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Preliminary Results of a Field Experiment to Characterize Wind Flow Through a Vertical Plane

by
M. Gary Verholek

April 1978

Pacific Northwest Laboratory
Richland, Washington 99352
Operated for the
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by

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SUMMARY

This report contains preliminary results of a field experiment to study the turbulent structure in the wind flow through a simulated disc of rotation of a large, horizontal-axis wind turbine blade. The wind flow impinging on the hypothetical turbine blade was simulated by a nine-element circular array of three component anemometers in a single vertical plane. The wind data were analyzed as: a single point, hub height measurement (at the center of the array); an arithmetic average of all sensors; and a synthesis of the data records assumed to represent measurement locations on a hypothetical, rotating turbine blade. The effects of areal averaging were examined using the arithmetic mean over the array. Similarly, the effects of averaging over the blade pair were examined by arithmetically averaging opposing data points representing the air flow past the rotating blade.

Wind flow through hypothetical, rotating turbine blades was simulated by sampling the anemometer records in a sequence around the array as if a sensor were on a turbine blade rotating in the plane of the array. The synthesized wind records were used to simulate the flow into a soft, flexible blade loaded by the actual nonuniform wind field, and a stiff, non-flexible blade that averaged the flow over the entire rotor.

The differences in the analytical results obtained in this study illustrate some of the differences that can result from using various atmospheric flow field assumptions when designing wind turbines. This study does not attempt to determine the applicability of given assumptions; differences are pointed out to aid designers in deciding which assumptions are most appropriate.

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PRELIMINARY RESULTS OF A FIELD EXPERIMENT
TO CHARACTERIZE WIND FLOW THROUGH
A VERTICAL PLANE

M. Gary Verholek

1.0 INTRODUCTION

In early 1977, Pacific Northwest Laboratory (PNL) initiated a Department of Energy-sponsored field experiment to study the turbulence structure of the flow field through the simulated disc of rotation of the blades of a hypothetical, large horizontal axis wind turbine. This experiment was conducted on DOE's Hanford Area in the desert of eastern Washington. The objective was to characterize the wind impinging on hypothetical wind turbine blades rotating in a vertical plane and to examine how it differed from that experienced by a single hub-height anemometer.

Three component wind measurements on a circular array of anemometers in a vertical plane were used to describe the flow. The wind data were analyzed as a single point, hub height measurement at the center of the array, as an arithmetic average of all sensors, and as a synthesis of the data records simulating measurement locations on the hypothetical, rotating turbine blade. The synthesized wind records were specifically analyzed from the aspect of a "soft" blade (single record) and a "stiff" blade (average of the data from opposing anemometers.)

2.0 CONCLUSIONS

The differences in the analytical results obtained for the four cases established for this study illustrate the differences that can result from using various atmospheric flow field assumptions when designing wind turbines. This study does not question the applicability of any given assumption; rather, the differences are stressed so that designers can better decide which assumptions are appropriate.

These results are preliminary and the direction of the continuing research will depend to a great extent on the response of the turbine designers. While the project is meteorologically interesting in itself, it was intended to provide designers with insight into the structure of the flow through the disc of rotation of a turbine blade. In addition, data stored on nine-track tapes are available to other technical organizations for appropriate applications. Tapes of data segments may be obtained from PNL if it is determined that the data are appropriate for the intended application.

3.0 EXPERIMENTAL PROCEDURES

For the field experiment, a circular array of anemometers 24.4 m (80 ft) in diameter was situated on five towers in a common plane (Fig. 1). The array was centered 24.4 m above the ground to simulate the disc of a large wind turbine blade 24.4 m in diameter. Eight R.M. Young, Model 27004, Gill uvw-anemometers were located on the five towers in a circular pattern at 45° separation, and a ninth anemometer was located at the center of the array.

The three Gills on the center tower were equipped with thermistors for determining temperature data. The thermistors were calibrated in a controlled temperature bath against a highly accurate mercury thermometer.

The Gill anemometers were tested in a wind tunnel to check the bearings and generators and to calibrate each sensor. The generators were calibrated using an 1800-rpm, constant speed motor and these calibrations were used to adjust a translator unit which provides input to a mini-computer over a range of -1 to +1 volt.

Every 0.1 sec the entire array of sensors was sampled and the voltages recorded. These voltages were later converted to temperature and velocity (corrected for the noncosine response of the Gills) and placed on nine-track tapes. Data were recorded in 1500-data point blocks, corresponding to 50 scans of the 30 sensors (9 times, u, v, w, and 3 temperatures). The observations were ordered sequentially around the array. The sampling sequence begins at the "hub" or center of the circular array, moves to the top anemometer and then progresses at 45° intervals around the circular array for nine values of u, v, w and three temperatures sampled from bottom to top.

GILL ANEMOMETERS NO. 1-9
TEMPERATURE PROBES NO. 10-12

Figure 1. Schematic of Instrument Array for Vertical Plane Field Experiment

Several data collection runs resulted in slightly less than 8 and $\frac{1}{2}$ hours of data.

The data are stored on nine-track tape and are available to other technical organizations for appropriate applications. Tapes of data segments may be obtained from PNL following a determination that the data are acceptable for the intended application.

4.0 WIND DATA ANALYSIS

Wind data analyses were performed for the following cases:

- Case 1. the single hub anemometer,
- Case 2. the arithmetic average over the array,
- Case 3. a synthesized wind record representing a measurement location on either rotating blade,
- Case 4. an arithmetic average of two complementary, synthesized records (one for each blade of the rotor).

Case 1 represents the situation in which only one sensor is available to characterize the flow into a blade and it is assumed that data taken at the hub will adequately characterize the flow over the rotor disc. Case 2 examines the spatial average and its relation to the single hub anemometer. Case 3 represents the situation of a soft, flexible blade. The soft blade is stressed as a result of differential loading along the blade elements. Therefore, the scale and structure of the turbulence are very important and act on each blade element independently. Case 4 represents the situation of a stiff blade (i.e., a blade that does not flex but merely averages the flow at both spars). For both Cases 3 and 4, results are compared to those for the single hub-height anemometer.

4.1 ANALYSIS PROCEDURES

Both the single "hub" anemometer data and averaged data from the entire array of nine anemometers were used to examine the turbulence in the flow into the array. Current design efforts use longitudinal turbulence models in which it is assumed that the blade averages the flow, so that the

examination of the longitudinal turbulence structure, represented by the single "hub" anemometer (Case 1), was necessary for comparison purposes. Furthermore, since the use of a single anemometer is the most common measurement mode, the central hub anemometer was used as a bench mark against which all other analyses were compared.

The turbulence was also examined by arithmetically averaging the nine anemometers and considering the single value as characteristic of the entire expanse of the array. The analysis used unweighted averages and included the hub anemometer. Since the lift is generated by the outer portions of the turbine blades rather than the center, a weighting process may be more appropriate, but the relative merit of any weighting scheme is debatable and in the context of this report will not be addressed. The turbulence analysis based on the array average was compared to that for the hub anemometer and differences were noted.

The nonuniform structure of the flow field with respect to the disc of rotation of the hypothetical, large horizontal axis wind turbine was studied by examining the wind field synthesized from actual data from the circular array of anemometers. A synthesized wind that would impinge on a rotating blade is constructed by sampling the multichannel data records sequentially around the array. The data string thus constructed is a sequence of the actual winds as though observed at some point on the hypothetical blade(s). The synthesized winds have been analyzed in two modes; as though experienced by an independent element of a "soft" blade, and also by an average of the wind at both blades, to examine what a rigid blade might experience.

