AN OVERVIEW OF THE NREL/SNL FLEXIBLE TURBINE CHARACTERIZATION PROJECT*†

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ABSTRACT

There has been a desire to increase the generating capacity of the latest generation of wind turbine designs. In order to achieve these larger capacities, the dimensions of the turbine rotors are also increasing significantly. These larger structures are often much more flexible than their smaller predecessors. This higher degree of structural flexibility has placed increased demands on available analytical models to accurately predict the dynamic response to turbulence excitation. In this paper we present an overview and our progress to date of a joint effort of the National Renewable Energy Laboratory (NREL) and the Sandia National Laboratory (SNL). In this paper we present an overview and status of an ongoing program to characterize and analytically model the dynamics associated with the operation of one of the most flexible turbine designs currently available, the Cannon Wind Eagle 300 (CWE-300). The effort includes extensive measurements involving a detailed inventory of the turbine's physical properties, establishing the turbine component and full-system vibrational modes, and documenting the dynamic deformations of the rotor system and support tower while in operation.

INTRODUCTION

One of the consequences of the increased rotor diameters seen on the latest turbine designs has been the continued increase in turbulence-induced loads with mean wind speed. The accompanying rise in fatigue loads, associated with larger diameter rotors using relatively rigid blades and hubs, ultimately limits the available lifetime. A new concept has been developed which exhibits an ability to significantly reduce the observed fatigue loads through a unique combination of a very flexible rotor and hub design. This turbine, the CWE-300, is used in this study to obtain a detailed understanding of the complex dynamics inherent in flexible designs, which is presently lacking. This understanding is necessary for the development of validated analytical tools that are capable of modeling this potentially very important concept.

In this paper we present an overview and status of an ongoing program to characterize and analytically model the dynamics associated with the operation of one of this flexible turbine. The effort includes extensive measurements involving a detailed inventory of the turbine's physical properties, establishing the turbine component and full-system vibrational modes, and documenting the dynamic deformations of the rotor system and support tower while in operation.

OBJECTIVES

Our specific objectives for this effort are to:

- Document the physical properties of the turbine's component (mass and stiffness distributions) and to determine their mechanical damping wherever possible.

- Establish component, sub-assembly, and the complete system vibration modes through in-situ, full-scale modal analyses.

- Summarize this information and develop analytical simulations of the turbine dynamics for

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turbulent inflows using the ADAMS®[‡,1] and FAST_AD[§,2,3] dynamic analysis codes for wind turbines.

- Compare numerical simulations *using limited operational measurements* to assess the level of our ability to analytically reproduce and understand the observed turbine dynamic responses.

- Use these results to contribute in the development of a detailed plan for a comprehensive test of a turbine for validating our current design codes and their ability to predict extreme events that determine turbine fatigue lifetimes.

APPROACH

We have established a collaborative effort between NREL, SNL, and the Cannon Wind Eagle Corporation to characterize and analytically model the dynamics associated with a pre-production prototype of the CWE-300 turbine. The test turbine is owned and operated by the National Wind Technology Center (NWTC). In order to develop representative analytical models of this turbine, extensive details concerning the physical properties and modal responses are necessary. An inventory of the turbine's known physical properties was developed through the efforts of NREL, CWE, and Dynamic Design. We determined the system vibration modes through extensive modal surveys of individual components (flex-beam, blade shell), sub-assemblies (rotor and hub), and the entire turbine as it is installed at the NWTC.[4,5,6]

Concurrently we are developing analytical simulations of this particular turbine using the ADAMS and FAST_AD dynamics codes (see Wright et al.[7]). Early in 1998 we will be making a limited set of measurements on the operating turbine at the NWTC over a range of inflow conditions. These measurements will include stresses in the nacelle rotating-frame (rotor and drivetrain), non-rotating frame (attitude angles), stresses and accelerations associated with the support tower, and inflow turbulence characteristics.

We will compare the observed stress distributions and the statistics of available dynamics parameters with those predicted by the ADAMS and FAST_AD simulations. We will also compare these results with measurements taken from an earlier version of the CWE-300 installed in Tehachapi Pass, California, that incorporated a rotor with a smaller diameter (26.8 m or 88 ft versus 29.3 m or 96 ft). Finally, we will assess the need for further measurements to fully describe the complex dynamics of this design.

