FLOW FIELD ANALYSIS

William C. Cliff
and
M. Gary Verholek

Battelle Pacific Northwest Laboratories
Richland, Washington 99352

ABSTRACT

The average mean wind speed integrated over a disk is shown to be extremely close to the mean value of wind speed which would be measured at the center of a disk for most geometries in which a WECS (Wind Energy Conversion System) would operate. Field test results are presented which compare instantaneous records of wind speed integrated over a disk with the wind speed measured at the center of the disk. The wind field that a rotating element would experience is presented which has been synthesized from the outputs of an array of anemometers.

INTRODUCTION

At the present time, the Battelle PNL (Pacific Northwest Laboratories) are engaged in attempting to statistically characterize the nominal and extreme wind fields associated with flow over the disk of rotation of WECS systems. This area is presently being addressed experimentally through a field test program as well as by theoretical computations.

In many cases, the only measure of wind speed near a wind turbine may be a single anemometer located at hub height. Questions, with regard to how well wind speed measurements from this single anemometer represent the flow field over the disk of rotation of the wind turbine and how the measurements relate to the wind field a blade element would experience as it rotates, need to be resolved. It is the intent of this paper to examine these questions theoretically and through the use of field data collected from a set of anemometers arranged to describe the swept area of a wind turbine. (See Figure 1.)

MEAN WIND SPEED

In general, the mean wind profile in which a wind turbine operates (neutral atmospheric boundary layer) may be described as follows:

$$\overline{U}_z = \frac{u_*}{k} \ln z/z_0 \tag{1}$$

where $\overline{U}_z$ = the mean wind speed at height z
u_* = surface shear velocity = $\sqrt{\tau_w/\rho}$
τ_w = surface shear stress
k = 0.4
ρ = fluid density
z = height above grade level
z_0 = surface roughness length

The ratio of the mean wind speed averaged of a disk of rotation of radius R and hub height z_h, $\overline{U}_{z_h R}$, to the mean wind speed at hub height, $\overline{U}_{z_h}$, could be expressed as:

$$\frac{\overline{U}_{z_h,R}}{\overline{U}_{z_h}} = \frac{2z_o}{\Pi R \ln z/z_o} \int_{\frac{z_h - R}{z_o}}^{\frac{z_h + R}{z_o}} \left[\frac{R^2 - z_h{}^2 + 2z_h z_o x - z_o{}^2 x^2}{R^2}\right]^{1/2} \ln x \, dx \qquad (2)$$

Table 1 gives some example results using Equation (2) to solve for the ratio of the mean velocity averaged over the disk of rotation to the mean velocity measured at hub height for various blade radii, hub heights and surface roughness.

To estimate the ratio of the mean velocity averaged over the disk of rotation to the mean wind at hub height, the following formula may be used in lieu of Equation (2).

$$\frac{\overline{U}_{z_h,R}}{\overline{U}_{z_h}} \simeq \frac{1}{2R}\left[\frac{(z_h+R)\left[\ln\left(\frac{z_h+R}{z_o}\right) - 1\right] - (z_h-R)\left[\ln\left(\frac{z_h-R}{z_o}\right) - 1\right]}{\ln z_h/z_o}\right] \qquad (3)$$

The results obtained from Equation (2) indicate that the average wind speed from a single anemometer at hub height will be representative of the average wind speed over the disk of rotation in almost all cases. However, the instantaneous wind speed measured at the hub will not represent the instantaneous average over the disk of rotation. Averaging over the disk of rotation will act as a low pass filter cutting off much of the high frequency content. The results of a field test program performed at Battelle PNL show the effect of spacial averaging over a disk. A schematic of the field test program is shown in Figure 1.

The field array consists of eight anemometer sets located on the circumference of a circle of radius 12.2 m (40 ft) and an anemometer set at the center of the circle and at a height of 24.4 m (80 ft). The instantaneous array average (simulating the average over a disk of rotation) was computed by arithmetically averaging the instantaneous output from the nine anemometer sets. A 15-second record showing both the array average and hub anemometer output is shown in Figure 2. The array average is much smoother than the single anemometer trace, as is expected. Spectral comparisons of the two traces also show the filtering effect of averaging over an area. That is, the spectral amplitude drops off at a quicker rate for the disk average than for the single anemometer record.