The flow encountered by either element of a "soft" blade was simulated by the synthesized wind field to indicate what loading each blade might experience independently. For the case of a rigid blade which smooths the flow, the primary and

complementary blade tip wind observations are merely averaged. The data are then analyzed and the results compared to the "soft" blade case and the single anemometer case. The rotation rate of the hypothetical blade can be controlled by lagging the samples around the circular array. The analysis in this report was performed using a rotation rate of 75 rpm.

4.2 PRELIMINARY RESULTS AND COMPARISONS

To examine the differences in the turbulent flow field for the four cases identified above, samples from the data records were analyzed as follows:

- a) Sample Traces -- time sequence plots of the longitudinal wind component.
- b) Spatial Correlations -- correlations of observations between the hub and the tip anemometers and between opposing tip anemometers.
- c) Frequency Distributions -- analysis of u , $\Delta u/\Delta t$ and $\Delta \theta/\Delta t$ in terms of frequency distributions and cumulative frequency distributions of occurrences.
- d) Power Spectra -- analysis in the frequency domain.

In the following discussion/comparison analysis modes, hub anemometer data are used as a single-point analysis benchmark. Data for the hub anemometer exhibit the following characteristics:

Mean Wind Speed:	$\bar{s}$	=	4.85 m/s
Standard Deviation:	σ_s	=	1.23 m/s
Turbulent Intensity:	I_T	=	$\sigma_s/\bar{s} = 0.25$
Mean Wind Direction:	$\bar{\theta}$	=	300.2°
Standard Deviation:	σ_θ	=	13.9°
Mean u-Component:	$\bar{u}$	=	4.68 m/s
Standard Deviation:	σ_u	=	1.25 m/s

The temperature differences between 12.19 m and 36.58 m resulted in lapse rate, $\gamma = -0.03^{\circ}\text{C}/100\text{ m}$, which according to Nuclear Regulatory Commission (NRC) Guide 1.23 indicates a slightly stable condition. However, σ_{θ} at the hub indicated a neutrally stable condition. This lack of agreement is not common and merely implies that a neutral to slightly stable condition existed.

4.2.1 Sample Traces

Sample traces are presented for the array average (Case 2, Fig. 2), for the blade average (Case 4, Fig. 3), and for the single blade tip (Case 3, Fig. 4), superimposed on similar data for the hub anemometer (Case 1). Figure 2 shows that the array average trace is much smoother than that of the hub. This is because the array averaging acts as a low-pass spatial filter.

The array velocity fluctuation U_A' is the average of instantaneous fluctuations at each anemometer. An examination of 10-minute averages has revealed that the mean at the hub is representative of the mean of the array average.⁽¹⁾

Using the synthesized wind to depict the flow into a rotating turbine blade, Fig. 4 reveals the small-scale turbulent structure. The fluctuations in the flow as would be felt by an individual WECS blade are much stronger than at the hub. While a periodic fluctuation at 0.8 sec due to the mean profile structure is evident, there are also fluctuations which indicate the nonuniform structure of the small-scale turbulence at the various anemometers along the circle of rotation. Such fluctuations (as revealed in Fig. 4) are indicative of the loads imposed on a turbine blade as it rotates through a wind field.

Figure 3 shows that the u-component velocity for the blade-average fluctuates more rapidly than does the velocity

at the hub, but is indeed smoothed when compared with that at the individual blade tip. Figure 3 also reveals a cyclical oscillation of the blade average trace that is twice the rotation frequency due to the rotation of the hypothetical blade set through the shear in the wind field. This results from averaging of the wind at the blades in the same angular configuration twice per rotation.

4.2.2 Spatial Correlations

The extent of the loading on a turbine rotor in a turbulent medium can be studied by examining how well the observations at various points in the array are correlated. Spatial correlations have been examined for each hub-blade tip position pair and for the complementary blade tip pairs (Fig. 5). Note the decrease in correlation with increasing distance and the change with angular position. There is a general increase in correlation with elevation, for both the longitudinal wind component and direction, which indicates a greater variability near the ground. The low value for the 1-2 pair of anemometers may be due to a decoupling in the boundary layer under the stable mountain drainage flow that existed during the observations. Further analysis is required before any conclusions can be drawn, but one may be able to infer the degree of representativeness of the hub anemometer in describing the wind field, or alternatively, the degree of coherence of the wind field across the span of the disc. It may ultimately be feasible to describe the dependence of these features on basic meteorological parameters.

4.2.3 Frequency Distributions of Turbulence Parameters

Fluctuations in the flow were examined by constructing:

- a) the cumulative frequency distribution of velocity changes at several time lags ($\Delta u/\Delta t$); and

- b) the cumulative frequency distribution of the directional differences at several time lags ($\Delta\theta/\Delta t$).

Tabulated distributions were made for: 1) the hub, 2) the array average, 3) the blade average, and 4) the individual blades.

Gust Rise Statistics ($\Delta u/\Delta t$)

The frequency of a change in velocity, Δu , over a time period, Δt , is important for indicating the magnitude and frequency of loads on a blade element operating in a given wind field. $\Delta u/\Delta t$ is the change of velocity (Δu) during a time (Δt) and represents a gust over time Δt . It is analogous, but not equivalent, to examining the velocity changes and asking how fast change Δu occurs. Instead, we have asked, "In time interval Δt , what were the changes in velocity?" and then counted the observed changes (Δu).

For the case of the hub anemometer, the cumulative frequency distribution of $\Delta u/\Delta t$, when analyzed for percentiles equivalent to one, two or three standard deviations of a normal distribution, exhibits an increasing spread for increasing Δt . That is, the fluctuation in velocity Δu increases with Δt (Fig. 6).

Examining the $\Delta u/\Delta t$ distribution for the array average (Fig. 7), we see that various percentiles occur at much lower velocity changes than for the hub. The substantial difference indicates that the use of the array average statistics for gust rise rates results in considerable smoothing. The average over the disc is obviously not representative of the gusting that is occurring at each point in the disc.

Figure 8 is the $\Delta u/\Delta t$ distribution for the blade tip case (Case 3). The percentiles do not exhibit the same tendencies demonstrated by the single hub anemometer. In this case, spatial, as well as temporal, variations are evident in the flow field. The differences in the pattern would also depend

on the rotation rate, but the uniformity in the pattern indicates a relationship that may be exploited for turbine design. A similar, but more compressed, pattern exists for the blade average case (Case 4), as illustrated in Fig. 9.

This evidence suggests that the spatial variations combined with the temporal variations to produce a nonuniform flow through the disc of rotation which cannot be represented by a single anemometer.

Rate of Change of Direction ($\Delta\theta/\Delta t$)

Figures 10 through 13 illustrate the rate of change of direction ($\Delta\theta/\Delta t$) distribution for the same period of time used in analyzing velocity changes. The patterns of the percentile levels are similar to those for $\Delta u/\Delta t$, though not as uniform as in the case of the blade and blade-average. The spatial and temporal variations are evident and again indicate the inadequacy of a single anemometer measurement to describe the flow through the rotor disc.

4.2.4 Power Spectral Estimates

Power spectra were calculated for the hub, array average, blade average and blade tip cases. The calculation scheme used 15 minutes of 10 hz data (9000 pts) and employed an International Math Sciences Library (IMSL) Fortran program to derive the spectral estimates for the autocorrelations. Interest in the power spectra has stemmed from design considerations of resonance frequencies and simulation schemes for atmospheric turbulence. In each case, the power spectral estimates for the hub anemometer were included as a bench mark to facilitate a comparison with single point turbulence spectra. In this initial analysis, the plots have not been normalized.