THE NWTC CWE-300 TURBINE

The CWE-300 turbine has a rated power of 300 kW, a hub height of 50 m and a rotor diameter of 29.3 m. Selected physical and operating characteristics of the turbine are summarized in Table 1 and it is pictured in Figure 1. The turbine is installed near the southern border of the NWTC property and enjoys very smooth immediate upwind fetches in the primary and secondary prevailing wind directions. There are no turbines operating upwind when the wind comes from the prevailing (westerly) wind direction.

PROGRAM PROGRESS TO DATE

Physical Property Inventory

The physical property inventory was completed at the end of May 1997. Dynamic Design, under contract to NREL, completed a summary of the known properties of the turbine and produced first-cut estimates of the mass and stiffness distributions of the rotor, nacelle, and support tower. CWE furnished detailed design drawings of the turbine. On an availability basis, CWE also provided physical properties for the various components and materials. Blade deflections were measured under known loads by mounting the entire nacelle with the rotor assembly attached to a rigid support structure. Static loads were applied at various positions along the blade and deflections were measured using string pots and inclinometers. The measured flex-beam tip deflection curves are shown in Figure 2.

Modal Surveys

Modal surveys with free-free support conditions were conducted on the rotor flex-beam, also called the flex-spar, and blade shell. The results of these surveys are summarized in Tables 2 and 3.

In both of these modal surveys, the components were suspended with an overhead crane using a soft rubber elastic support to simulate a free-free support condition. This class of support was selected for two primary reasons. First, the free-free condition is easier to predict theoretically than a clamped or grounded condition. And, second, when a component is part of an assembly, the free-free condition provides the best

[‡] ***A***utomated ***D***ynamics ***A***nalysis of ***M***echanical ***S***ystems. ADAMS is a registered trademark of Mechanical Dynamics, Inc.

[§] Version of the ***F***atigue, ***A***erodynamics, ***S***tructures, and ***T***urbulence code that uses the University of Utah ***A***ero***D***yn aerodynamics subroutine package to calculate blade aerodynamic forces.

picture of its dynamic response function for incorporation into the model of assembly.

A full-system modal survey was performed on the NWTC CWE-300 turbine in late November and early December 1997. Up to 128 accelerometers were placed on the turbine structure and simultaneously recorded. A combination of impact and wind excitation was used to locate the structural modes and, when possible, obtain estimates of the corresponding modal damping. Modal surveys, using both excitation methods, were carried out with the rotor blades in the vertical and horizontal positions. Summaries of the modal frequencies and their damping estimates for these four cases are listed in Tables 4 and 5. As can be seen, measured modes extend from below 1 Hz to as high as 21.55 Hz. We found the modal response bandwidth of this turbine covers an effective range of about 0.45 to 25 Hz.

Numerical Model Development

The analytical modeling of this turbine is being accomplished in two overlapping efforts. The first focused on the modeling and experimental correlation of rotor components and then progress to the modeling of the full rotor assembly. The second was the modeling of the entire turbine system.

The first major effort started with the modeling of the flex-beam spar and the correlation of the predicted and measured modal responses. With the characterization of this primary component essentially complete, a model was developed for the rotor assembly (flex-beam, blade shells, and elastomer interfacing between the hub and the flex-beam).

The second major modeling effort has been the development of an analytical model for the entire turbine system, with the results of the first modeling effort being incorporated into the second.

Model development: An ADAMS model of the rotor and its components has been completed and finite element models of the rotor components have also been developed. The former will be used as the primary model for all response and load investigations. The latter models were developed for three reasons: 1) to confirm the ADAMS model; 2) to quantify modal data for correlation with experimental measurements; and 3) to produce mass and stiffness matrices for updating models. Model validations are being based on experimental test results. As previously mentioned, the tests on the rotor and its components have been completed with only a few exceptions. The primary measurement that is currently incomplete is the measurement of the impedance of the hub.. We have completed the correlation studies using the available data and will repeat the process when the hub impedance measurements become available.

The analytical determined modes were correlated with their experimental counterparts using Modal Assurance Criteria (MAC) factors. This technique produces both a direct and orthogonal correlation.

