector coincides with the propeller axis.

The effect of correcting for the non-cosine response of the anemometer on the turbulence intensities in the longitudinal and lateral directions, and the $\overline{uw}/\sigma_u\sigma_w$ normalised Reynolds stress is harder to predict. Both parameters are dimensionless quantities and the denominator and numerator increase when the data stream is corrected. Changes in the above parameters would seem to depend on the average wind direction with respect to the horizontal anemometers, as this will determine what correction factors are applied to the data, and their relative effect on the different anemometers.

Because the propeller of the w anemometer is often stalled, it considerably underestimates the wind direction parallel to its axis. Consequently, the correction factors used on it are quite large, so $\sigma_w/\bar{V}_{\tilde{Z}}$ will always be increased by correcting for non-cosine response.

In Figure 3 it can be observed that correcting for the non-cosine response has increased $\sigma_w/\bar{V}_{\tilde{Z}}$ and $\sigma_u/\bar{V}_{\tilde{Z}}$ but decreased $\sigma_v/\bar{V}_{\tilde{Z}}$. Similar features can be observed in Figure 4.

The effect of correcting for the non-cosine response on the $\overline{uw}/\sigma_u\sigma_w$ normalised Reynolds stress [Figure 5] seems always to decrease the value. More results are required to see if this is a general trend.

At this stage, results are not available for the effect of the correction on spectral densities and correlation functions.

5.2 Sampling frequency and record length

The sampling frequency and record length are closely related because the sampling frequency multiplied by the record length determines the number of points to be processed.

In many cases the maximum number of points which can be processed is a restriction imposed by the computer. Most fast Fourier transform subroutines used to calculate spectral densities and correlation functions, require all of the data stream to be in memory at one time. Lowering the sampling frequency means that for a fixed number of points (the maximum array length for a particular computer for example) a longer recording can be taken. This means that lower frequency spectral estimates can be calculated.

It is desirable from a statistical point of view to have as many data samples as possible in order to calculate a power spectrum which has the smallest amount of random error. The standard error of each spectral component of the power spectrum is equal to 1, which means that some kind of averaging is required. Averaging is usually done over an ensemble of estimates from different data streams or over frequency from a particular data stream.

Sampling the wind speed sensor at a frequency much higher than frequencies contained in the sensor signal means that consecutive data will be highly correlated and therefore redundant, yet sampling at too low a frequency will cause aliasing, i.e. confusion between the high and low frequency components in the data. The problems manifested by either of these conditions are either increased time and cost of processing or errors in the calculated parameter.

It is generally considered that averaging over time periods of between 10 minutes and 1 hour will produce stationary data because of the energy gap in the power spectrum at frequencies corresponding to periods in that range. The parameters have been plotted for averaging periods which include that range [Astley, Lindley, Bowen, Flay (1977), Lindley, Astley, Flay, Bowen (1977)].

Figure 2 shows that there is very little difference in the velocity profile averaged over 4.5 minutes and over 36 minutes. Figure 3 shows very little change in the value of $\sigma_w/\bar{V}_z$, but a noticeable difference in $\sigma_u/\bar{V}_z$ and $\sigma_v/\bar{V}_z$. Figure 4 shows very little difference in all three turbulence intensities when averaged over 4.5 and 9.1 minutes. $\sigma_u/\bar{V}_z$ has been observed to vary with both the recording period as above and also with sampling frequency.

The effect of sampling at different frequencies is to reduce the value of $\sigma_u/\bar{V}_z$ when the sampling frequency is reduced below 1.875 H_z. This means that the turbulence has very little contribution from frequencies in the digital signal above about 1.875 H_z, but has contributions below 1.875 H_z.

The power spectral densities plotted in Figures 6, 7 and 8 for the longitudinal (u), lateral (v), and vertical (w) velocity components have been given for different sampling frequencies for one data stream. In the three graphs, taking the line obtained by sampling at 7.5 H_z as the best estimate, it can be seen that the curve at 1.875 H_z follows this curve closely except at high frequencies. Sampling at lower frequencies produces results which vary considerably from the 7.5 H_z "standard".