Comparing the spectra of the hub and the array average (Fig. 14), the effect of the averaging process is immediately

obvious. Even though the high frequency tail is contaminated with noise, the sharper roll-off of the array spectra is evident.

Analysis of the rotating blade system reveals some other important results. In Figure 15, the power spectrum of the hub is compared to the power spectrum of the average of the two-blade elements. Note that a spike exists at 2.5 hz, which is twice the rotation frequency for a blade rotating at 75 rpm. This spike can be attributed to the half-rotation similarities resulting from the average of the two blades in the wind field.

Similarly, analysis of the single rotating blade revealed spikes in the power spectrum at 1.25 hz and also at the higher harmonics (Fig. 16). These spikes are due to the rotation of the blade through vertical shear in the wind field.

Figure 2. Trace of the Longitudinal Wind Component, Hub Versus Array Average

Figure 3. Trace of the Longitudinal Wind Component, Hub Versus Blade Average

Figure 4. Trace of the Longitudinal Component of the Synthesized Wind

ANEMOMETER PAIR	$R_{xy}(u)$	$R_{xy}(\theta)$
1-2	0.918	0.777
-3	0.940	0.853
-4	0.937	0.842
-5	0.931	0.787
-6	0.877	0.643
-7	0.920	0.798
-8	0.927	0.845
-9	0.936	0.817
2-6	0.830	0.539
3-7	0.898	0.708
4-8	0.903	0.721
5-9	0.899	0.675

Figure 5. Spatial Correlations Across the Array

Δu (m/s)	Δt (sec)							
	0.1	0.3	0.5	1.0	3.0	5.0	10.0	
-3.0	0.000	0.000	0.000	0.000	.011	0.000	.123	0.13% ILE
-2.9	0.000	0.000	0.000	0.000	.017	0.000	.140	
-2.8	0.000	0.000	0.000	0.000	.022	0.000	.173	
-2.7	0.000	0.000	0.000	0.000	.022	0.000	.263	
-2.6	0.000	0.000	0.000	0.000	.022	.005	.324	
-2.5	0.000	0.000	0.000	0.000	.028	.017	.397	
-2.4	0.000	0.000	0.000	0.000	.039	.034	.564	
-2.3	0.000	0.000	0.000	0.000	.067	.073	.704	
-2.2	0.000	0.000	0.000	0.000	.106	.158	.911	2.28% ILE
-2.1	0.000	0.000	0.000	.006	.195	.274	1.168	
-2.0	0.000	0.000	0.000	.011	.268	.408	1.497	
-1.9	0.000	0.000	.006	.022	.313	.508	1.844	
-1.8	0.000	0.000	.011	.056	.453	.721	2.285	
-1.7	0.000	0.000	.017	.078	.665	1.134	2.978	
-1.6	0.000	0.000	.028	.134	.838	1.441	3.559	
-1.5	0.000	.011	.034	.207	1.101	1.905	4.537	15.87% ILE
-1.4	0.000	.017	.045	.324	1.508	2.570	5.766	
-1.3	0.000	.028	.089	.447	1.916	3.307	6.777	
-1.2	0.000	.039	.145	.570	2.497	4.308	8.146	
-1.1	0.000	.045	.218	.771	3.408	5.671	10.034	
-1.0	0.000	.089	.380	1.263	4.922	7.850	12.666	
-.9	0.000	.140	.587	1.911	6.514	9.973	15.068	
-.8	0.000	.330	.983	3.151	9.118	12.939	18.465	15.87% ILE
-.7	.017	.721	1.989	5.498	12.805	17.498	23.269	
-.6	.039	1.335	3.503	7.933	16.493	21.504	27.482	
-.5	.140	2.743	5.949	11.967	21.588	26.398	32.052	
-.4	.480	6.850	11.934	18.968	28.666	33.209	37.957	
-.3	2.360	14.023	20.521	27.421	36.393	39.952	43.192	
-.2	10.872	26.828	32.488	37.566	44.042	46.377	47.941	
-.1	41.198	47.533	48.835	49.640	51.405	52.634	52.640	15.87% ILE
0.0	47.640	28.421	22.750	17.236	10.291	8.392	6.570	
.1	11.168	24.052	29.421	33.130	38.309	38.980	40.796	
.2	3.760	14.113	19.174	25.208	32.203	34.041	37.036	
.3	1.271	4.040	15.558	18.571	20.448	28.779	30.862	
.4	.341	4.245	7.721	12.727	20.487	23.404	28.270	
.5	.112	2.553	5.784	9.285	15.772	19.924	25.013	
.6	.067	1.637	3.520	6.838	14.079	17.325	22.336	15.87% ILE
.7	.022	.872	2.240	4.335	10.861	14.224	18.638	
.8	.011	.503	1.381	3.067	8.492	12.001	16.319	
.9	.006	.318	.830	2.391	6.855	10.340	14.543	
1.0	0.000	.190	.570	1.810	5.591	8.945	12.833	
1.1	0.000	.124	.374	1.218	4.335	7.157	10.928	
1.2	0.000	.078	.274	.950	3.643	6.118	9.950	
1.3	0.000	.050	.229	.743	2.916	5.274	8.956	2.28% ILE
1.4	0.000	.028	.155	.592	2.278	4.257	7.844	
1.5	0.000	.011	.101	.453	1.721	3.503	6.917	
1.6	0.000	.006	.061	.313	1.441	2.957	6.218	
1.7	0.000	.006	.017	.223	1.145	2.454	5.267	
1.8	0.000	0.000	.017	.162	.978	2.123	4.302	
1.9	0.000	0.000	.006	.123	.788	1.765	3.593	
2.0	0.000	0.000	0.000	.078	.620	1.492	3.106	2.28% ILE
2.1	0.000	0.000	0.000	.034	.369	1.190	2.447	
2.2	0.000	0.000	0.000	.017	.258	1.000	2.062	
2.3	0.000	0.000	0.000	.006	.173	.844	1.665	
2.4	0.000	0.000	0.000	.006	.123	.599	1.346	
2.5	0.000	0.000	0.000	.006	.084	.397	1.089	
2.6	0.000	0.000	0.000	.006	.067	.307	.933	
2.7	0.000	0.000	0.000	0.000	.050	.201	.732	0.13% ILE
2.8	0.000	0.000	0.000	0.000	.034	.123	.514	
2.9	0.000	0.000	0.000	0.000	.034	.084	.413	
3.0	0.000	0.000	0.000	0.000	.034	.061	.263	
3.1	0.000	0.000	0.000	0.000	.022	.045	.134	
3.2	0.000	0.000	0.000	0.000	.011	.017	.078	

Figure 6. Cumulative Frequency Distribution of the Change in Velocity, Δu , in time Δt for the HUB (Case 1)
The percentile (% ILE) levels are equivalent to the one, two and three standard deviation levels for a normal distribution.