Rotor component modeling**:** For the CWE-300 wind turbine, the development of an analytical model for the rotor assembly depends heavily on an adequate description of the flex-beam. This structural element ties the blade shells to the hub, and therefore, must carry all of the blade loads. It dynamic behavior dominates the dynamics of the rotor assembly. All of the analytical modes of interest for the flex-beam (first three flapwise modes, two lead-lag modes, and two torsion modes) showed excellent agreement with the experimental results. With confidence in the flex-beam model, we are able to identify the static stiffness properties of the hub assembly by comparing static test data from the assembly with its analytical counterpart.

For the blade shell, we built two analytical models. The first, identified as Model I, is based on physical properties estimated by Dynamic Design. The second, or Model II, is based on properties estimated from Stanford University's 3D-Beam code developed under an NREL subcontract[8]. Both models showed marginal correlation with the test data, with the torsional modes showing particularly poor correlation. The latter is probably due to a lack of static deflection measurements in the lag direction that were available in the flapwise. In terms of frequencies, both models showed fair agreement with the first two experimental flapwise modes. For the first two lead-lag modes, Model I showed poor correlation while Model II was in fair agreement. The torsional frequencies of the models, while in fair agreement with each other, showed an order of magnitude discrepancy when compared with the experimental data. These discrepancies arose primarily as a consequence of the analytical models not capturing the twist component in all of the modes. The blade shell model, if used in its current form, may lead to erroneous results because the elastic coupling between the flapwise and pitching motions is not being simulated correctly.

Full-system modeling: A comprehensive ADAMS model of the NWTC CWE-300 turbine has been developed and tested. This model includes blade flap, lag, and torsion flexibility as well as nacelle yaw and tilt angles and tower fore-aft and side-to-side degrees of freedom. The rotor speed is assumed constant at 55.3 RPM. The University of Utah AeroDyn subroutine package[3] is used to supply the proper aerodynamic forces at 15 points along each blade.

As discussed above, the blades are modeled as two components: a flexible shell and a flex-beam spar. The blade shell is connected to the flex-beam using a spherical joint. In addition, the blade shell is connected to the hub via a cylindrical joint that in turn connects the root-rib of the shell to the hub.

The model is undergoing extensive testing prior to a formal validation process with experimental data. We have conducted simulations with several turbulent inflow conditions, as well as steady winds at various wind speeds including 6, 12, 18, 22, and 27 m/s. The turbulent simulations used were specifically formulated to produce conditions (very rapid wind direction changes) that conceivably could cause the rotor blade to strike the support tower. While our initial search for such conditions was focused on low wind speeds (6-10 m/s), we found that none of our simulated inflows in that range as well as the higher ones resulted in the likelihood of a tower-strike event.

At higher wind speeds (18-27 m/s) the model exhibits a somewhat unstable behavior. We notice that the blade edgewise or lead-lag bending moments and the low-speed shaft torque loads increased significantly. These result depended heavily on the amount of damping incorporated into the model for the structural damping of the blade elements and for the various joints associated with the complex hub design of this turbine. Currently we have little data from which we can estimate such values. If the real machine is more heavily damped than our model, it is likely that the unstable behavior will not be present. In addition, this predicted instability seems to depend on the value of the rotor edgewise stiffness as well as an interaction between the rotor symmetric edgewise mode and nacelle tilt and yaw angle motions. The blade edgewise bending moments, as well as the low-speed-shaft torsion, can be decreased by the modification of the blade edgewise-stiffness distribution and the rotor structural damping.

The unstable character of the model was also influenced by the mass distribution within the nacelle and by the allowable range for the tilt angle. The FAST_AD model of this turbine predicted similar trends for this set of simulations. It also predicted some unstable behavior at high wind speeds. It is difficult to get an exact replication of the machine behavior between the two codes because of differences in the level of model sophistication available in ADAMS and FAST_AD.

