Measurement of Turbulent Wind Velocities Using a Rotating Boom Apparatus

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J. R. Connell**

April 1984

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MEASUREMENT OF TURBULENT WIND
VELOCITIES USING A ROTATING
BOOM APPARATUS

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J. R. Connel

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SUMMARY

The present report covers both the development of a rotating-boom facility and the evaluation of the spectral energy of the turbulence measured relative to the rotating boom. The rotating boom is composed of a helicopter blade driven through a pulley speed reducer by a variable speed motor. The boom is mounted on a semiportable tower that can be raised to provide various ratios of hub height to rotor diameter. The boom can be mounted to rotate in either the vertical or horizontal plane. Probes that measure the three components of turbulence can be mounted at any location along the radius of the boom.

Special hot-film sensors measured two components of the turbulence at a point directly in front of the rotating blade. By using the probe rotated 90° about its axis, the third turbulent velocity component was measured. Evaluation of the spectral energy distributions for the three components of velocity indicates a large concentration of energy at the rotational frequency. At frequencies slightly below the rotational frequency, the spectral energy is greatly reduced over that measured for the nonrotating case measurements. Peaks in the energy at frequencies that are multiples of the rotation frequency were also observed.

We conclude that the rotating boom apparatus is suitable and ready to be used in experiments for developing and testing sensors for rotational measurement of wind velocity from wind turbine rotors. It also can be used to accurately measure turbulent wind for testing theories of rotationally sampled wind velocity.

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MEASUREMENT OF TURBULENT WIND VELOCITY USING A ROTATING BOOM APPARATUS

by

V. A. Sandborn^(a)
J. R. Connell

INTRODUCTION

Design and testing of wind turbine blades requires a detailed knowledge of the time history of the wind approaching the blade. Since the wind turbine blades move across the atmospheric boundary layer, the time-varying velocities experienced by the blade are much different than those seen by a sensor at a fixed point. Thus, direct measurements of the local turbulence encountered along the path of segments of a rotating turbine blade are needed.

It has been shown by Connell (1981) that the spectrum of turbulence experienced by a rotating system is markedly different than the spectrum observed at a fixed point. Less turbulent energy is observed at frequencies below the rotation frequency and more energy appears in the higher frequencies associated with the harmonics of the rotation. The energy at the rotational frequency is the dominant part of the spectrum. The spectral results reported by Connell were obtained using arrays of anemometers on towers as well as using a laser anemometer scanning a circle in a vertical plane.

In some cases it will not be physically or economically realistic to erect a vertical plane array of anemometers near the wind turbine to be studied. Alternative methods of estimating wind at the rotor blade must be found. These may be either models or measurements using other sensors. Measurements of rotationally sampled wind under varying conditions are required to test and improve the models. Placement of wind sensors on rotating blades is a realistic alternative to vertical plane arrays for measurement of

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turbulent wind experienced by the blades. A rotating boom apparatus that is dedicated for the purpose of testing and proving wind sensors to be used on turbine blades and can also give rotationally sampled wind data for testing and improving theory has become an important part of the DOE wind program.

A rotating boom apparatus with a modest diameter, variable hub height and variable rotation rate has been designed. The primary wind sensor selected for the rotating boom was the hot-film anemometer in a cylindrical split-film configuration. Other hot-film configurations as well as wind measurement devices based upon other principles can be tested and compared to the split hot-film anemometer using the rotating boom apparatus. The rotating boom facility will be used for developing and testing the stable of wind sensor types required for measuring the rotationally sampled wind directly at turbine rotors. It also is to be used for testing and developing models of rotationally sampled turbulent wind for incorporation into turbine aerodynamics models.

The work reported herein was directed toward the improvement of an earlier rotating boom facility developed to measure the turbulence approaching a rotating blade. Special hot-film anemometer pods were developed to mount directly on the blade and record the three components of the turbulence. A semiportable tower with a rotating boom, which can be operated in either the horizontal or vertical plane, was set up. Limited evaluation of the turbulent velocity components encountered by the rotating system was made for two hub heights in the horizontal-axis configuration. A brief example of turbulence as encountered in the vertical-axis configuration is presented also.

This report documents the main features of the rotating boom apparatus and demonstrates its capabilities at Colorado State University, prior to the time it was shipped for use at the Pacific Northwest Laboratory.

ROTATING BOOM FACILITY

The rotating boom developed provided for mounting thermal anemometer sensors at any location along the radius and was able to take the electrical signal off the rotating system slip rings. The boom consisted of a 3.8 m-long, 17 cm-wide helicopter blade. The helicopter blade was employed because of its lightweight aerodynamic structure. A counterweight was employed to balance the system, as shown in Figure 1.

