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WIND GUST SPECTRA

by

Irving A. Singer
Brookhaven National Laboratory
Upton, L.I., N.Y.

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Irving A. Singer
Meteorologist
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Introduction

Wind loading is an important factor in the design of many structures, and in recent years, the problems associated with wind fluctuations have increased. Strangely enough, the interest in "space" has intensified research in low-level atmospheric turbulence. At present missiles, high speed aircraft and "large steerable antennas" can all be severely affected by turbulent motions within a few hundred meters of the surface. Atmospheric motion may be described as consisting of two parts - a mean motion and turbulent fluctuations. Until recently, most engineering applications of meteorology entailed the estimation of mean and absolute peak values, from which appropriate load factors were devised. The structure of turbulent fluctuations is now of importance if the control systems of the large "dish", the fast moving plane and the sensitive missile are to operate safely and accurately over the entire range of wind fluctuations. Some recent studies have provided detailed measurements of the time history of wind fluctuations, and techniques of random process theory have been employed to gain insight into the physical processes controlling the turbulent fluctuations to the mutual satisfaction of both the engineering and meteorological profession. The major purpose of this paper is to review some of the recent activities

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and studies of atmospheric turbulence at Brookhaven National Laboratory in an effort to correlate and summarize these results for practical application. It will not go deeply into the fundamental physical concepts of atmospheric turbulence that would only be of interest to a few.

The order of presentation is as follows:

1. The applicability and limitations of the data;
2. Some basic principles and semantics of the statistics of turbulence;
3. Characteristics of the intensity of turbulence, power spectra, and correlation functions in the lowest 300 feet.

Applicability and Limitations of the Data

The tower data used in this report were obtained from the 420 foot meteorological tower at Brookhaven National Laboratory. This equilateral triangular structure of open steel work has landings at each of the measuring levels. The diameter of the structural steel members decreases from bottom to top, but all other dimensions remain constant. The measurements were made at the 75, 150, and 300 foot levels.

It is evident that interpretation of almost all studies of the data will require consideration of the topography. In the immediate vicinity of the observation area, the terrain is fairly flat. The maximum height variation from the base of the tower over a 150 foot radius does not exceed 15 feet. The highest hill in the area has an elevation of 240 feet, and it is approximately six miles from the tower. The vegetation consists mainly of scrub oak and pine about 30 feet high, with several large irregular areas of field grass near the tower itself. On a broader scale, this section of Long Island would still be described as relatively flat. The Laboratory is situated in a large level area approximately equidistant from the north and south shores. Hills and ridges representing terminal moraines of the glacial periods are along the north shore. The entire south shore slopes gently toward the sea.

All horizontal wind speed measurements were made by Bendix-Friez Aerovanes. The vane section of these instruments is 28% critically damped, with a mean free period of 40 seconds at a wind speed of 1 foot per second and a damping coefficient of $0.042\bar{U}$ (ft/sec). The vertical and horizontal angles were measured by a Brookhaven-designed bivane having the same response

characteristics as the Aerovane. The instruments are mounted at the end of 18 foot booms. Direct measurements are reliable to $\pm 1 \frac{1}{2}^\circ$ and the voltage output of the speed units ^{is} ~~are~~ routinely checked and adjusted so that speed measurements are reliable to ± 0.1 m/sec.

It is important to keep in mind in the succeeding discussion that the turbulence reflected by the Brookhaven measurements is probably fairly typical of flat, open terrain with generally similar vegetation. It cannot reveal the effects of local aerodynamics, and does not even provide firm grounds for speculation about such problems. Aerodynamic turbulence can either be self-induced (such as oscillations of two stacks fairly close to each other as the wind passes between them) or derived from local terrain features. Even at Brookhaven, local aerodynamic flow can be quite marked during inversion conditions, as can be seen in Figure 1, where smoke was emitted at three elevations and went in three different directions. Extreme directional shear of this nature must be expected routinely, and no account of this type of turbulence will be made.

All data were taken during mathematically stationary conditions with little vertical shear of the horizontal wind. All runs were approximately one hour in duration and readings were taken at 0.6-second intervals. Six-second averages were formed and all analyses were based on these averages.