We are currently using the full-system modal data to compare the predicted and measured modal frequencies. In many cases the predicted and measured modal responses were in exceptionally close agreement. The current full-system model currently based on a rigid drivetrain. The lack of a flexible drivetrain in our model is probably responsible for many of the discrepancies that exist between the model and the measured data. A simulation of a flexible drivetrain is currently being incorporated into the ADAMS model. Further conclusions about the turbine's behavior will have to wait until we can compare the code predictions with measured data. We will, however, cautiously approach the higher wind speeds when we operationally test the turbine. For more details, see Wright, et al.[7]

INITIAL IMPRESSIONS

We expected to find this turbine design to exhibit complex dynamic responses to turbulence excitation and we have not been disappointed. Small changes in the mechanical configuration or component physical properties (e.g., structural and mechanical damping, stiffness distributions, etc.) often invoke substantial changes in the response of the turbine to not only turbulent but to steady winds without shear and tower shadow as well. As a result, it is not always possible to anticipate the entire range of responses to a configuration change without first performing a representative numerical simulation for guidance. An understanding of the complex dynamics of such a flexible system is unlikely to be achieved without a reasonably accurate and sophisticated analytical model. Thus, we are making detailed comparisons of the ADAMS and FAST_AD predictions and with experimental data.

The flexible nature of this turbine not only increases the importance of accurate measurements of the modal response of the turbine, but it makes them more difficult to measure. A large number of simultaneous measurement points are needed to capture the higher mode shapes that may or may not be important to the overall response. The low frequency of many of the modes of this turbine (as shown in Table 5) requires accelerometers that have accurate amplitude and phase responses below 1 Hz. Because the first few fundamental mode shapes are very important, accurate measurements of both the modal frequencies and associated damping place severe demands on the instrumentation used as well as and the methods of applying excitation.

INSTRUMENTATION

Based on the analyses of the turbine described above, the turbine and its inflow has been instrumented. These measurements will include stresses in the nacelle rotating-frame (rotor and drivetrain), non-rotating frame (attitude angles), stresses and accelerations associated with the support tower, and inflow turbulence characteristics. The complete set of measurements and the instrumentation used is described in Table 6. All strain gauges and other transducers are currently in place and monitoring circuits have been initially tested. Final checkouts and calibration will begin shortly.

FUTURE PLANS

After calibration of the instrumentation is completed, a limited operational data set from the NWTC CWE-300 turbine will be obtained. These measurements are scheduled to start this month, January, 1998. The data obtained from this test series will be used to validate and assess the full-system ADAMS and FAST_AD models and the ADAMS model of the rotor assembly. These assessments will also be used to identity any shortcomings in the data that may require additional testing. The data from these tests will also be used to examine the fatigue loading spectra for this class of turbines. The load spectrum will be compared and contrasted with the load spectra from other classes of turbines and from varying levels of turbulence.

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Table 1. Physical and Operating Characteristics of NWTC CWE-300 Wind Turbine.

General	
Rated wind speed	16 m/s
Rated output	315 kW
Rated power	300 kW
Hub height	50 m
Cut-in wind speed	4 m/s
Cut-out wind speed	30 m/s
Survival speed	52 m/s
Rotor speed	55.34 rpm
Rotor	
Diameter	29.3 m
Length	12.8 m
Material	Fiberglass reinforced epoxy
Location	Downwind of tower
Tower	
Type	Tubular, guyed, tilt-up
Material	Galvanized steel
Yaw Drive	
Type	Active below 50 kW output
Breaking System	
Aerodynamic	Full-blade stall controlled
Mechanical	None
Fail safe	Centrifugal switch
Generator	
Type	4-pole, induction