The blade was very rigid in twist, but more flexible in flatwise bending than is optimal for the present application. Appendix A includes a limited analysis of the blade flexure and the experimental evaluation of the present blade stiffening technique. The measurements indicate that blade flexure vibrations occur at frequencies greater than 150 Hz, which should be beyond the area of interest in turbulence measurements. The blade was stiffened in flatwise bending using a cantilever arrangement of radial piano wire supported by standoff rods through the blade at several radial locations.

FIGURE 1. Rotating Boom Test Facility

The helicopter blade is set at zero angle of attack along most of its length. The blades are made with a slight twist, so the outer tip is at a slight angle of attack. The rotating boom set up in the horizontal-axis configuration is such that the blade tip is pulled by its lift away from the tower. No movement of the blade across its plane of rotation could be observed visually during the rotational measurements reported here.

The boom is driven through a 4.78-cm drive shaft by a variable speed motor with a belt-pulley system.^(a) A 10-conductor slip ring^(b) was mounted on the drive shaft. Constant-temperature anemometer electronics were mounted in compact containers directly on the rotating boom and the electrical output was fed through the slip rings to a recording system. Provisions for attaching batteries directly to the rotating boom to operate the anemometers were also made. For the present study, a 15-V, 3-A power supply fed through the slip rings was employed to operate the anemometers.

A detailed evaluation of possible variable height towers for use with the rotating boom facility was made. The tower was required to be variable in height from 7.5 to 22 m, to be operational in a wind of 88 km/hr, and to withstand a wind of 193 km/hr. A self-supporting, nested, crank-up tower was procured to meet the specifications. The tower has a special tilt-over accessory, so that the facility can rest horizontally when not in use. Figure 2 is a set of photographs of the tower with the rotating boom facility mounted for operation in the horizontal plane. Appendix C describes the tower and the motor mounting assembly plates for horizontal- and vertical-axis wind turbine operation. Detailed instructions for erection and adjustment, together with a structural analysis of the tower, are on file at PNL.

(a) See Figure A.4, Appendix A

(b) See Appendix B

FIGURE 2. Photographs of the Rotating Boom Facility
Mounted on the Semiportable Tower

TURBULENT VELOCITY EVALUATION

The three-dimensional turbulent velocity components can be measured by a number of different anemometer techniques. The present study evaluated the use of hot-film sensors to obtain the velocities. Two types of film probes were considered: the split film and special three-component systems. The hot-film sensors were mounted on a support tube directly on the rotating boom. The electronic circuits that operated the sensors were also mounted on the rotating system to reduce electrical noise problems. The output of the anemometers was taken off the rotating system through slip rings. The anemometers were operated with the axis of boom rotation in both horizontal and vertical positions.

HOT-FILM SENSORS

Commercial hot-film probes were employed in the present study. The sensors are platinum films plated on cylindrical quartz substrates, 0.152 mm in diameter. In order to measure the three components of the turbulent velocities, more than one sensor must be used at a time. The types of probes evaluated are shown in Figure 3. The split-film sensor was employed for the evaluation of the turbulent spectra in the present study as described in Appendix D. The three-component probe shown in Figure 3a requires a great deal more data reduction to evaluate the velocities. The probes were mounted in front of the rotating boom or turbine blade on rods, so that the distance between the probe and the leading edge of the boom was adjustable. Provisions for mounting the sensors at the tip of and also along the rotating boom were available as discussed in Appendix E.

The sensors were calibrated with a special flow facility designed for the purpose (Appendix D). It was set up directly at the tower site and the calibration was made for the same atmospheric conditions as for the actual measurements. Also the same electrical connections as employed in the rotational measurements (i.e., slip rings) were maintained throughout the calibrations. Calibration of both the velocity and angle sensitivities was required for each sensor.

FIGURE 3. Split-Film and Three-Component Turbulent Sensors

The present study demonstrated that the instantaneous sum of the voltages from the two films, having identical sensitivities, is directly proportional to the tangential velocity component (see Appendix D). The instantaneous difference is proportional to the velocity component normal to the plane of the split of the sensor (see Figure D.1). It may be desirable for some purposes to employ analog circuits to perform the sum and difference of the two output voltages before the signals are digitized. The analog signal conditioning would avoid any interchannel time displacement, which might be important at the high rates of wind velocity fluctuations to be measured.