Δu (m/s)	Δt (sec)							
	0.1	0.3	0.5	1.0	3.0	5.0	10.0	
-3.0	0.000	0.000	0.000	0.000	0.000	0.000	.011	0.13% ILE
-2.9	0.000	0.000	0.000	0.000	0.000	0.000	.089	
-2.8	0.000	0.000	0.000	0.000	0.000	0.000	.101	
-2.7	0.000	0.000	0.000	0.000	0.000	0.000	.151	
-2.6	0.000	0.000	0.000	0.000	0.000	0.000	.291	
-2.5	0.000	0.000	0.000	0.000	0.000	0.000	.391	
-2.4	0.000	0.000	0.000	0.000	0.000	0.000	.447	
-2.3	0.000	0.000	0.000	0.000	0.000	0.000	.458	
-2.2	0.000	0.000	0.000	0.000	0.000	0.000	.503	
-2.1	0.000	0.000	0.000	0.000	0.000	0.000	.542	
-2.0	0.000	0.000	0.000	0.000	0.000	0.000	.626	
-1.9	0.000	0.000	0.000	0.000	0.000	0.000	.698	
-1.8	0.000	0.000	0.000	0.000	0.000	0.000	.860	
-1.7	0.000	0.000	0.000	0.000	0.000	.022	1.050	
-1.6	0.000	0.000	0.000	0.000	0.000	.095	1.413	
-1.5	0.000	0.000	0.000	0.000	0.000	.291	1.777	2.28% ILE
-1.4	0.000	0.000	0.000	0.000	0.000	.485	2.151	
-1.3	0.000	0.000	0.000	0.000	.005	.670	2.654	
-1.2	0.000	0.000	0.000	0.000	.095	.944	3.274	
-1.1	0.000	0.000	0.000	0.000	.274	1.218	3.939	
-1.0	0.000	0.000	0.000	0.000	.430	1.581	5.090	15.87% ILE
-.9	0.000	0.000	0.000	0.000	.726	2.090	6.967	
-.8	0.000	0.000	0.000	0.000	1.218	2.929	9.369	
-.7	0.000	0.000	0.000	.056	1.777	4.933	12.878	
-.6	0.000	0.000	.011	.173	3.050	8.241	17.908	
-.5	0.000	.011	.074	.559	5.855	13.034	23.404	
-.4	.006	.045	.307	1.743	11.766	19.577	29.773	
-.3	.006	.508	2.162	7.101	22.191	28.493	37.248	
-.2	.257	6.844	13.353	22.833	37.192	41.779	46.567	
-.1	50.584	51.874	52.459	52.014	52.779	54.315	55.009	
0.0	43.841	40.226	33.605	26.817	15.286	10.995	6.553	15.87% ILE
.1	.541	7.905	13.951	21.174	31.940	34.695	38.443	
.2	.066	1.101	3.525	8.866	20.867	26.214	32.672	
.3	.006	.145	.755	3.699	13.325	19.594	27.281	
.4	.006	.022	.168	1.380	9.001	14.694	23.113	
.5	.006	.017	.051	.497	5.765	10.889	19.420	
.6	.006	.017	.028	.134	3.743	8.151	16.006	
.7	0.000	0.000	0.000	.056	2.553	5.732	13.291	
.8	0.000	0.000	0.000	.011	1.570	4.302	11.207	
.9	0.000	0.000	0.000	0.000	.911	3.335	9.291	
1.0	0.000	0.000	0.000	0.000	.609	2.503	7.419	
1.1	0.000	0.000	0.000	0.000	.380	1.821	5.933	
1.2	0.000	0.000	0.000	0.000	.324	1.369	4.928	
1.3	0.000	0.000	0.000	0.000	.201	1.117	4.112	
1.4	0.000	0.000	0.000	0.000	.101	.916	3.263	2.28% ILE
1.5	0.000	0.000	0.000	0.000	.017	.637	2.615	
1.6	0.000	0.000	0.000	0.000	0.000	.447	2.073	
1.7	0.000	0.000	0.000	0.000	0.000	.279	1.693	
1.8	0.000	0.000	0.000	0.000	0.000	.223	1.425	
1.9	0.000	0.000	0.000	0.000	0.000	.195	1.190	0.13% ILE
2.0	0.000	0.000	0.000	0.000	0.000	.134	1.022	
2.1	0.000	0.000	0.000	0.000	0.000	.073	.805	
2.2	0.000	0.000	0.000	0.000	0.000	.045	.559	
2.3	0.000	0.000	0.000	0.000	0.000	.017	.469	
2.4	0.000	0.000	0.000	0.000	0.000	.006	.380	
2.5	0.000	0.000	0.000	0.000	0.000	0.000	.341	
2.6	0.000	0.000	0.000	0.000	0.000	0.000	.330	
2.7	0.000	0.000	0.000	0.000	0.000	0.000	.313	
2.8	0.000	0.000	0.000	0.000	0.000	0.000	.263	
2.9	0.000	0.000	0.000	0.000	0.000	0.000	.251	
3.0	0.000	0.000	0.000	0.000	0.000	0.000	.223	
3.1	0.000	0.000	0.000	0.000	0.000	0.000	.184	
3.2	0.000	0.000	0.000	0.000	0.000	0.000	.084	

Figure 7. Cumulative Frequency Distribution of the Change in Velocity, Δu , in time Δt for the ARRAY AVERAGE (Case 2)

Δu (m/s)	Δt (sec)						
	0.1	0.3	0.5	1.0	3.0	5.0	10.0
-3.3	.117	.045	.057	.056	.061	.095	.251
-3.2	.140	.044	.044	.095	.073	.105	.296
-3.1	.223	.140	.095	.128	.101	.123	.352
-3.0	.291	.173	.112	.134	.117	.151	.464
-2.9	.341	.218	.151	.173	.190	.173	.520
-2.8	.444	.253	.207	.240	.223	.245	.626
-2.7	.615	.374	.279	.307	.285	.341	.765
-2.6	.704	.447	.335	.305	.352	.402	.916
-2.5	.816	.542	.402	.469	.430	.503	1.129
-2.4	1.089	.687	.587	.669	.603	.710	1.548
-2.3	1.302	.832	.673	.863	.793	.848	1.849
-2.2	1.587	.949	.744	1.162	.950	1.112	2.179
-2.1	1.911	1.179	1.039	1.503	1.264	1.553	2.766
-2.0	2.363	1.425	1.324	1.855	1.564	1.915	3.402
-1.9	2.732	1.643	1.620	2.179	1.939	2.354	4.024
-1.8	3.252	2.050	2.017	2.501	2.304	2.815	4.810
-1.7	4.023	2.532	2.517	3.350	3.140	3.503	6.073
-1.6	4.576	3.095	3.201	3.950	3.782	4.179	7.168
-1.5	5.704	3.888	3.972	4.799	4.710	5.207	8.766
-1.4	7.039	4.972	5.051	6.034	5.984	6.454	10.632
-1.3	8.330	5.939	6.118	7.241	7.245	7.637	12.347
-1.2	9.688	7.174	7.363	8.771	8.593	9.302	14.190
-1.1	11.032	8.466	8.129	10.570	10.470	11.245	16.494
-1.0	14.145	11.191	11.554	13.194	12.995	14.090	19.593
-0.9	16.280	13.347	13.828	15.262	15.342	16.358	22.154
-0.8	19.381	15.414	15.764	18.107	18.604	19.550	25.368
-0.7	23.247	20.308	20.577	21.761	22.862	23.783	29.409
-0.6	26.929	23.616	24.153	25.085	26.443	27.533	32.873
-0.5	31.259	28.421	28.611	28.895	30.611	32.041	36.739
-0.4	36.516	34.147	33.718	34.225	36.225	37.145	40.812
-0.3	41.338	39.561	38.902	39.354	41.321	42.120	44.913
-0.2	45.572	44.332	43.399	44.075	45.880	46.505	48.455
-0.1	49.930	49.355	48.327	48.997	50.623	51.293	52.031
0.0	54.470	7.224	7.794	7.743	7.146	6.520	4.939
0.1	43.506	43.427	43.845	43.265	42.237	42.132	43.036
0.2	39.578	38.801	39.047	38.773	37.913	38.203	39.784
0.3	34.907	33.862	33.778	34.075	33.471	33.773	36.572
0.4	30.320	28.180	27.901	28.800	28.651	29.254	32.746
0.5	26.677	23.957	23.538	24.834	25.398	25.828	30.113
0.6	23.728	20.532	19.928	21.705	22.448	22.968	27.583
0.7	20.001	16.733	16.152	17.956	19.001	19.599	24.320
0.8	16.878	13.984	13.420	15.208	16.280	17.085	21.694
0.9	14.599	11.206	11.341	13.034	14.101	14.962	19.783
1.0	12.950	9.704	9.360	11.263	12.325	13.017	17.733
1.1	10.576	7.464	7.358	8.883	9.945	10.560	15.073
1.2	9.095	6.319	6.145	7.637	8.632	9.420	13.677
1.3	7.760	5.118	5.146	6.414	7.246	8.174	12.353
1.4	6.179	4.095	4.078	5.229	5.767	7.051	10.811
1.5	5.324	3.252	3.352	4.330	4.861	6.012	9.688
1.6	4.470	2.676	2.972	3.598	4.123	5.179	8.704
1.7	3.670	2.173	2.773	2.838	3.425	4.377	7.526
1.8	2.950	1.693	1.911	2.358	2.327	3.559	6.732
1.9	2.475	1.374	1.615	2.040	2.313	3.158	6.017
2.0	2.006	1.156	1.298	1.721	2.006	2.755	5.436
2.1	1.559	.983	1.056	1.307	1.531	2.313	4.609
2.2	1.335	.743	.911	1.045	1.246	1.751	4.090
2.3	1.151	.615	.760	.838	1.050	1.537	3.649
2.4	.972	.458	.603	.581	.939	1.255	3.145
2.5	.842	.369	.497	.458	.726	1.034	2.710
2.6	.508	.270	.391	.380	.615	.844	2.352
2.7	.430	.235	.246	.307	.486	.593	1.944
2.8	.302	.154	.176	.229	.391	.549	1.693
2.9	.248	.162	.179	.201	.318	.475	1.441
3.0	.146	.095	.123	.162	.246	.419	1.224
3.1	.151	.067	.083	.112	.190	.341	.978
3.2	.123	.067	.061	.074	.173	.291	.855
3.3	.105	.039	.039	.061	.117	.235	.760

