SPECTRAL RATIOS IN THE RURAL ATMOSPHERIC SURFACE LAYER

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1. Introduction

For many years the Silsoe Research Institute has been involved with full-scale studies of wind loads on a variety of walls, fences and buildings. As part of this research the lower 25m of the rural atmospheric boundary layer at the Silsoe site has been studied on various occasions. In 1986 and 1998, streamwise and transverse turbulence spectra were measured using directional pitot tubes at various heights between 0.32m and 25m, see Hoxey and Richards [1]. It was observed that in the lowest 10m the turbulence spectra change rapidly with height and that the measured spectra exhibit significant frequency ranges where the spectral density can be matched by a power law function

$$S_{aa}(n) = C_a n^{-\alpha} \qquad (1)$$

but with the exponent α less than the 5/3 value expected in the inertial subrange and with its value decreasing as the ground is approached. It was also noted that at very low frequencies the horizontal spectra scaled with height approximately in proportion to the square of the mean wind speed. Further investigations using three component sonic anemometers in 1991 and 1993 at heights between 0.115m and 10m [2-4] have confirmed these observations and have provided further information on the structure of turbulence at low levels . It appears that the power law range is a blending region between a very low frequency range where the fluctuations at different levels are well correlated and scale approximately in proportion to the square of the mean wind speed and the high frequency inertial subrange. This paper focuses on the ratios between spectra at frequencies below the inertial subrange. It is this part of the spectra which show the effects of the ground, both in limiting the vertical components of turbulence and providing surface friction which results in both the mean and fluctuating components of the horizontal velocity approaching zero as the ground is approached.

2. Experimental techniques

Most of the spectral measurements presented in this paper are those from the 1991 sonic anemometer study. The velocity profile at the Silsoe Research Institute has been measured at various times and the measurements from 1988 and 1991 are well matched by a simple logarithmic profile with a roughness length z_0=0.01m. On all occasions in 1991 when spectra were recorded the mean wind speed at a height of 10m exceeded 8m/s. The turbulence spectra presented in this paper are therefore assumed to be for neutral atmospheric stability. The Reynolds stresses measured by the sonic anemometers at heights of 1m and 10m were in good agreement with that estimated by squaring the friction velocity u_* deduced from the velocity profile [2].

Three component turbulence spectra and cospectra were obtained at heights of 0.115m, 1.01m, 3.0m and 10m using two 3-component ultrasonic anemometers (Gill Instruments Ltd). During each run one anemometer was placed at 10m while the other was placed at various heights. The instrument has a path length of 150mm and transmits digital information at a frequency of 20.8 Hz. The runs were processed as 20.03 minute records, each consisting of 25000 data points. It should be noted that the results are affected by the limiting response of the anemometers at high frequencies. It has been estimated that this attenuation, which is dependent on wind speed, varies from a 20% loss at 10Hz at 10m to a 20% loss at 2.5Hz at 0.115m. This attenuation is most evident in the rapid fall off of the spectra for 0.115m at high frequencies.

In addition to the measurements made in 1991 some longer term measurements have been made in recent years on the same site and with the same sonic anemometer at a height of 10m. With these records the 1 minute averages have been recorded over a period of days or months. By analysing such records it has been possible to obtain estimates of spectral ratios at frequencies between 10^{-5} and 10^{-2} Hz.

3. The effect of the ground in limiting vertical turbulence

The inertial subrange, where turbulence structures are approximately isotropic, can only exist if the size of the eddies is significantly smaller than the distance to the ground. This can be shown to correspond to requiring the reduced frequency $f=nz/U >>1$. Conversely if $f<<1$ then the presence of the ground will distort any eddy structure and will primarily limit the vertical component of the turbulence. Figure 1 shows the average results for $S_{vv}(f)/S_{uu}(f)$ and $S_{ww}(f)/S_{uu}(f)$ obtained at four heights.