Figure 1. NWTC Cannon Wind Eagle 300

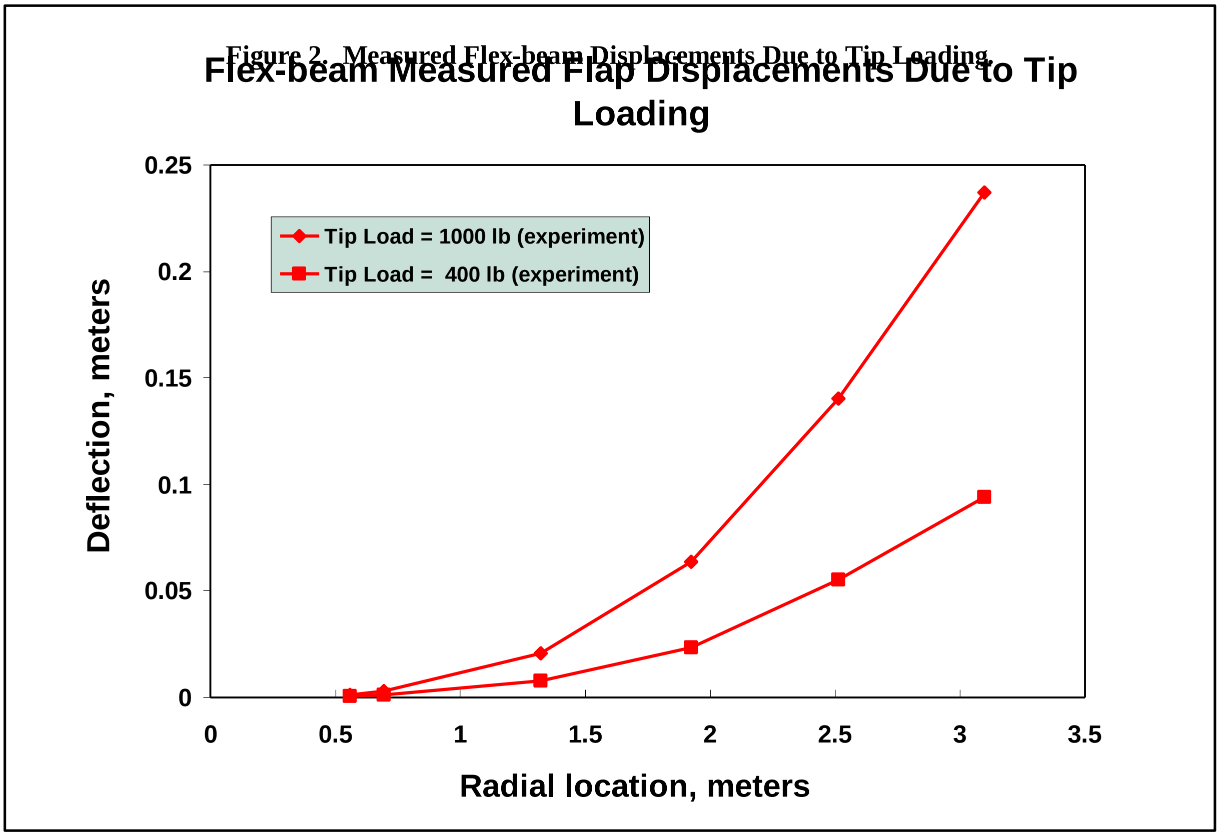

Figure 2. Measured Flex-beam Displacements Due to Tip Loading

Table 2. Flexbeam Natural Frequencies, Damping Factors and Mode Shape Description at that Frequency.

MODE #	FREQUENCY (Hz)	DAMPING (Hz)	DAMPING (%)	MODE SHAPE DESCRIPTION
1	2.15	44.88E-3	2.09	This is a rigid body mode rocking about the vertical (X) axis
2	5.99	5.64E-3	94.19E-3	First flap or out-of-plane bending
3	13.30	11.02E-3	82.84E-3	Second flap bending
4	25.33	76.61E-3	302.45E-3	Third flap bending
5	43.04	37.30E-3	86.67E-3	Fourth flap bending
6	44.75	73.91E-3	165.15E-3	First lag or in-plane bending
7	51.35	290.55E-3	565.79E-3	First torsion bending
8	62.99	115.54E-3	183.42E-3	Fifth flap bending
9	73.59	457.66E-3	621.89E-3	Second torsion bending
10	90.56	84.67E-3	93.50E-3	Sixth flap bending
11	94.58	181.46E-3	191.85E-3	Second lag bending

Table 3. Blade Shell Natural Frequencies, Damping Factors and Mode Shape Description at that Frequency.

MODE #	FREQUENCY (Hz)	DAMPING (Hz)	DAMPING (%)	MODE SHAPE DESCRIPTION
1	0.792	55.49E-3	6.99	A rigid body mode rocking about the vertical (X) axis
2	1.68	26.67E-3	1.59	First flap or out-of-plane bending
3	3.72	31.54E-3	847.56E-3	Second flap bending
4	7.36	41.66E-3	566.13E-3	First lag or in-plane bending
5	7.76	45.96E-3	592.51E-3	Third flap bending
6	12.63	43.92E-3	347.84E-3	Fourth flap bending
7	16.87	70.86E-3	420.00E-3	First torsion bending.
8	18.18	151.36E-3	832.36E-3	Fifth flap bending
9	21.32	115.97E-3	544.06E-3	Second lag ending
10	23.95	136.61E-3	570.46E-3	Sixth flap bending

Table 4. Full-System Natural Frequencies and Damping Factors with Blades Vertical.