MEASURING SYSTEM

A block diagram of the anemometer measuring system is shown in Figure 4. The film sensors are mounted on the adjustable probe holders as shown in Appendix E. The split-film sensors have four-pin electrical connectors on the base end of the probe; any one of the probes plugs into the probe holders interchangeably. The sensors are connected by coaxial cable to the modular anemometer units, which are mounted directly on the rotating boom as can be seen in Figure 5. Two sets (Appendix E) of three modular anemometer electronics were available for the studies. The anemometers were powered by a 15-V, 3-A dc supply mounted on the nonrotating tower. The power was delivered to the anemometers through the slip-ring assembly (see Appendix B).

FIGURE 4. Digitizer-Recorder-Block Diagram of the Anemometer-Recorder

FIGURE 5. Photographs of the Modular Anemometer Pod and Slip-Ring Assembly

The output of the anemometers was taken off the rotating system through the slip rings. The anemometer signals were recorded on a 4-track FM tape recorder (1-7/8 ips). Signal conditioners were employed to suppress the average dc voltage output of the anemometers and amplify the fluctuations, so that fluctuating voltages could be recorded with reasonable signal-to-noise levels.

A 9-track computer-based digital data acquisition system (Appendix F) has been procured as part of the facility. The digital system has the ability to digitize the anemometer signals at a rate of 1500 samples per second and to compute the velocities directly. The digital system was not available during the wind measurement experimental phase of the present study.

VELOCITY SPECTRUM EVALUATION

The spectra of the three velocity components were evaluated for this report from the taped signals using an analog spectrum analyzer. A 1/10-octave analog-spectrum analyzer was employed. Figure 6 is a block diagram of the spectral evaluation. For frequencies between 0.625 and 500 Hz, the signals were played back at 7-1/2 ips. The minimum frequency available for the analyzer was 2.5 Hz. The taped signals were played back at a higher tape speed, so that lower frequency energy contents could be evaluated. For frequencies between 0.156 and 0.625 Hz, the playback speed was 30 ips. The output of the spectrum-analyzer was measured with a root-mean-square circuit and an integrating digital voltmeter. Each point of the spectrum was obtained by integrating the analyzer output for the equivalent of 640 s of real time. The same section of the recorded signal was re-evaluated for each spectral point. Spectra of the individual sensor signals and of the instantaneous sum of the two signals were measured. The results of the analysis of the signals indicated that only the instantaneous sums and the difference of the signals needed to be evaluated. The measured spectra are tabulated in Tables 1 and 2.

The present analysis of the output of the split-film sensors (see Appendix D) indicates that the velocity cross-correlation terms, $\overline{u_t u_\alpha}$ and $\overline{u_t u_r}$, can be neglected in computing $u_t^2 + u_\alpha^2$ from e^2 . Although the results are for a light and variable wind field, with no apparent mean wind field, it

FIGURE 6. Block Diagram of the Spectrum Evaluation

appears likely that for all cases where the rotating velocity ($\bar{u}_t$) is large compared to the mean wind speed, the cross-components will be negligible. For conditions where the wind and rotation speeds are about equal, the cross-components should be evaluated before it is assumed that they can be neglected.

TABLE 1. Spectral Evaluation of Horizontal-Axis Operation
(Wind Light and Variable: Wind Mainly Through the Tower)