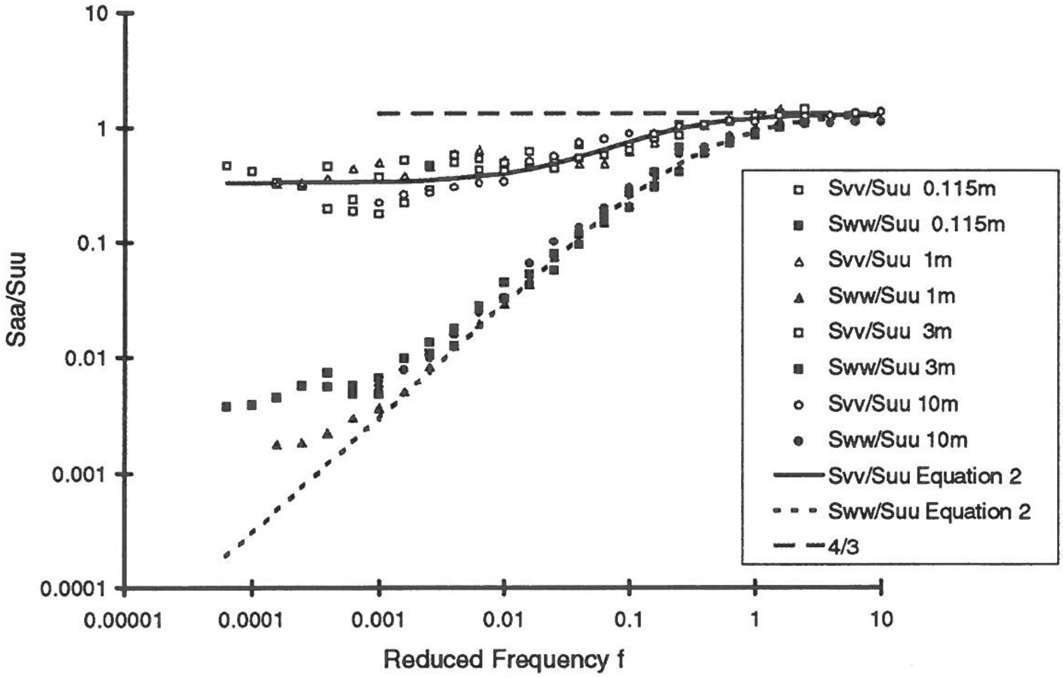

Figure 1. Spectral ratios for the averaged spectra at each height.

It may be observed that as the reduced frequency decreases it is the vertical to streamwise spectral ratio that is affected much more than the transverse to streamwise ratio. In fact it appears that the transverse to streamwise spectral ratio decreases towards a constant ratio of about one third.

These behaviours may be modelled by

$$\frac{S_{vv}}{S_{uu}}=\frac{1}{3}+\frac{1}{1+4/(30f)} \quad \text{and} \quad \frac{S_{ww}}{S_{uu}}=\frac{1}{0.75+1/(3f)} \tag{2}$$

While both of these ratios tend towards the inertial subrange limit of 4/3, the low frequency ends are quite different. As the surface is approached the eddy structures tend to become more two-dimensional with the vertical component severely suppressed and so the ratio of S_{ww}/S_{uu} tends to reduce in proportion to reduced frequency.

There is some suggestion in Figure 1 that the vertical to streamwise spectral ratio does not continue to decrease for $f< 0.001$, however the results from the longer term records mentioned above support the form of equation 2 down to at least $f=0.0001$. The particular data was obtained over a 12 day period and so it is difficult to define a mean wind direction over such a long period. As a result Figure 2 is plotted as the ratio between the vertical spectra and the total horizontal spectra ($S_{uu} + S_{vv}$).

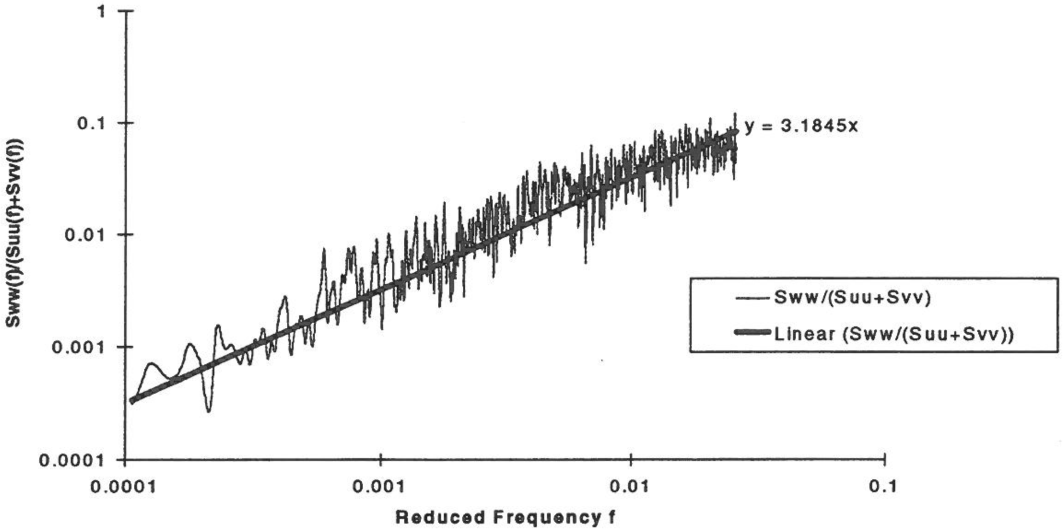

Figure 2. Spectral ratio determined from a 12 day record.

4. The influence of the ground on horizontal turbulence.

Suppression of the component of turbulence perpendicular to a plane can occur even with an ideal frictionless surface, however real rough surfaces, such as the ground, will also impose a boundary condition which requires the horizontal components of the turbulent to also reduce as the surface is approached. This process may be studied by considering cross spectra between components at two heights.

Since simultaneous measurements were made at two heights it has been possible to look at the coherence of the velocity components. The general pattern of results is illustrated in Fig. 3, which shows the coherence between each velocity component at 1m and the same component at 10m. As might be anticipated the coherence of both the U and V components is close to unity at very low frequencies and decreases towards zero at high frequencies. The coherence of the vertical (W) components does not exhibit such high values at low frequencies but is similar to the others above 0.1 Hz.