Analysis of Data

A. Mathematical Concepts

1. Co-ordinate System: Meteorologists normally use a Cartesian co-ordinate system where the space variables are x , y and z . In the horizontal, x is in the direction of the mean wind and y is across the wind. The vertical co-ordinate, z , is directed positively upward. It is generally assumed that atmospheric motion can be separated into a mean flow whose components are $\bar{U}$, $\bar{V}$, $\bar{W}$ and superimposed turbulent fluctuations whose components are u , v and w in the x , y and z directions respectively. Thus,

$$V_i = \bar{V}_i + v_i \quad (1)$$

$i = x, y, z$

The mean values are defined by:

$$\bar{V}_i = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T V_i(t) dt \quad (2)$$

The variances or mean square deviations are defined by:

$$\sigma_{V_i}^2 = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T V_i^2(t) dt \quad (3)$$

If equation (1) is substituted for V_i in the Navier-Stokes equation of motion¹, the result is that the equation of mean flow is the same as the ordinary equation of motion except that the usual viscous stresses are augmented by virtual stresses (Reynolds stresses) proportional to $\tau_{ij} = -\rho \overline{v_i v_j}$ which represent the mean rate of transfer of momentum across a surface due to velocity fluctuations, and to $I = \overline{v_i^2}$ which is proportional to the kinetic energy of the turbulent motion. I is defined as the intensity of turbulence.

These virtual stresses provide a representation of the turbulent pattern. However, they are insufficient to define the flow since identical values may be obtained from quite different variations of velocity.

An early approach in the description of turbulent fluctuations was the mixing-length theory. It was analogous to the theory of the mean free path of molecules from the kinetic theory of gases. This discontinuous process could not adequately describe the continuous nature of atmospheric motion which then led to a statistical approach to turbulence.²

2. Statistical Properties: It is extremely difficult to represent the wind in a mathematical form due to its extreme variability. However, if the general meteorological conditions are not changing rapidly, it is assumed that the statistical properties remain constant even though detailed wind variations are not repeated. The concepts pertaining to the random processes have been successfully applied to the statistical properties of wind fluctuations. Measurements are repeatedly taken under

similar meteorological conditions, and the entire set of records constitute an ensemble while the individual record is assumed to be an example of a random process. It is further assumed that this random process is Gaussian, stationary, homogeneous and isotropic:

Gaussian - has the probability density function given by ✓

$$p(v) = \frac{1}{\sqrt{2\pi} \sigma_v} \exp(-v^2/2\sigma_v^2) \quad (4)$$

- Stationary - invariant in time co-ordinate translation;
- Homogeneous - invariant in space co-ordinate translation;
- Isotropic - invariant in rotation or translation of the space-coordinate system.

Therefore in a homogeneous isotropic field, the mean square values of the velocity components are equal ($u=v=w$).

It is seen in Figure 2 that the wind components can be approximated by a Gaussian distribution. The u component can usually be fitted by such a distribution for all meteorological conditions. However, the v and w fit is dependent on the stability, and their departure from a Gaussian distribution increases with stability. A further test for normality is the flatness (FL) and skewness factors (SK) which are equivalent to the third and fourth moments. A Gaussian distribution has the value 3 for the former and 0 for the latter.

$$SK(t) = \frac{[v_i(t) - v_i(t+\Delta\tau)]^3}{\left\{ [v_i(t) - v_i(t+\Delta\tau)]^2 \right\}^{3/2}} \quad (5)$$

$$FL(t) = \frac{[v_i(t) - v_i(t + \Delta\tau)]^4}{\left\{ [v_i(t) - v_i(t + \Delta\tau)]^2 \right\}^2} \quad (6)$$

Curves of these functions in Figure 3 are remarkably similar to those obtained by Stewart³ in wind tunnel experiments.

3. Power Spectra: For a stationary random process, the correlation function is directly related to the power spectrum and reflects the frequency characteristics of the process. The autocorrelation coefficient is defined as:

$$R_{v_i v_i}(\tau) = \frac{v_i(t) v_i(t + \tau)}{v_i(t)^2} \quad (7)$$

In the application of atmospheric turbulence, one is often concerned with the relations between different velocity components. A cross-correlation coefficient can be defined as:

$$R_{v_i v_j}(\tau) = \frac{v_i(t) v_j(t + \tau)}{\sigma_{v_i} \sigma_{v_j}} \quad (8)$$

Similar spatial correlation functions can be defined by use of Taylor's hypothesis.