Frequency Hz	Runs of 8-22		Frequency Hz	Run 3		Frequency Hz	Run 4	
	nS_{u_t}	nS_{u_α}		nS_{u_t}	nS_{u_α}		nS_{u_r}	
0.156	2.827-1	1.986-1	0.156	1.027-2	5.599-3	0.156	4.789-3	
0.188	1.575 "	1.426 "	0.188	4.911-3	3.365 "	0.188	4.036 "	
0.250	2.514 "	2.657 "	0.250	8.900 "	4.530 "	0.250	2.826 "	
0.375	1.474 "	1.188 "	0.375	4.653 "	2.880 "	0.375	2.810 "	
0.500	1.316 "	9.917-2	0.500	7.610 "	6.241 "	0.500	3.582 "	
0.625	1.097 "	9.877 "	0.625	2.254-2	1.741 "	0.625	1.628-2	
0.938	1.090 "	8.041 "	0.750	1.671-1	1.291-1	0.750	1.184-1	
1.250	7.733-2	7.798 "	0.375	3.697 0	2.328 0	0.875	1.638 0	
1.880	6.202 "	6.059 "	0.881	3.915 "	3.505 "	0.894	5.254 "	
2.500	6.092 "	4.772 "	0.888	4.039 "	3.537 "	0.906	5.049 "	
3.750	3.570 "	3.281 "	0.894	4.021 "	3.640 "	0.919	4.104 "	
5.000	4.269 "	3.805 "	0.900	3.981 "	3.593 "	0.938	3.064 "	
6.250	4.179 "	2.682 "	0.906	3.693 "	3.396 "	0.969	1.149 "	
9.330	2.851 "	2.515 "	0.938	2.440 "	1.862 "	1.000	5.229-1	
12.500	2.792 "	2.180 "	1.000	3.654-1	3.798-1	1.130	5.706-2	
18.800	1.937 "	1.606 "	1.130	4.773-2	4.269-2	1.250	2.299 "	
25.000	1.946 "	1.483 "	1.250	2.422 "	3.033 "	1.380	2.308 "	
37.500	1.285 "	7.986-3	1.380	2.583 "	3.427 "	1.500	4.447 "	
50.000	1.239 "	6.440 "	1.500	3.872 "	5.317 "	1.630	2.108-1	
62.500	9.147-3	4.251 "	1.630	1.218-1	1.596-1	1.750	5.536 "	
93.800	1.248-2	2.779 "	1.690	3.062 "	3.719 "	1.780	5.972 "	
125.000	2.510 "	4.524 "	1.750	4.682 "	5.566 "	1.790	5.984 "	
188.000	2.506 "	2.037 "	1.760	4.783 "	5.697 "	1.810	5.849 "	
250.000	5.001 "	5.297-1	1.780	4.004 "	5.943 "	1.880	3.650 "	
313.000	2.007-3	3.561 "	1.810	4.289 "	5.903 "	2.190	3.555-2	
			1.880	2.769 "	3.846 "	2.500	1.020 "	
			2.190	3.991-2	3.348-2	2.630	1.826-1	
			2.500	1.231-1	1.696-1	2.680	1.770 "	
			2.630	1.905 "	3.316 "	2.750	1.509 "	
			2.650	1.929 "	3.640 "	2.810	1.143 "	
			2.660	1.927 "	3.651 "	3.130	4.413-2	
			2.690	1.872 "	3.582 "	3.500	1.010-1	
			2.810	1.117 "	2.106 "	3.580	1.034 "	
			3.130	4.627-2	6.535-2	3.630	9.807-2	
			3.500	9.839 "	1.756-1			
			3.530	9.794 "	1.768 "	3.750	7.212 "	
			3.560	9.782 "	1.790 "	4.060	4.962 "	
			3.750	7.805 "	1.249 "			
			4.060	5.496 "	7.120-2	4.380	7.775 "	
			4.380	8.675 "	1.320-1	4.470	7.973 "	
			4.440	8.650 "	1.336 "			
			4.500	8.326 "	1.314 "	4.560	7.298 "	

TABLE 1. Continued

Frequency Hz	Runs of 8-22		Frequency Hz	Run 3		Frequency Hz	Run 4	
	nS_{u_t}	nS_{u_α}		nS_{u_t}	nS_{u_α}		nS_{u_r}	
			5.000	6.152 "	8.358-2	5.000	5.508 "	
			5.250	7.751 "	1.070-1	5.310	6.648 "	
			5.310	7.823 "	1.098 "			
			5.380	7.630 "	1.097 "	5.380	7.016 "	
			5.630	6.230 "	8.775-2	5.440	6.084 "	
			6.130	6.763 "	9.393 "	5.630	5.672 "	
			6.180	6.852 "	9.530 "	6.140	6.227 "	
			6.250	6.733 "	9.294 "			
			6.880	5.681 "	8.071 "	6.250	6.124 "	
			7.060	5.832 "	8.432 "	6.310	5.845 "	
			7.130	5.880 "	8.458 "			
			10.000	5.445 "	6.679 "	6.880	5.621 "	
			20.000	3.908 "	5.156 "	7.130	5.668 "	
			30.000	3.544 "	4.459 "	7.250	5.430 "	
			50.000	3.250 "	3.144 "	10.000	4.654 "	
						20.000	3.506 "	
			70.000	2.744 "	2.498 "	30.000	2.867 "	
			100.000	3.341 "	2.049 "	50.000	2.054 "	
						100.000	1.284 "	

TABLE 2. Spectral Evaluation Horizontal-Axis Operation
Runs for 3 to 4.5 m/s Winds (Close to Normal
to Rotating Boom and Not Through Tower)