Figures 9, 10 and 11 are the autocorrelations corresponding to the power spectral densities in Figures 6, 7 and 8. It can be seen that the sampling frequency has had little effect on the curves obtained. Sampling at a lower frequency than 1.875 H_z will still yield an autocorrelation close to the 7.5 H_z "standard".

5.3 Trend removal

Field measurements of wind structure should always be attempted during periods when the wind is blowing strongly. This implies that the atmosphere will be neutrally stable since almost all of the turbulence in the wind will be of mechanical origin, generated by surface friction. The wind velocity is then likely to be steady and from the same direction over the recording period. It is then highly likely that the data will be stationary so that no trend removal is necessary and the wind structure parameters can be legitimately compared with similar data found elsewhere in the literature. It may be desirable, however, to attempt to remove a trend from the data to see if one exists.

The effect of a trend removal on the velocity data is to reduce the fluctuations about the mean value throughout the recording period. This then reduces the corresponding turbulence intensities. No results are yet available on the effect of trend removal on the computation of Reynolds stresses.

It is well known that trends in the data stream particularly affect the power spectra at low frequencies, and this has been confirmed in the present work. [See also Lindley, Astley, Flay, Bowen (1977)].

Trend removal affects the autocorrelation in a way which causes the correlation to fall to zero more quickly. This effect is enhanced as higher order polynomial trends are removed from the data. Thus the autocorrelation calculated from a data stream with a parabolic trend removal has been observed to fall to zero more quickly than the autocorrelation with a linear trend removal, which in turn fell more quickly to zero than the autocorrelation calculated with data with no trend removal.

However, this effect should be small for stationary data.

6 CONCLUSIONS

Correcting for the non-cosine response for this type of sensor has been shown to be essential. It has significant effects on the deduction of average velocity from data taken from an orthogonal array. Smaller errors would be incurred in the derivation of turbulence intensity and Reynolds stress without such a correction.

The data presented in Figures 6, 7 and 8 suggest a minimum required sampling frequency for this sensor. The anemometers, having a distance constant of 0.9 m at zero angle of attack, do not respond well to frequencies in the wind above about 0.2 H_z. Consequently unless corrections are made for frequency response (and none have been made in this experiment), results are subject to major errors at frequencies above this. A data sampling frequency of 1.875 H_z seems to be consistent with the limitations of the instrumentation.

Sampling at this lower frequency results in 8192 data points per channel for a 73 minute record which makes it possible for most computers to contain all data in memory at one time whilst a fourier transform is computed.

Results obtained so far on the effect of record length and trend removal have not enabled any firm conclusions to be drawn.

7 REFERENCES

ASTLEY, R.J., LINDLEY, D., BOWEN, A.J., FLAY, R.G.J. (1977). Aspects of wind flow in urban and rural boundary layers. Royal Met. Soc. Summer Conf. on Urban Meteorology, McQuarrie University, Sydney, N.S.W., February.

BENDAT, J.S. and PIERSOL, A.G.(1971). Random Data Analysis and Measurement Procedures, U.S.A. John Wiley and Sons Inc.

BRIGHAM, E.O. (1974). The Fast Fourier Transform 1st ed. Englewood Cliffs, New Jersey, Prentice Hall.

ESDU 74031 (1974). Characteristics of atmospheric turbulence near the ground. Engineering Sciences Data Unit, London.

GILL, G.C. (1975). Development and use of the Gill UVW anemometer. Boundary Layer Meteorology, vol.8 pp 475-95.

HORST, T.W. (1972). A computer algorithm for correcting non-cosine response in the Gill anemometer. Pacific Northwest Lab. Ann. Report for 1971 to the USAEC Divn of Biology and Medicine, Vol.II Physical Sciences, Part I: Atmospheric Sciences, BNWL-1651-1, Battelle, Pacific Northwest Laboratories, Richland, Wash.

LINDLEY, D., ASTLEY, R.J., FLAY, R.G.J., BOWEN, A.J. (1977). Topographical modification to the atmospheric boundary layer. Symposium on the Interaction Between Climate and Building Design, Edinburgh, September.