2.28% ILE

15.87% ILE

15.87% ILE

2.28% ILE

Figure 8. Cumulative Frequency Distribution of the Change in Velocity, Δu , in time Δt for a Single BLADE (Case 3)

Δu (m/s)	Δt (sec)							
	0.1	0.3	0.5	1.0	3.0	5.0	10.0	
-3.1	0.000	0.000	0.000	0.000	0.000	0.000	.161	0.13% ILE
-3.0	0.000	0.000	0.000	0.000	0.000	0.000	.146	
-2.9	0.000	0.000	0.000	0.000	0.000	0.000	.168	
-2.8	0.000	0.000	0.000	0.000	0.000	0.000	.212	
-2.7	0.000	0.000	0.000	0.000	0.000	.006	.268	
-2.6	0.000	0.000	0.000	0.000	0.000	.034	.296	
-2.5	.006	0.000	0.000	0.000	0.000	.034	.346	
-2.4	.006	.006	.006	.006	.006	.056	.464	
-2.3	.006	.011	.006	.006	.011	.073	.603	
-2.2	.011	.017	.011	.006	.022	.112	.726	
-2.1	.017	.022	.028	.006	.045	.128	.844	2.28% ILE
-2.0	.034	.039	.034	.017	.067	.184	.967	
-1.9	.061	.067	.050	.028	.106	.246	1.156	
-1.8	.054	.117	.078	.067	.162	.374	1.363	
-1.7	.144	.184	.112	.128	.285	.531	1.659	
-1.6	.223	.291	.146	.235	.453	.721	1.961	
-1.5	.330	.413	.291	.352	.637	.983	2.391	
-1.4	.553	.631	.508	.564	.888	1.408	2.983	
-1.3	.810	.967	.782	.916	1.251	1.894	3.676	
-1.2	1.229	1.525	1.257	1.461	1.816	2.523	4.682	15.87% ILE
-1.1	1.972	2.352	1.843	2.362	2.578	3.481	5.933	
-1.0	2.877	3.341	2.749	3.173	3.537	4.749	7.866	
-.9	4.313	5.011	4.542	4.721	5.363	6.548	10.330	
-.8	6.257	6.932	6.553	6.531	7.190	8.872	13.129	
-.7	9.587	10.263	9.783	9.236	9.911	12.255	17.297	
-.6	13.820	14.034	13.883	12.546	13.467	16.113	21.459	
-.5	19.626	19.141	19.800	17.624	18.342	21.141	26.862	
-.4	27.102	26.337	27.241	23.722	25.638	28.387	33.197	
-.3	34.354	33.353	34.220	30.896	33.561	35.751	39.393	
-.2	42.650	41.550	42.656	40.874	42.413	44.455	46.824	15.87% ILE
-.1	49.902	48.919	50.042	50.271	51.143	52.042	52.841	
0.0	8.453	8.461	8.302	9.984	9.107	7.794	6.347	
.1	41.650	42.606	41.611	39.751	39.756	40.170	40.818	
.2	33.136	34.086	33.270	30.605	31.253	32.734	35.203	
.3	26.409	26.962	26.147	24.052	25.057	27.085	30.672	
.4	19.674	19.655	19.109	17.817	19.012	21.370	25.789	
.5	14.366	14.474	14.414	13.504	14.985	17.504	22.275	
.6	10.684	9.637	10.224	9.503	11.202	13.575	18.481	
.7	7.367	6.267	7.235	6.693	8.542	10.721	15.353	15.87% ILE
.8	5.151	4.335	5.291	4.844	6.665	8.509	12.906	
.9	3.436	2.866	3.615	3.235	4.866	6.548	10.783	
1.0	2.436	2.656	2.548	2.447	3.615	5.011	9.123	
1.1	1.603	1.391	1.559	1.710	2.643	3.888	7.531	
1.2	1.067	.944	1.050	1.112	1.805	3.073	6.241	
1.3	.676	.620	.715	.816	1.251	2.475	5.246	
1.4	.380	.374	.456	.503	.922	1.944	4.363	
1.5	.285	.184	.341	.341	.670	1.542	3.715	
1.6	.179	.123	.196	.190	.436	1.179	3.078	2.28% ILE
1.7	.123	.078	.117	.112	.279	.883	2.570	
1.8	.089	.056	.067	.050	.198	.642	2.198	
1.9	.034	.034	.039	.028	.101	.441	1.838	
2.0	.011	.022	.022	.011	.073	.291	1.564	
2.1	.006	.006	.011	.006	.039	.195	1.246	
2.2	.006	.006	.006	0.000	.022	.151	1.011	
2.3	0.000	.006	.006	0.000	.017	.059	.860	
2.4	0.000	.006	0.000	0.000	.011	.073	.710	
2.5	0.000	.006	0.000	0.000	.011	.061	.570	0.13% ILE
2.6	0.000	.006	0.000	0.000	0.000	.050	.492	
2.7	0.000	.006	0.000	0.000	0.000	.045	.385	
2.8	0.000	0.000	0.000	0.000	0.000	.045	.341	
2.9	0.000	0.000	0.000	0.000	0.000	.034	.291	
3.0	0.000	0.000	0.000	0.000	0.000	.011	.246	
3.1	0.000	0.000	0.000	0.000	0.000	.011	.179	
3.2	0.000	0.000	0.000	0.000	0.000	.011	.145	

Figure 9. Cumulative Frequency Distribution of the Change in Velocity, Δu , in time Δt for the BLADE AVERAGE (Case 4)