No Rotation			37 RPM Run			55 RPM Run		
Frequency Hz	nS _{u_t}	nS _{u_α}	Frequency Hz	nS _{u_t}	nS _{u_α}	Frequency Hz	nS _{u_t}	nS _{u_α}
0.156	2.178-1	1.719-1	0.156	2.718-3	5.629-3	0.156	1.640-3	6.887-3
0.313	1.741 "	1.946 "	0.188	2.835 "	4.180 "	0.188	1.700 "	4.567 "
0.625	1.647 "	1.886 "	0.250	2.134 "	4.257 "	0.250	1.601 "	3.700 "
1.000	1.303 "	1.626 "	0.313	3.249 "	5.620 "	0.313	1.599 "	4.654 "
2.000	9.946-2	1.085 "	0.375	4.892 "	1.041-2	0.438	1.565 "	3.015 "
3.000	7.595 "	7.412-2	0.438	9.817 "	1.660 "	0.563	3.637 "	7.600 "
4.000	6.024 "	6.422 "	0.464	2.185-2	3.214 "	0.688	1.710-2	2.449-2
5.000	4.675 "	5.195 "	0.500	5.375 "	6.018 "	0.813	3.723-1	4.070-1
6.000	3.921 "	5.103 "	0.525	1.288-1		0.875	4.208 "	3.535 0
			0.531		1.711-1			
7.000	4.110 "	3.935 "	0.538	2.676 "		0.906	8.927 0	7.558 "
8.000	3.593 "	4.681 "	0.544	3.144 "		0.922	9.138 "	7.815 "
9.000	3.326 "	4.178 "	0.550	4.326 "		0.938	8.008 "	
10.000	3.469 "	4.674 "	0.556	5.711 "		1.130	7.431-2	9.222-2
20.000	2.099 "	3.212 "	0.563	9.108 "	6.776 "	1.380	7.876-3	1.315 "
30.000	1.381 "	2.376 "	0.594	5.162 0	3.590 0	1.630	9.055 "	2.797 "
50.000	8.484-3	1.977 "	0.613	7.311 "	5.791 "	1.840	6.328-2	1.372-1
70.000	6.231 "	1.297 "	0.619	7.887 "	6.291 "	2.130	7.037-3	3.000-2
			0.625	7.636 "	5.592 "			
100.000	6.579 "	8.909-3	0.656		2.535 "	2.380	5.241 "	2.380 "
			0.688		5.780-1			
			0.813	2.577-2	7.398-2	2.630	7.622 "	2.756 "
			0.938	1.150 "	2.156 "	2.770	9.249 "	2.979 "
			1.060	1.016 "	1.870 "	3.060	5.196 "	2.324 "
			1.240	4.580 "	7.688 "	3.310	4.931 "	2.241 "
			1.340	2.399 "	6.281 "	3.500	5.569 "	
			1.530	1.057 "	2.473 "	3.560		2.553 "
			1.720	1.186 "	2.558 "	3.630	6.719 "	
						3.690		2.542 "
			1.840	1.594 "	2.745 "	3.880	5.192 "	1.938 "
			1.970	1.299 "	2.654 "	4.130	3.845 "	1.716 "
			2.160	7.420-3	2.039 "	4.380	3.553 "	1.840 "
			2.340	8.764 "	2.285 "	4.440		1.908 "
			2.470	9.917 "	2.755 "	4.500		1.888 "
			2.590	8.256 "	2.311 "	4.630	3.922 "	1.741 "
			2.780	7.322 "	1.922 "	4.880	3.583 "	1.505 "
			2.970	7.603 "	1.972 "	5.130	3.644 "	1.495 "
			3.090	7.507 "	1.990 "	5.250	3.841 "	1.587 "
			3.220	6.806 "	1.849 "	5.380	3.869 "	1.685 "
			3.410	5.946 "	1.667 "	5.500	3.926 "	
			3.590	5.861 "	1.632 "	5.630		1.498 "
			3.720	6.166 "	1.739 "	5.810	3.371 "	

TABLE 2. Continued

No Rotation			37 RPM Run			55 RPM Run		
Frequency Hz	nS_{u_t}	nS_{u_α}	Frequency Hz	nS_{u_t}	nS_{u_α}	Frequency Hz	nS_{u_t}	nS_{u_α}
			3.880	5.759 "	1.690 "	5.880		1.260 "
			4.000	5.271 "	1.570 "	6.000	3.135 "	
			4.190	5.383 "	1.529 "	6.130		1.358 "
			4.310	5.397 "	1.439 "	6.250	3.439 "	1.676 "
			4.500	5.154 "	1.471 "	6.310		1.672 "
			4.630	4.872 "	1.372 "	6.380	3.597 "	
			4.810	4.739 "	1.278 "	6.500	3.579 "	
			4.940	4.865 "	1.231 "	6.560		1.614 "
			5.000		1.308 "	6.750	3.247 "	1.523 "
			5.060		1.350 "	6.880		1.416 "
			5.130		1.333 "	7.000	3.085 "	
						7.060		1.380 "
						7.190	3.018 "	1.387 "
						7.250	3.058 "	
						7.310	3.007 "	1.384 "