G.I. Taylor⁴ postulated that turbulence consists of a space pattern which is translated at the mean wind speed, with changes in this pattern occurring relatively slowly. ($\bar{U} > \overline{u'^2}$). These changes can then be neglected and a fixed

instrument may be considered as a probe moving at the mean wind speed through a stationary pattern of disturbance. The time correlation function $R(\tau)$, where τ is the lag, is equal to the space correlation function in the x-direction $R(\Delta x/\bar{U})$. Although the lower limit of Taylor's hypothesis ($\bar{U} > I$) has not been established, it is a useful practical tool. Thus, the reduced wavelengths are related to the frequency by $K = \bar{U}/\omega$.

The spatial correlation coefficient equivalent to equation (7) is

$$R_{v_i v_i}(\Delta x) = \frac{v_i(x) v_i(x + \Delta x)}{v_i(x)^2} \quad (9)$$

The power spectrum is defined by

$$S_{v_i v_i}(\omega) = \frac{2}{\pi} \int_0^\infty R_{v_i v_i}(\tau) \cos \omega \tau \, d\tau \quad (10)$$

where ω is the angular frequency in radians per second.

The power spectrum has the property that

$$\sigma_{v_i}^2 = \int_0^\infty S_{v_i v_i}(\omega) \, d\omega \quad (11)$$

Thus, it is possible to obtain the contribution made to the total variance by individual frequency intervals.

The cross-spectrum is similarly defined by

$$S_{v_i v_j}(\omega) = \frac{1}{\pi} \int_0^{\infty} R_{v_i v_j}(\tau) \exp(-i\omega\tau) d\tau \quad (12)$$

It is a complex quantity with real part (cospectrum) providing a measure of the in-phase energy and the imaginary part (quadrature-spectrum) providing a measure of the out-of-phase components. The cross spectra measures the contributions of the frequencies to the covariance of two variables.

The square of the cross-correlation function, coherence, can be defined as

$$COH = \frac{S_{v_i v_i}^2}{S_{v_i v_i} S_{v_j v_j}} \quad (13)$$

4. Universal Equilibrium Theory: In the analysis of turbulence, two frequency ranges are of importance; first, the energy producing range where turbulent energy is produced by wind shear and buoyancy at relatively long wavelengths. Second, there is an equilibrium range where energy at first is transferred to smaller and smaller wavelengths and finally is dissipated into heat. The "inertial" subrange is where energy is merely transferred from longer to shorter wavelengths. In this range the concept of "local isotropy" was developed by Kolmogoroff⁵ and is referred to as the theory of universal equilibrium, or the similarity theory. Here the average properties are determined by the dissipation rate. The

following three equations are important consequences of the theory:

$$\text{Structure Function} \equiv \overline{[v_i(t) - v_i(t + \tau)]^2} \propto (\epsilon \tau)^{2/3} \quad (14)$$

$$1 - r(\tau) \propto (\epsilon \tau)^{2/3} \quad (15)$$

and the form of the energy spectrum can be predicted by

$$S(k) \propto \epsilon^{2/3} k^{-5/3} \quad (16)$$

The "viscous dissipation" subrange (high frequency end of equilibrium range) is that in which energy is dissipated by viscosity at a rate denoted by ϵ .

The computational methods of obtaining the autocorrelation coefficients and the spectra for this paper follow the procedures recommended by Tukey⁶. In this procedure, the spectra are determined by the Fourier transform of the autocorrelation coefficients. The spectral estimates are smoothed to increase the statistical reliability.

B. Intensity of Turbulence, $\overline{v_i^2}$

From a practical point of view, the standard deviations of the wind components are essentially constant with height, but they are not equal to each other. The "coefficients of anisotropy"⁷ are

$$\sigma_w / \sigma_u = 0.4$$

$$\sigma_v / \sigma_u = 0.9$$

(17)

If isotropy existed, the coefficients would be unity. In general, the horizontal components are approximately equal and are twice as great as the vertical. The ratio tends to increase slightly with instability. However, the intensity of turbulence is not a function of height.