$\Delta \theta$	Δt (sec)						
	0.1	0.3	0.5	1.0	3.0	5.0	10.0
-39.0	0.000	0.000	0.000	0.000	0.000	.045	.123
-38.0	0.000	0.000	0.000	0.000	0.000	.067	.151
-37.0	0.000	0.000	0.000	0.000	0.000	.089	.190
-36.0	0.000	0.000	0.000	0.000	.006	.114	.218
-35.0	0.000	0.000	0.000	0.000	.006	.212	.235
-34.0	0.000	0.000	0.000	0.000	.017	.235	.268
-33.0	0.000	0.000	0.000	0.000	.022	.285	.291
-32.0	0.000	0.000	0.000	0.000	.022	.330	.352
-31.0	0.000	0.000	0.000	0.000	.028	.358	.480
-30.0	0.000	0.000	0.000	0.000	.056	.380	.559
-29.0	0.000	0.000	0.000	0.000	.101	.413	.631
-28.0	0.000	0.000	0.000	.006	.156	.514	.777
-27.0	0.000	0.000	0.000	.022	.229	.570	.950
-26.0	0.000	0.000	0.000	.028	.274	.682	1.123
-25.0	0.000	0.000	0.000	.045	.374	.737	1.279
-24.0	0.000	0.000	0.000	.067	.497	.844	1.542
-23.0	0.000	0.000	0.000	.067	.620	.933	1.793
-22.0	0.000	0.000	.006	.073	.782	1.145	2.090
-21.0	0.000	0.000	.006	.089	.944	1.307	2.453
-20.0	0.000	0.000	.006	.106	1.050	1.486	2.866
-19.0	0.000	0.000	.006	.140	1.296	1.726	3.374
-18.0	0.000	0.000	.006	.184	1.503	2.101	4.011
-17.0	0.000	0.000	.011	.240	1.771	2.453	4.821
-16.0	0.000	0.000	.039	.380	2.162	2.983	5.542
-15.0	0.000	.006	.073	.464	2.564	3.537	6.537
-14.0	0.000	.011	.128	.615	3.039	4.295	7.704
-13.0	0.000	.022	.156	.838	3.615	5.207	9.095
-12.0	0.000	.039	.212	1.050	4.419	6.218	10.593
-11.0	0.000	.073	.346	1.492	5.458	7.492	12.207
-10.0	.011	.112	.542	2.050	6.805	9.107	14.247
-9.0	.022	.201	.810	2.944	8.593	11.017	16.677
-8.0	.045	.369	1.369	4.151	10.654	13.118	19.040
-7.0	.101	.698	2.173	5.950	13.515	17.622	21.934
-6.0	.212	1.458	3.492	8.235	16.867	19.409	25.292
-5.0	.469	2.735	5.715	11.765	21.007	24.258	28.918
-4.0	1.129	5.302	9.721	16.749	26.225	29.650	33.108
-3.0	3.162	11.096	18.042	24.649	32.655	35.896	38.337
-2.0	10.330	23.666	29.409	35.494	41.019	42.058	43.583
-1.0	43.583	47.612	48.617	49.355	48.807	48.505	48.533
0.0	45.690	28.940	22.169	15.079	9.095	7.777	5.112
1.0	16.733	23.454	20.220	35.572	42.103	43.723	45.340
2.0	2.444	11.330	17.347	24.946	33.983	37.185	41.164
3.0	.410	5.163	9.705	17.247	24.817	30.135	35.790
4.0	.285	2.513	5.098	11.637	21.431	23.945	30.722
5.0	.117	1.238	2.207	6.427	15.934	19.354	25.074
6.0	.050	.615	1.134	3.547	13.254	15.744	22.141
7.0	.022	.374	1.129	3.043	10.224	12.649	18.454
8.0	.017	.257	.796	2.631	8.017	10.123	15.171
9.0	.006	.173	.559	1.754	6.291	8.107	12.526
10.0	.006	.117	.390	1.352	4.911	6.453	10.062
11.0	.006	.067	.274	.964	3.838	5.353	8.313
12.0	.006	.050	.207	.743	3.005	4.414	6.850
13.0	0.000	.017	.152	.553	2.363	3.531	5.732
14.0	0.000	0.000	.073	.304	1.730	2.844	4.799
15.0	0.000	0.000	.034	.197	1.330	2.221	4.056
16.0	0.000	0.000	.022	.125	1.134	1.742	3.514
17.0	0.000	0.000	.011	.073	.933	1.419	2.950
18.0	0.000	0.000	.006	.045	.810	1.210	2.441
19.0	0.000	0.000	0.000	.022	.715	1.078	2.123
20.0	0.000	0.000	0.000	.011	.609	.944	1.855
21.0	0.000	0.000	0.000	.006	.542	.850	1.587
22.0	0.000	0.000	0.000	.001	.460	.721	1.358
23.0	0.000	0.000	0.000	.000	.441	.659	1.156
24.0	0.000	0.000	0.000	.000	.391	.594	1.039
25.0	0.000	0.000	0.000	.000	.363	.544	.922
26.0	0.000	0.000	0.000	.000	.296	.521	.838
27.0	0.000	0.000	0.000	.000	.257	.447	.743
28.0	0.000	0.000	0.000	0.000	.201	.380	.676
29.0	0.000	0.000	0.000	0.000	.184	.333	.593
30.0	0.000	0.000	0.000	0.000	.184	.297	.504
31.0	0.000	0.000	0.000	0.000	.173	.280	.508
32.0	0.000	0.000	0.000	0.000	.156	.224	.475
33.0	0.000	0.000	0.000	0.000	.134	.207	.425
34.0	0.000	0.000	0.000	0.000	.128	.213	.409
35.0	0.000	0.000	0.000	0.000	.106	.173	.363
36.0	0.000	0.000	0.000	0.000	.089	.154	.313
37.0	0.000	0.000	0.000	0.000	.067	.162	.270
38.0	0.000	0.000	0.000	0.000	.050	.155	.274
39.0	0.000	0.000	0.000	0.000	.034	.145	.218

0.13% ILE

2.28% ILE

15.87% ILE

15.87% ILE

2.28% ILE

Figure 10. Cumulative Frequency Distribution of the Change in Direction, $\Delta \theta$, in time Δt for the HUB (Case 1)