SPECTRAL EVALUATION

Measured spectra weighted by the frequency, n , for horizontal axis operation at rotating boom hub heights of 24 and 70 ft are shown in Figure 7. Figure 7a shows the velocity tangential to the rotational motion of the boom spectrum measured with the plane of the split-film parallel to the r direction. The spectrum of the α component from the same orientation is included in Figure 7b for the horizontal-axis case. The r component spectrum in Figure 7b was for measurements with the plane of the split parallel to the α coordinate. Light wind conditions remained roughly constant for the measurements. The spectrum measured with the sensors stationary (Eulerian spectrum) is also shown for comparison in Figure 7a. The time series length for each data point on the spectrum was approximately 640 seconds.

The large reduction in energy of the rotationally measured wind spectrum at frequencies immediately below the rotation frequency is demonstrated in Figure 7a. At frequencies above the rotation frequency, n_0 , peaks are shown at $2n_0$, $3n_0$, $4n_0$, $5n_0$, $6n_0$, $7n_0$. Further, the general level of energy is higher in the rotational spectrum than in the Eulerian spectrum in Figure 7a.

The spectra are similar to the rotating spectra of U_α observed with a laser anemometer (Connell 1981) and previous measurements with the present facility (Sandborn 1980). The spanwise, u_r , and tangential, u_t , velocity spectra shown have not been previously reported. The angular spectrum, u_α , indicates considerably more energy compared to either the tangential or spanwise spectra at frequencies greater than the rotation frequency (i.e., at 1 to 2 Hz). For the August 21 tests the wind fluctuations were mainly out of the southeast, which would be through the tower. A major contribution to the turbulence would be made by the tower shadow.

Figures 7c and 7d show measurements of the spectra of tangential and axial wind, respectively, for the rotating boom operating at a hub height of 70 feet. Two different rotational speeds are included on the plots. The wind was light and variable for these runs also. The energy levels in the spectra for frequencies in the multiples of n_0 are less at 70 ft hub height than for a

hub height of 24 ft. The wind shear would be expected to be more linear and turbulence would be reduced at the greater height.

A high frequency peak is observed in the area from 150 to 250 Hz. These high frequency measurements are indicated in Figure 7e. However, these peaks are observed in the nonrotating spectra, as well as in some of the rotation cases. Thus, it is expected that the high frequency results are not associated with the actual turbulence encountered by the sensor. The high frequency is thought to be associated with the recording system and should not be included in the main analysis.

FIGURE 7a. Measured Velocity Spectra; Tangential Velocity, Horizontal-Axis Operation, 24 Ft Hub Height

FIGURE 7b. Measured Velocity Spectra; Angular and Radial Velocities, Horizontal-Axis, 24 Ft Hub Height

FIGURE 7c. Measured Velocity Spectra; Tangential Velocity, Horizontal-Axis Operation, 70 Ft Hub Height

FIGURE 7d. Measured Velocity Spectra; Angular Velocity, Horizontal-Axis Operation, 70 Ft Hub Height

FIGURE 7e. Measured High Frequency Velocity Spectra; Horizontal-Axis Operation

AUTOCORRELATIONS

Autocorrelations of wind velocity components measured for several rotating boom runs are shown in Figure 8. These correlations were obtained with a hybrid computer which computed 100 points of time lag over a preselected time period. The computer was set up to compute the autocorrelations starting at specific times and not necessarily always starting at zero (i.e., precomputation times were employed to expand the total time over which the autocorrelations were computed). This precomputation allows the maximum number of data points to be evaluated during a cycle of the arm rotation. Figures 8a, c, f and h show the autocorrelations for measurements with the arm not rotating. In approximately 6 seconds of time, the autocorrelation for the approach turbulence in the horizontal-axis tests (Figures 8a and c) drops to zero. While there is some indication of a negative correlation, particularly for the data of Figure 8a, it is within the uncertainty of the measurement.