Figure 4 shows that the standard deviation of the wind components is proportional to the wind speed. The constant of proportionality decreases with height to account for the increase of wind speed with height. The wind speed in turn is proportional to the Reynolds stress ($\overline{uw}$) as given in Figure 5.

These simple relationships should be of importance to structural engineers. Once the relationship between the intensity of turbulence and wind speed has been established for a site by measurements at one height, reasonable estimates of the mean wind and the intensity of turbulence may be made for other heights.

C. Power Spectra Analysis

1. Spectra: The spectral density of the wind components at 300 feet versus the reduced wavelength for three typical meteorological conditions are presented in Figure 6. At night when the temperature normally increases with height, (the stable or inversion case), most of the energy is associated with large horizontal fluctuations and small vertical oscillations. The u and v components are much greater than the w component and most of the energy is at large wavelengths. This can be verified by observation of a smoke pattern from a continuous elevated point source during inversion conditions where the plume appears like a horizontal meandering river with little vertical thickness. The total turbulent kinetic energy is much less than the unstable cases.

The unstable cases considered are the "typical day" with moderate to strong winds, associated with both mechanical and convective turbulence, and the "unstable day" associated with light winds and mainly convective turbulence. During the typical day, the u and v components are approximately equal to each other and larger than the w component. The effect of greater instability is to increase the total energy at large wavelengths, especially in the w component. An increase of wind speed increases the total energy at shorter wavelengths, especially in the w component. An increase of wind speed increases the total energy at shorter wavelengths.

The isotropic limit⁸ ($F=0.6$) is approximately equal to the observation height, 100 meters and it is clear when these short wavelengths are reached (such as unstable conditions) that the

spectral densities of the three components are approximately equal and "local isotropic" laws prevail. The $-5/3$ law appears to hold at these wavelengths.

An important feature of the spectra is that the horizontal components, u and v , retain the general properties of isotropy to larger wavelengths (500 meters for unstable conditions). This is seen by the retention of the $-5/3$ slope of the u , v spectra. The reason for this property is that the development of long wavelength components in the vertical velocity spectra is prevented by the ground, but no such limit is imposed on the horizontal components. This characteristic of horizontal isotropy at large wavelengths is further verified by the structure function.

In Figure 7, spectra of identical components are plotted for comparison. The horizontal components are essentially the same during unstable conditions and have considerably more energy than during an inversion. The property of horizontal isotropy to larger wavelengths is clearly evident. The spectra of the w component can only be interpreted during very unstable conditions.

Two fundamental aspects of local isotropy are that the structure function is linearly related to the correlation coefficient and to the stress as a function of time. This statement is easily obtained from equations 14 and 15 and is verified by Figure 8. A linear relationship exists between the structure function and $2\sigma^2(1-R)$ for the three height intervals considered.

Since unstable cases have essentially the same spectral shape within the frequency range of interest for the horizontal components, it would be advantageous if they could be classified.

2. Normalized Spectra: Figure 9 indicates wind speed spectra during strong winds⁹ when adiabatic conditions prevail. All these spectra can be normalized by dividing the energy by the variance of the wind speed. This is shown in Figure 10 where all the spectra are approximately equal. This was repeated for other meteorological conditions¹⁰ and the results are shown in Figure 11. The advantage of normalizing by the variance is that the procedure shows that spectra for similar gustiness¹¹ classes have identical forms and probably the same physical properties of atmospheric turbulence. During an inversion, most of the energy is at low frequencies. For unstable conditions, the low frequency part of the spectrum, the energy is controlled by radiative and convective turbulent processes as the "unstable case" has the maximum energy. At higher frequencies, the wind speed is the controlling feature. A variety of other scientists normalize the spectra by $\bar{U}^2$ in order to non-dimensionalize the ordinate. The two normalizing factors are proportional to each other in accordance with Figure 5.