$\Delta\theta$	Δt (sec)						
	0.1	0.3	0.5	1.0	3.0	5.0	10.0
-31.0	0.000	0.000	0.000	0.000	0.000	0.000	.028
-30.0	0.000	0.000	0.000	0.000	0.000	0.000	.039
-29.0	0.000	0.000	0.000	0.000	0.000	0.000	.061
-28.0	0.000	0.000	0.000	0.000	0.000	0.000	.106
-27.0	0.000	0.000	0.000	0.000	0.000	.011	.140
-26.0	0.000	0.000	0.000	0.000	0.000	.034	.168
-25.0	0.000	0.000	0.000	0.000	0.000	.056	.190
-24.0	0.000	0.000	0.000	0.000	0.000	.084	.257
-23.0	0.000	0.000	0.000	0.000	0.000	.152	.385
-22.0	0.000	0.000	0.000	0.000	0.000	.190	.542
-21.0	0.000	0.000	0.000	0.000	0.000	.218	.637
-20.0	0.000	0.000	0.000	0.000	.011	.245	.721
-19.0	0.000	0.000	0.000	0.000	.022	.279	.860
-18.0	0.000	0.000	0.000	0.000	.039	.295	1.145
-17.0	0.000	0.000	0.000	0.000	.084	.324	1.413
-16.0	0.000	0.000	0.000	0.000	.134	.374	1.771
-15.0	0.000	0.000	0.000	0.000	.168	.441	2.196
-14.0	0.000	0.000	0.000	0.000	.257	.537	2.833
-13.0	0.000	0.000	0.000	0.000	.324	.849	3.525
-12.0	0.000	0.000	0.000	0.000	.469	1.251	4.693
-11.0	0.000	0.000	0.000	.011	.659	1.855	6.118
-10.0	0.000	0.000	0.000	.056	1.022	2.595	7.788
-9.0	0.000	0.000	0.000	.101	1.508	3.838	9.609
-8.0	0.000	0.000	.011	.162	2.274	5.531	11.665
-7.0	0.000	0.000	.028	.318	3.654	7.715	15.560
-6.0	0.000	.006	.056	.603	6.257	10.637	19.610
-5.0	0.000	.034	.318	1.726	9.984	14.548	23.633
-4.0	.006	.173	.899	4.363	15.677	20.739	28.426
-3.0	.017	1.084	3.514	10.230	23.214	28.521	34.192
-2.0	.989	8.364	15.029	24.258	34.644	37.751	40.365
-1.0	48.891	50.014	49.757	49.573	48.897	47.779	47.377
0.0	50.455	41.673	35.181	26.521	15.252	12.140	7.526
1.0	.659	8.319	15.088	23.912	35.857	40.086	45.103
2.0	.022	.961	3.481	10.118	23.068	28.147	37.969
3.0	.006	.162	.410	3.995	14.099	19.335	29.672
4.0	.006	.045	.235	1.810	9.163	13.285	22.420
5.0	0.000	.017	.095	.665	5.632	9.386	17.476
6.0	0.000	.011	.022	.229	3.542	6.710	13.129
7.0	0.000	0.000	.006	.095	2.140	4.754	9.665
8.0	0.000	0.000	0.000	.061	1.212	3.179	7.123
9.0	0.000	0.000	0.000	.011	.832	2.157	5.380
10.0	0.000	0.000	0.000	0.000	.497	1.559	3.782
11.0	0.000	0.000	0.000	0.000	.268	1.105	2.972
12.0	0.000	0.000	0.000	0.000	.124	.799	2.335
13.0	0.000	0.000	0.000	0.000	.056	.520	1.995
14.0	0.000	0.000	0.000	0.000	.022	.295	1.682
15.0	0.000	0.000	0.000	0.000	.006	.223	1.358
16.0	0.000	0.000	0.000	0.000	0.000	.105	1.123
17.0	0.000	0.000	0.000	0.000	0.000	.067	.860
18.0	0.000	0.000	0.000	0.000	0.000	.028	.726
19.0	0.000	0.000	0.000	0.000	0.000	.005	.603
20.0	0.000	0.000	0.000	0.000	0.000	0.000	.464
21.0	0.000	0.000	0.000	0.000	0.000	0.000	.369
22.0	0.000	0.000	0.000	0.000	0.000	0.000	.302
23.0	0.000	0.000	0.000	0.000	0.000	0.000	.240
24.0	0.000	0.000	0.000	0.000	0.000	0.000	.201
25.0	0.000	0.000	0.000	0.000	0.000	0.000	.123
26.0	0.000	0.000	0.000	0.000	0.000	0.000	.073
27.0	0.000	0.000	0.000	0.000	0.000	0.000	.022
28.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
29.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
31.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000

0.13% ILE

2.28% ILE

15.87% ILE

15.87% ILE

2.28% ILE

0.13% ILE

Figure 11. Cumulative Frequency Distribution of the Change in Direction, $\Delta\theta$, in time Δt for the ARRAY AVERAGE (Case 2)

$\Delta\theta$	Δt (sec)						
	0.1	0.3	0.5	1.0	3.0	5.0	10.0
-39.0	.137	.034	.022	.039	.084	.112	.240
-38.0	.145	.061	.039	.067	.095	.123	.307
-37.0	.173	.061	.045	.089	.112	.164	.346
-36.0	.207	.061	.050	.095	.134	.190	.408
-35.0	.212	.061	.056	.112	.151	.240	.450
-34.0	.229	.073	.061	.117	.207	.279	.592
-33.0	.263	.089	.073	.145	.274	.352	.732
-32.0	.274	.112	.112	.196	.313	.419	.838
-31.0	.346	.123	.134	.240	.380	.475	.961
-30.0	.402	.173	.173	.296	.419	.554	1.095
-29.0	.436	.291	.218	.358	.453	.637	1.201
-28.0	.525	.257	.246	.425	.531	.715	1.352
-27.0	.642	.335	.285	.486	.626	.799	1.503
-26.0	.788	.346	.313	.592	.721	.922	1.687
-25.0	.877	.430	.409	.659	.816	1.045	1.905
-24.0	.994	.531	.480	.805	.961	1.207	2.134
-23.0	1.134	.602	.575	.933	1.101	1.374	2.425
-22.0	1.263	.710	.617	1.117	1.268	1.570	2.816
-21.0	1.464	.827	.827	1.324	1.469	1.849	3.185
-20.0	1.749	1.039	.989	1.564	1.783	2.145	3.604
-19.0	2.050	1.291	1.191	1.844	2.095	2.430	4.106
-18.0	2.389	1.531	1.441	2.221	2.441	2.900	4.699
-17.0	2.742	1.777	1.765	2.631	2.883	3.503	5.498
-16.0	3.359	2.241	2.179	3.168	3.409	4.173	6.408
-15.0	4.000	2.732	2.625	3.827	4.162	4.821	7.408
-14.0	4.794	3.257	3.224	4.632	5.062	5.749	8.520
-13.0	5.704	4.045	3.967	5.743	6.134	7.025	9.934
-12.0	7.062	4.972	4.814	7.017	7.397	8.453	11.481
-11.0	8.459	6.017	6.363	8.598	9.017	10.090	13.481
-10.0	10.151	7.593	8.073	10.336	10.850	12.057	15.880
-9.0	12.369	9.531	9.944	12.526	13.330	14.364	18.264
-8.0	15.168	11.939	12.159	15.365	16.814	17.090	20.822
-7.0	18.264	15.241	15.401	18.174	19.135	20.297	23.945
-6.0	22.174	19.130	19.292	21.856	22.733	23.878	27.299
-5.0	26.538	23.761	23.756	25.119	26.962	28.393	31.102
-4.0	31.627	29.337	29.199	31.251	31.873	32.957	35.404
-3.0	37.125	35.695	35.406	36.879	37.572	37.929	39.566
-2.0	43.248	42.634	42.136	43.025	43.427	43.220	44.125
-1.0	49.852	49.966	49.522	49.209	49.686	49.025	48.947
0.0	5.961	7.520	7.725	9.472	10.403	5.894	4.880
1.0	43.192	42.500	42.729	43.424	43.913	45.085	46.170
2.0	36.862	35.509	35.739	37.929	37.907	39.393	41.472
3.0	31.365	29.013	29.057	32.045	32.248	33.711	35.896
4.0	26.298	23.683	23.499	26.515	26.934	28.750	32.443
5.0	21.666	19.113	19.046	22.135	22.443	24.141	27.974
6.0	17.900	15.425	15.325	17.979	18.660	20.051	24.370
7.0	14.777	12.269	12.112	14.599	15.369	16.733	20.688
8.0	12.269	9.721	9.732	11.889	12.800	13.816	17.616
9.0	10.213	7.801	7.876	9.609	10.626	11.397	15.006
10.0	8.520	6.352	6.090	7.716	8.777	9.369	12.705
11.0	7.045	5.006	4.922	6.375	7.213	7.654	10.744
12.0	5.833	4.095	3.987	5.235	6.028	6.380	9.051
13.0	4.877	3.386	3.207	4.296	5.028	5.436	7.665
14.0	4.134	2.738	2.687	3.553	4.160	4.442	6.425
15.0	3.503	2.190	2.134	2.928	3.391	3.699	5.425
16.0	2.961	1.771	1.730	2.441	2.844	3.123	4.576
17.0	2.564	1.453	1.508	2.062	2.369	2.535	3.872
18.0	2.201	1.201	1.257	1.726	2.017	2.162	3.285
19.0	1.877	.983	1.062	1.441	1.771	1.750	2.738
20.0	1.587	.760	.883	1.190	1.475	1.430	2.363
21.0	1.363	.631	.765	1.050	1.207	1.179	2.022
22.0	1.168	.531	.642	.894	1.006	.994	1.743
23.0	1.073	.447	.542	.765	.844	.832	1.531
24.0	.961	.391	.479	.667	.760	.642	1.341
25.0	.855	.313	.380	.598	.631	.592	1.145
26.0	.732	.274	.313	.508	.542	.508	.955
27.0	.631	.223	.235	.447	.469	.441	.866
28.0	.570	.196	.184	.385	.408	.397	.715
29.0	.531	.156	.151	.268	.318	.352	.637
30.0	.441	.145	.123	.223	.268	.307	.553
31.0	.386	.123	.117	.201	.212	.257	.480
32.0	.352	.117	.078	.162	.184	.212	.436
33.0	.279	.089	.067	.151	.156	.190	.380
34.0	.257	.067	.061	.126	.117	.162	.330
35.0	.223	.056	.045	.112	.100	.134	.318
36.0	.184	.045	.045	.064	.084	.117	.307
37.0	.156	.034	.045	.076	.045	.112	.229
38.0	.140	.022	.036	.050	.034	.101	.173
39.0	.117	.017	.022	.045	.026	.089	.134