FIGURE 8a. Autocorrelation Evaluation for the Velocity Component; Horizontal Axis, u_{α} , No Rotation

FIGURE 8b. Autocorrelation Evaluation for the Velocity Component; Horizontal Axis, u_{α} , Rotation

FIGURE 8c. Autocorrelation Evaluation for the Velocity Component; Horizontal Axis, u_t , No Rotation

FIGURE 8d. Autocorrelation Evaluation for the Velocity Component; Horizontal Axis, u_t , Rotation

FIGURE 8e. Autocorrelation Evaluation for the Velocity Component; Horizontal Axis, u_r , Rotation

FIGURE 8f. Autocorrelation Evaluation for the Velocity Component; Vertical Axis, u_α , No Rotation

FIGURE 8g. Autocorrelation Evaluation for the Velocity Component; Vertical Axis, u_α , 39 rpm

FIGURE 8h. Autocorrelation Evaluation for the Velocity Component; Vertical Axis, u_t , No Rotation

FIGURE 8i. Autocorrelation Evaluation for the Velocity Component; Vertical Axis, u_t , 39 rpm

FIGURE 8j. Autocorrelation Evaluation for the Velocity Component; Vertical Axis, u_α , 48.4 rpm

FIGURE 8k. Autocorrelation Evaluation for the Velocity Component; Vertical Axis, u_t , 48.4 rpm

Figures 8f and h, for vertical-axis rotation conditions, show a more distinct negative correlation and suggest a total time scale on the order of 3 to 4 seconds before zero is reached.

Figures 8b, d, e, g, i, j and k show the autocorrelations for the tests with the boom rotating. In general, these autocorrelations are dominated by the rotation frequency and it is difficult to identify other effects. The horizontal-axis runs, Figures 8b, d and e, show a systematic variation in the magnitude of the correlation at large time lags. The cause of the decrease and then increase in magnitude of the oscillations could not be readily explained. When the actual time-lag points are too far apart to define the frequency adequately, it is possible to obtain the highly distorted autocorrelation curve shown on the insert to Figure 8i. For this distorted curve, less than two time lag points are obtained for each rotation. For the data shown on Figures 8b, d and e, at least 14 time-lag points are obtained for each frequency oscillation.

For vertical axis cases (Figures 8g, i, j, and k), the autocorrelations are nearly identical over a large number of cycles. No evidence of a decrease in the correlations was found for the allowable range of the present computer. Apparently the clear field of rotation at a constant elevation above the ground produces a nearly uniform periodic velocity fluctuation. Figure 9 shows typical voltage traces of the sensor output for the vertical axis tests. Both the maximum and minimum values show high frequency peaks, which would appear as multiples of the rotation values in a spectrum.

NOTE: All time scales are the same.

FIGURE 9. Typical Voltage Traces From One of the Split-Film Sensors for the Vertical-Axis Test

PROBABILITY EVALUATION

The probability distributions about the mean for the velocity components were evaluated with the same hybrid computer. Figure 10 shows the probability distribution for the vertical- and horizontal-axis tests. Figures 10a through e illustrate the horizontal-axis tests. Although the signals are highly periodic, the probability distributions appear to be more characteristic of a slightly skewed random type shape. The vertical axis tests (Figures 10j and k) show the characteristics more closely associated with periodic signals, such as the double peaked probability distributions. The peaks at positive and negative velocities represent the extremes in the rotation cycle where the sensor is moving upwind and downwind, respectively. The higher voltage (higher velocity) peaks are more pronounced than the "downwind" values. The vertical velocities, shown in Figures 10g and h, have broad areas of roughly the same magnitude of the probability, but do not show the pronounced dual peaks of the tangential velocity.

a) Horizontal Axis, u , no rotation

b) Horizontal Axis, u , rotation

c) Horizontal Axis, u_t , no rotation

d) Horizontal Axis, u_t , rotation

e) Horizontal Axis, u_r , rotation

FIGURE 10. Probability Distribution Shapes for the Three Velocity Components

FIGURE 10. (Continued)

EXPERIMENT TO MEASURE WIND AT A BLADE OF A DARRIEUS WIND TURBINE

Preliminary tests were made on a 4.5 m-high Darrieus wind turbine. Figure 11 shows photographs of the Darrieus with the anemometers. Figure 12 shows typical traces of the output of one of the split-film sensors when the turbine was turning. The turbine was not operating with a load, so the rpm varied over a wide range. The noncommercial slip ring used on the Darrieus gave signals too noisy to obtain useful wind measurements. With an improved slip-ring system it should be possible to obtain turbulence data from the Darrieus with the same accuracy as with the rotating boom. Experiments with a Darrieus using better slip rings were deferred to a later time.