D. Cross-correlation

The cross-correlation coefficient can be treated¹² as a rapidly decreasing exponential function of frequency. Most of the correlation coefficients between different components at the same height are extremely small, as can be seen in Table I. The few that are correlated have their correlation only at large wavelengths (>500 m). The u, v components are negatively correlated during inversion conditions. This is at long wave-lengths and is associated with large-scale (thousands of meters) horizontal meandering of the wind. As expected,

the u, w, components are negatively correlated since downward vertical motion is associated with an increase of wind speed. This vertical flux of momentum is also associated with large wavelengths.

Therefore, the cross-spectra of the different components are not presented since they are all essentially zero in the range of interest. This statement is to be expected since it has been shown that for wavelengths of approximately 100 m the atmosphere has the general properties of isotropy which would result in random and uncorrelated motions.

The correlation coefficient of similar components at different heights is related to the height ratios according to the following equations:

$$\begin{aligned} R_{u, u_2} &= \left(Z_2 / Z_1 \right)^{-2/3} \\ R_{v, v_2} &= \left(Z_2 / Z_1 \right)^{-1} \\ R_{w, w_2} &= \left(Z_2 / Z_1 \right)^{-4/3} \end{aligned} \tag{18}$$

Therefore, a logarithmic spacing of instruments in the vertical should produce identical correlation coefficients.

The coherence of similar components is plotted in Figure 12, and it is readily seen that even with similar components the correlation falls off rapidly with reduced frequency further verifying the approach of the isotropic limit.

The frequency at which the coherence first becomes zero or reaches the value $1/e$ can provide a picture of the relative dimensions of an eddy. The shape of an eddy is proportional to the distance between the instruments and to the wind speed divided by this frequency.

The results obtained are:

- unstable - eddy is approximately circular
- inversion - eddy is eight times as long as it is high
- typical day - eddy is twice as long as it is high

This interpretation is about the xz plane, and it is doubtful that symmetry about the horizontal axis would be found.

The maximum cross-correlation of similar components measured at two points separated vertically for the typical day does not occur at the same time for the u and v components. The maximum for u component occurs earlier by a time proportional to the vertical separation and the mean wind speed (Taylor's hypothesis). The lag in time for the v component is twice as large as u and there is no lag in the w component. This could be interpreted as the mean slopes of the eddy axis.

Summary and Recommendations

The major points of the paper can be summarized as follows:

1. Intensity of turbulence is constant with height;
2. Local isotropy exists at wavelengths shorter than approximately 100 meters;
3. Horizontal isotropy continuous up to wavelengths of approximately 500 meters;
4. Cross spectra are essentially zero in range of interest;
5. Cross correlation coefficient of similar wind component is a function of the ratio of heights.

The results obtained are only applicable between 75 and 300 feet over fairly smooth terrain. Information at greater heights and in the horizontal are completely lacking. Similar meteorological measurements in complex terrains should be taken. Data of this type are needed to answer many of the questions of interest. The effects of aerodynamic turbulence on the spectral characteristics of atmospheric turbulence is also an unknown quantity. An interesting experiment, and I believe an essential one, is that the frequency characteristics of a large steerable antenna should be obtained under a variety of field conditions and compared with a complete set of meteorological measurements made at the same site. Until this experiment is done, it will be difficult to answer many of the questions before us.

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TABLE I: CROSS-CORRELATION COEFFICIENTS

<u>Components</u>	<u>Unstable</u>	<u>Stable</u>
150 uv	-0.13	-0.71
150 vw	0.03	-0.07
150 uw	-0.61	-0.03
75-150 uu	0.77	0.62
150-300 uu	0.76	0.58
75-300 uu	0.51	0.39
75-150 vv	0.65	0.68
150-300 vv	0.63	0.76
75-300 vv	0.38	0.43
75-150 ww	0.48	0.07
150-300 ww	0.49	0.04
75-300 ww	0.15	0.00

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HORIZONTAL WIND SPEED SPECTRA FOR HURRICANE AND STRONG WIND CASES

NORMALIZED HORIZONTAL WIND SPEED SPECTRA
FOR HURRICANE AND STRONG WIND CASES

NORMALIZED HORIZONTAL WIND SPEED SPECTRA FOR TYPICAL STABILITY CONDITIONS