2.28% ILE

15.87% ILE

15.87% ILE

2.28% ILE

0.13% ILE

Figure 12. Cumulative Frequency Distribution of the Change in Direction, $\Delta\theta$, in time Δt for a BLADE (Case 3)

$\Delta\theta$	Δt (sec)						
	0.1	0.3	0.5	1.0	3.0	5.0	10.0
-34.0	0.000	0.000	0.000	0.000	.006	.028	.034
-33.0	0.000	0.000	0.000	0.000	.011	.034	.050
-32.0	0.000	0.000	0.000	0.000	.011	.034	.056
-31.0	0.000	0.000	0.000	0.000	.017	.034	.095
-30.0	0.000	0.000	0.000	0.000	.017	.039	.134
-29.0	0.000	0.000	0.000	0.000	.017	.050	.162
-28.0	0.000	0.000	0.000	0.000	.028	.056	.229
-27.0	0.000	0.000	0.000	0.000	.039	.061	.285
-26.0	0.000	0.000	0.000	.011	.050	.067	.358
-25.0	.017	.006	.016	.022	.050	.089	.453
-24.0	.028	.011	.022	.028	.061	.105	.525
-23.0	.039	.011	.034	.045	.067	.151	.670
-22.0	.050	.020	.049	.073	.106	.195	.782
-21.0	.061	.045	.056	.106	.134	.240	.955
-20.0	.067	.057	.078	.134	.179	.335	1.184
-19.0	.084	.084	.101	.179	.212	.419	1.598
-18.0	.134	.112	.129	.229	.279	.520	1.933
-17.0	.168	.137	.145	.313	.358	.793	2.335
-16.0	.240	.219	.274	.305	.508	1.095	2.777
-15.0	.310	.358	.369	.531	.765	1.385	3.313
-14.0	.430	.536	.514	.603	1.050	1.850	4.129
-13.0	.587	.777	.737	.944	1.413	2.419	4.972
-12.0	.972	1.006	1.049	1.300	2.011	3.229	6.218
-11.0	1.358	1.440	1.654	2.000	2.827	4.201	7.593
-10.0	2.106	2.056	2.207	3.078	4.118	5.592	9.565
-9.0	3.229	3.056	3.212	4.386	5.638	7.435	11.738
-8.0	4.777	4.397	4.637	6.179	9.257	10.001	14.224
-7.0	7.079	6.436	7.140	8.961	10.867	12.978	17.493
-6.0	10.463	9.542	10.431	12.503	14.699	16.017	21.253
-5.0	14.844	14.140	15.247	17.370	19.655	21.778	25.309
-4.0	21.141	20.649	21.221	23.532	25.292	27.421	30.091
-3.0	29.925	29.426	29.957	31.000	32.566	33.739	35.773
-2.0	38.069	40.270	37.946	40.477	41.097	41.650	41.717
-1.0	48.369	51.791	49.533	50.405	50.159	49.735	48.114
0.0	11.246	10.191	11.269	9.420	9.101	8.017	6.665
1.0	40.360	39.024	40.203	40.181	40.745	42.254	45.226
2.0	29.362	28.926	29.661	31.167	32.650	34.539	38.298
3.0	20.543	21.308	21.001	23.761	25.420	27.577	31.728
4.0	13.967	15.213	14.124	17.442	19.437	21.415	25.549
5.0	9.330	10.520	9.431	12.347	14.364	16.403	20.359
6.0	6.123	7.269	6.241	8.682	10.408	12.364	16.124
7.0	4.224	4.727	4.280	6.106	7.553	9.230	12.615
8.0	2.950	3.235	2.922	4.302	5.531	6.771	9.872
9.0	2.042	2.182	1.975	2.922	3.782	4.972	7.721
10.0	1.358	1.413	1.413	2.140	2.749	3.682	5.917
11.0	.943	.905	.944	1.458	2.000	2.810	4.643
12.0	.743	.603	.721	1.024	1.441	1.939	3.570
13.0	.525	.436	.525	.737	1.056	1.441	2.877
14.0	.318	.324	.352	.541	.737	1.129	2.363
15.0	.218	.212	.240	.301	.587	.894	1.911
16.0	.145	.151	.173	.274	.447	.704	1.603
17.0	.114	.123	.117	.246	.330	.542	1.346
18.0	.078	.095	.078	.190	.229	.385	1.106
19.0	.061	.067	.056	.134	.151	.295	.877
20.0	.028	.061	.034	.085	.123	.235	.715
21.0	.011	.061	.022	.073	.084	.190	.626
22.0	.011	.039	.011	.050	.067	.155	.581
23.0	.006	.030	.006	.039	.050	.123	.469
24.0	.006	.011	.006	.028	.045	.078	.374
25.0	.006	.011	.006	.022	.039	.061	.285
26.0	.006	.011	.006	.022	.039	.050	.229
27.0	0.000	.011	0.000	.011	.039	.034	.184
28.0	0.000	.011	0.000	.006	.034	.022	.145
29.0	0.000	.006	0.000	.006	.017	.011	.117
30.0	0.000	0.000	0.000	0.000	.017	.006	.106
31.0	0.000	0.000	0.000	0.000	.017	.005	.061
32.0	0.000	0.000	0.000	0.000	.011	.005	.039
33.0	0.000	0.000	0.000	0.000	.011	0.000	.034

Figure 13. Cumulative Frequency Distribution of the Change in Direction, $\Delta\theta$, in time Δt for the BLADE AVERAGE (Case 4)

Figure 14. Power Spectra of Hub and Array Average

Figure 15. Power Spectra of Hub and Blade Average

Figure 16. Power Spectra of Hub and Blade Tip

5.0 REFERENCES

1. Cliff, W. C. and Verholek, M. G., "Flow Field Analysis," NASA CP-2034, Wind Turbine Structural Dynamics, NASA-LeRC, Cleveland, OH 44135, November 1977.

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