Using the anemometer array depicted in Figure 1, a wind record (simulating the wind field experienced at 12.2 m from the hub by a rotating blade) was synthesized by incrementally sampling the wind records from the anemometers around the circumference of the circle. Each 0.1 second, the wind record was sampled from the next anemometer output.

Thus, each 0.8 second, one complete revolution around the array had occurred. This simulates a rotation rate of 75 rpm. A 15-second synthesized wind record is shown in Figure 3 along with the wind trace taken from the hub anemometer at the same time. The synthesized wind trace shows principally the vertical profile of the wind (temperature measurements indicated neutral conditions).

DISCUSSION

Q. If wind data are available only from a hub-height anemometer, how can the full-disk wind flow field be estimated?

A. In general, the average value of the wind speed over the disk wind flow field is extremely close to the average value at the hub, as shown in Table 1. However, instantaneously, the two will be different. The average over the disk could be simulated by filtering the hub anemometer output with a first-order filter down 3 dB at a frequency of $\overline{U}/D$, where $\overline{U}$ is the mean velocity and D is the diameter of the system. Unfortunately, filtering processes are inherently time-averaging processes which, if used "on line" in a decision loop, have some negative features.

Q. How do the half-power frequency and turbulence factor change between a single anemometer and the total average of all anemometers? How does the energy in the 0.1- to 1-Hz range change by using the average of all anemometers rather than a single anemometer?

A. In most cases, the spacial averaging over the disk of rotation does not significantly decrease the total amount of energy in the spectrum; thus, the half-power point would not change significantly. The changes of the half-power frequency would have to be computed on a case-by-case basis. Obviously, a small disk does not have as large an averaging effect as a large disk.

The region of the spectra greatly affected by spacial averaging is the high-frequency region. For the atmosphere, this would include the range of 0.1 to 1 Hz, the region where most of the energy is lost. Thus, the region from 0.1 to 1 Hz would have significantly less energy when area-averaged over a disk commensurate with a large WECS. Again, the effect would be a function of disk size and height above ground level.

Battelle welcomes all comments and concerns which identify or assist in identifying important wind characteristics associated with WECS design.

1. Formal requests for assistance: Dr. Charles E. Elderkin, Program Manager (509) 946-2335

2. Informal discussion of wind characteristics for WECS design: Dr. William C. Cliff (509) 942-5066

Battelle, PNL
Department of Atmospheric Sciences
Richland, WA 99352

TABLE I. - RATIO OF MEAN VELOCITY AVERAGED OVER A DISK OF ROTATION TO MEAN VELOCITY MEASURED AT HUB HEIGHT

z_h,R	z_o (meters)[a]			
(meters)	0.005	0.05	0.5	5.0
70:50	0.99	0.99	0.98	0.97
50:30	0.99	0.99	0.99	0.98
15:10	0.99	0.99	0.98	0.97

(a) The terrain features associated with various surface roughnesses:
0.005 m = smooth
0.05 m = moderate
0.5 m = rough
5.0 m = extremely rough (town)