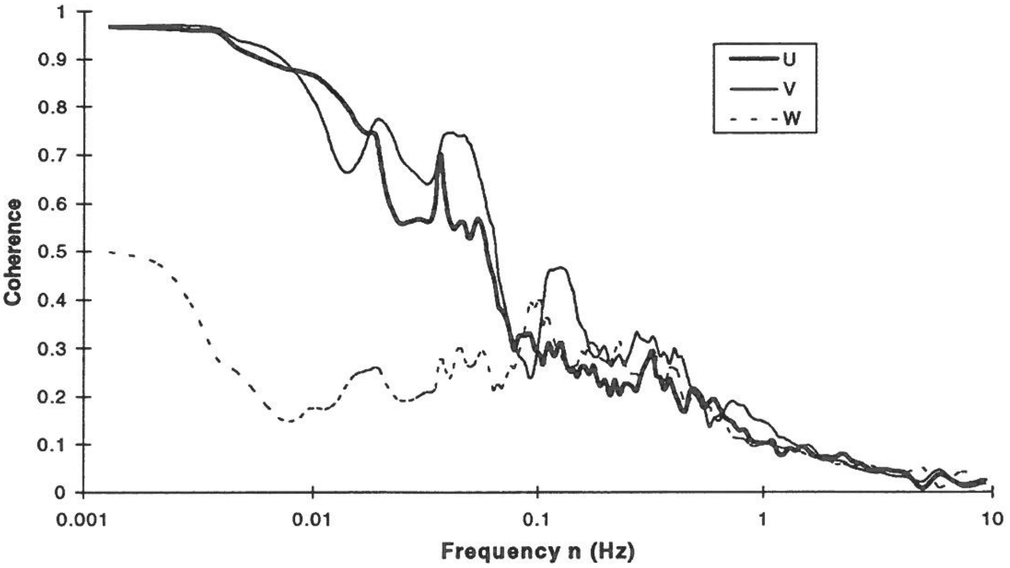

Figure 3. Coherence between velocity components at 1m and 10m heights (Run E).

The high U and V coherence at low frequencies show that both anemometers are sensing the passage of large scale turbulent structures. In general the results also show that the spectral density at frequencies below 0.01 Hz reduces with height approximately in proportion to the square of velocity. This observation is consistent with very low frequency fluctuations behaving in a quasi-steady manner and hence are subject to the same velocity profile observed in the mean wind speed. This may be illustrated by calculating the low frequency spectral gain factor between the velocity component at 10m (height 1) and at a lower height (height 2)

$$|H(n;z)|^2 = |S_{12}(n;z)|^2 / S_{11}(n;z)^2 \qquad (3)$$

where S_{12} and S_{11} are the cross and auto spectral densities. The results are shown in Figure 4.

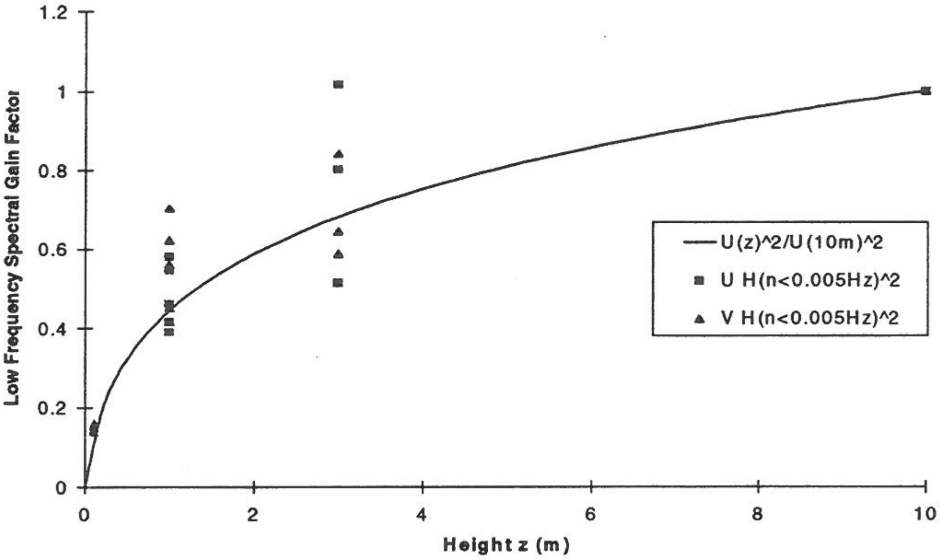

Figure 4. Low frequency spectral gain factor

This figure shows that, although there is some scatter in the results, the coherent part of both the U and V low frequency spectrum at a low height is related to the corresponding spectrum at the higher height in proportion to the mean wind speed squared.

5. Conclusions

Measurements of atmospheric turbulence spectra at low heights in a rural surface layer have shown that the ratio of vertical to streamwise spectra is proportional to reduced frequency at low frequencies while the ratio of transverse to streamwise spectra tends towards about one third. It addition at very low frequencies the streamwise and transverse spectral densities vary approximately in proportion to the square of the mean velocity.

References

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