MODE SHAPE DESCRIPTION	IMPACT EXCITATION		WIND EXCITATION
	FREQUENCY (Hz)	DAMPING (%)	FREQUENCY (Hz)
Blade first symmetric flap bending			0.453
Blade first asymmetric lag bending			0.828
Tower second fore-aft bending			0.922
Tower second side-to-side bending			1.016
Blade second asymmetric bending	1.357	0.927	1.281
Blade second symmetric flap bending			1.609
Blade second flap with a little first symmetric lag	2.404	0.395	2.375
Blade third symmetric flap bending			3.547
Blade third asymmetric flap bending	3.920	0.538	3.844
Blade second asymmetric lag bending	5.727	0.744	5.703
Blade first torsion bending	15.845	0.604	15.609
Blade third symmetric lag bending	19.319	0.254	
Blade second torsion bending	21.554	0.401	

Table 5. Full-system Natural Frequencies and Damping factors with Blades Horizontal.

MODE SHAPE DESCRIPTION	IMPACT EXCITATION		WIND EXCITATION
	FREQUENCY (Hz)	DAMPING (%)	FREQUENCY (Hz)
Blade first symmetric flap bending			0.438
Second tower fore-aft bending			0.906
Second tower fore-aft bending			0.953
Tower second side-to-side bending and first asymmetric lag bending			1.000
Blade first symmetric lag bending			1.234
Blade second symmetric flap bending	1.761	0.936	1.656
Blade second asymmetric flap bending	2.164	0.880	2.188
Blade third symmetric flap bending			3.656
Blade third asymmetric flap bending	4.012	0.680	3.922
Blade second asymmetric lag bending	5.813	0.919	5.719
Blade first torsion bending	16.043	0.235	16.016
Blade third symmetric lag bending	20.609	0.086	
Blade second torsion bending	21.574	0.172	

Table 6. Turbine and Inflow Measurements.

NACELLE ROTATING FRAME	
Blade shell flapwise bending	1000-ohm strain gauge
Flex-beam flapwise bending	1000-ohm strain gauge
Flex-beam edgewise bending	1000-ohm strain gauge
Pitch beam bending	1000-ohm strain gauge
Pitch arm link force	1000-ohm strain gauge
Low-speed shaft 0° bending	1000-ohm strain gauge
Low-speed shaft 90° bending	1000-ohm strain gauge
Low-speed shaft torsion	350-ohm strain gauge
Rotor position	1/Rev pulse
NACELLE NON-ROTATING FRAME	
Nacelle tilt angle	Precision potentiometer
Nacelle yaw angle	Precision potentiometer
SUPPORT TOWER	
3.3-m elevation torsion	350-ohm strain gauge
21.9-m elevation fore-aft bending	350-ohm strain gauge
21.9-m elevation side-to side bending	350-ohm strain gauge
33.5-m guy level fore-aft bending	350-ohm strain gauge
33.5-m guy level side-to-side bending	350-ohm strain gauge
40.6-m elevation fore-aft bending	350-ohm strain gauge
40.6-m elevation side-to-side bending	350-ohm strain gauge
46.4-m elevation torsion	350-ohm strain gauge
Tower-top fore-aft acceleration	Accelerometer
Tower-top side-to-side acceleration	Accelerometer
Tower-top fore-aft inclination	Precision inclinometer
Tower-top side-to-side inclination	Precision inclinometer
CONTROLLER	
Generator power	Precision power transducer
INFLOW	
3-m air temperature	Resistance temperature detector
67 – 3m temperature difference	Resistance temperature detector
3-m barometric pressure	Digital barometer
3-m horizontal wind direction	Vane/precision potentiometer
67-m horizontal wind direction	Vane/precision potentiometer
3-m wind speed	Cup anemometer
67-m wind speed	Cup anemometer
50-m (hub) horizontal wind direction	Sonic anemometer
50-m (hub) horizontal wind speed	Sonic anemometer
50-m (hub) vertical wind speed	Sonic anemometer