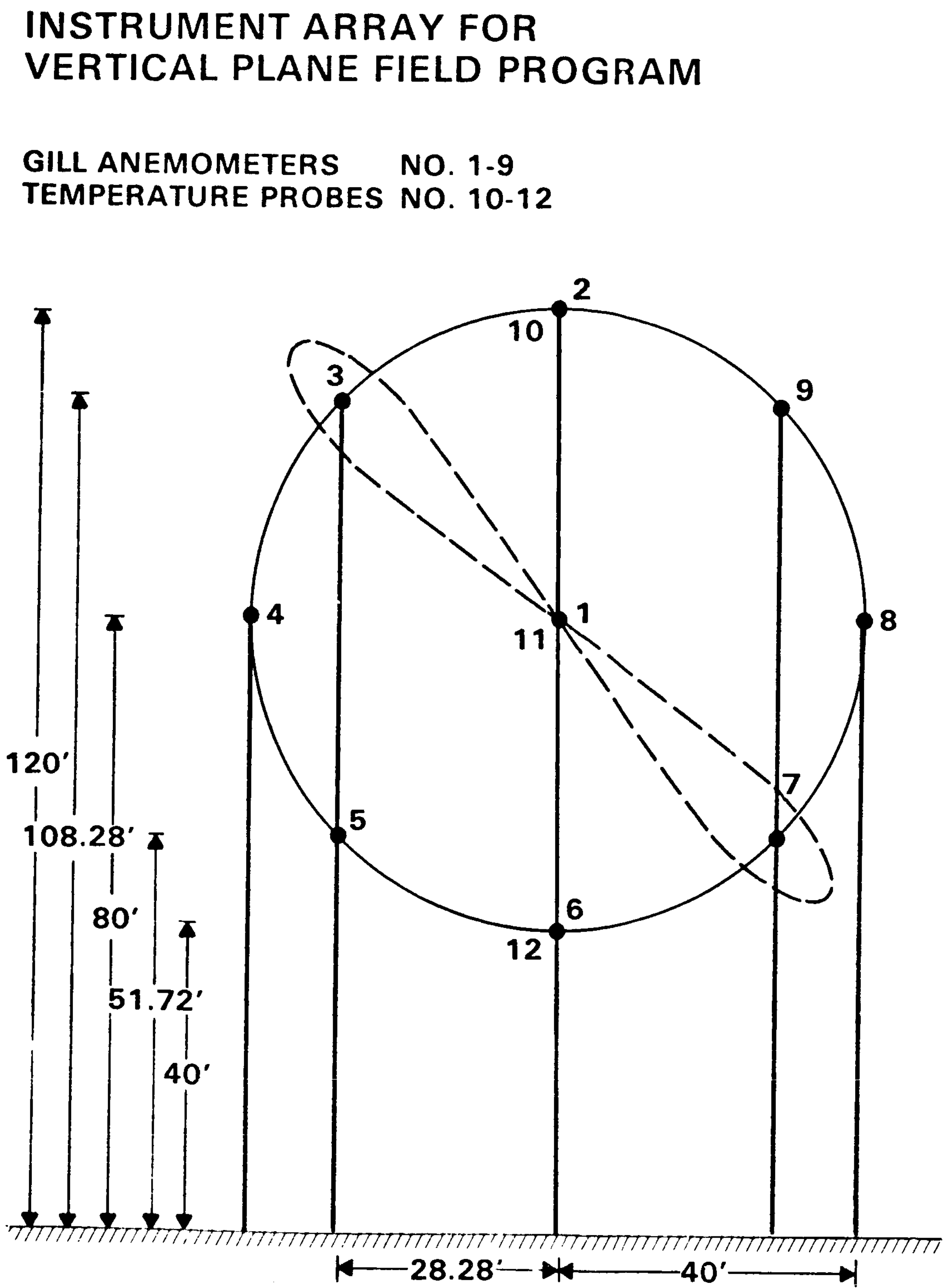

Figure 1. - Field test setup for vertical plane test.

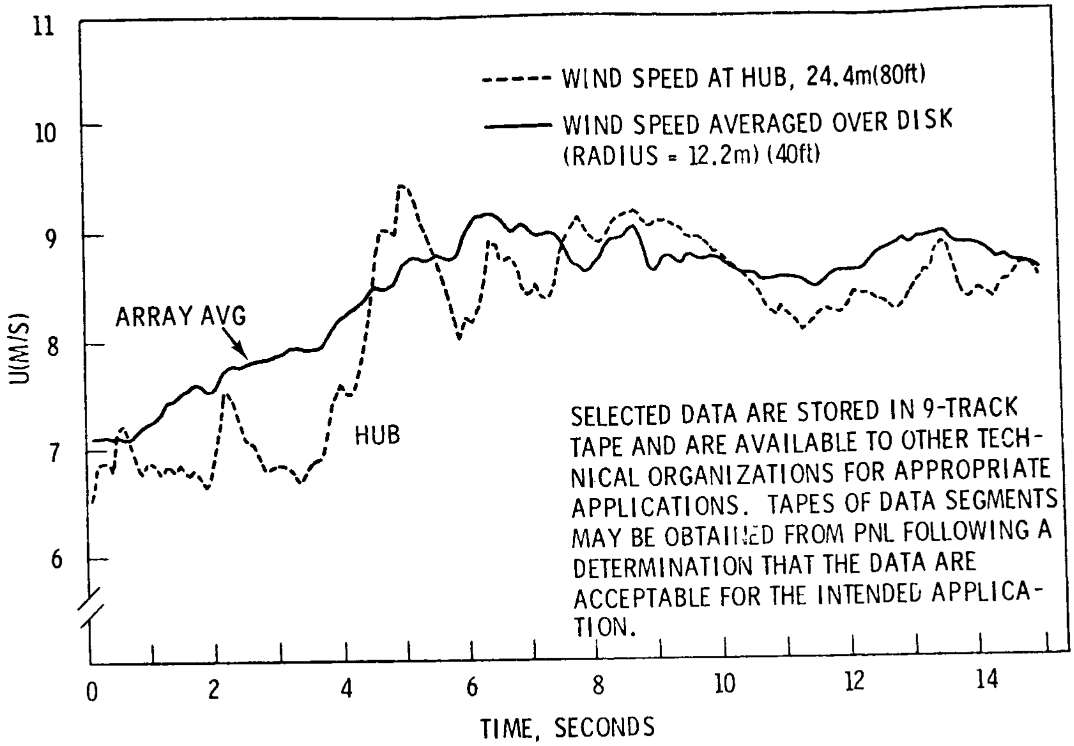

Figure 2. - Wind speed at hub versus wind speed averaged over disk.

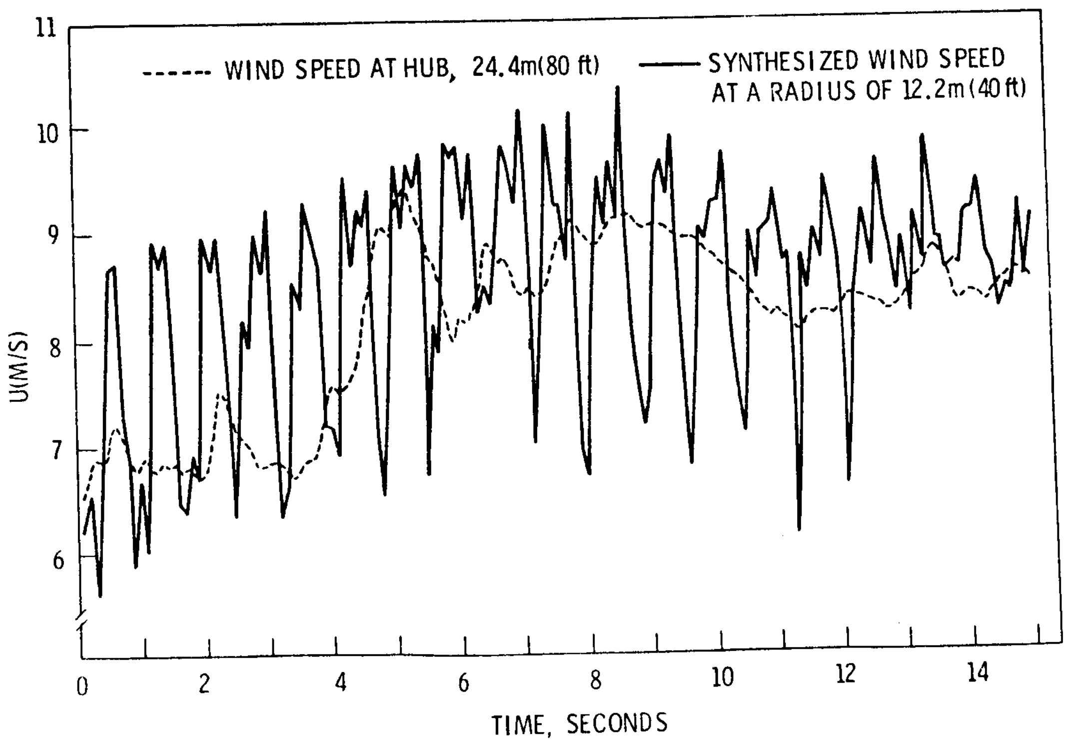

Figure 3. - Synthesized wind speed versus wind speed at hub.