FIGURE 11. Darrieus Wind Turbine
With Split-Film
Anemometers Mounted
on the Blade

FIGURE 12. Voltage Trace from a Split-Film Sensor Operating on a Darrieus Wind Turbine

CONCLUSIONS

The split-film anemometer has been demonstrated to be suitable for measuring wind fluctuations from a rotating boom simulating a wind turbine rotor blade. The accuracy of measurement can be kept high by careful attention to sensor calibration and to maintaining slip-ring noise at a low level. The calibration requires research grade work. Suitable slip rings can be obtained commercially.

Examples of spectra of the three components of rotationally measured wind velocity, using the rotating boom apparatus, provide an independent indications that earlier rotational sampling measurements and theory were correctly interpreted as representing wind at rotating turbine blades.

We conclude that the rotating boom apparatus is suitable and ready to be used in experiments for developing and testing sensors for rotational measurement of wind velocity. It can also be used for testing and improving theories of rotationally sampled wind velocity.

REFERENCES

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- Sandborn, V. A. 1980. A Rotating-Boom Facility for Evaluation of Wind Characteristics Approaching a Wind Turbine Blade. Research Memo. No. 46, Colorado State University, Fort Collins, Colorado.
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APPENDIX A

APPENDIX A

ROTATING BOOM AND DRIVE SYSTEM

The rotating boom assembly consists of a helicopter blade 3.8 m long and 17 cm wide. The blade is mounted to a 4.9-cm-dia drive shaft as shown in Figure A.1. A counterweight is provided to balance the boom in rotation, (Figure A.1). The thermal anemometer pod is mounted directly on the rotating boom.

FIGURE A.1. Rotating Boom Assembly

The helicopter blade was found to be extremely rigid in twist, but it proved to be more flexible in bending than desired for the present application. The blade was clamped in the arrangement shown in Figure A.2. The deflection of the blade was measured. The product of the modulus of rigidity, G , and the moment of area about the flapping axis, I , (the "moment of inertia" in

FIGURE A.2. Determination of the Effective Elasticity of the Helicopter Blade

engineering terminology) is related to the beam deflection due to a concentrated load by the cantilever beam relation below in units of inches and pounds.

$$GI = \frac{WL}{3\delta}, \quad (A.1)$$

where δ is the tip deflection, L is the blade length and W is the blade weight. Each variable's units are shown below:

$$\langle G \rangle = m \ell^{-1} t^{-2}$$

$$\langle I \rangle = \ell^4$$

$$\langle W \rangle = m \ell t^{-2}$$

$$\langle L \rangle = \ell$$

$$\langle \delta \rangle = \ell,$$

where m is mass, ℓ is length and t is time. The effective weight of the blade was 100 N and the value of EI was found to be $5.97 \times 10^4 \text{ cm}^2 \text{ N}$. The simple wire bracing technique shown in Figure A.3 increased the value of EI to $1.31 \times 10^5 \text{ cm}^2 \text{ N}$. The tip deflection due to the weight of the blade is 2.4% of the length for the braced blade.

During the operation of the rotating boom, the helicopter blade is normally at zero angle of attack to the plane of rotation. The blade has a slight twist, so that the tip will be at a small angle of attack to the plane of rotation. On the facility the effect of the tip angle of attack would be

FIGURE A.3. Bracing of Helicopter Blade to Reduce the Flexure

to pull the blade outward from the tower. Visual observation of the blade tip during rotation in light and variable winds did not show any flexing of the boom.

DRIVE SYSTEM

The boom is driven through the shaft by a 1/2 hp variable speed motor. The motor drives the shaft through a 47.6 cm-dia sheave. Figure A.4 is a schematic diagram of the drive system. For the initial setup of the facility on the walkup scaffold tower, the motor was mounted behind the sheave for better distribution of the weight. For the semiportable tower setup, the drive motor was moved to a position between the sheave and the boom.

FIGURE A.4. Schematic Diagram of the Drive System

The rotation speed of the boom can be controlled by the motor speed and by the choice of the sheave. The 1/2 hp motor was found to operate best at high rpm. Some overheating was experienced in the early tests at low rpm settings. It appears desirable to change the motor sheave rather than operate

the motor for extended periods at the low rpm. The particular motor used represents the largest horsepower, variable speed motor available that will operate on 110 V ac. Larger motors are available, but they require 200 V ac for operation.

APPENDIX B

APPENDIX B

SLIP RINGS

Slip-ring assemblies were required for the rotating boom and the Darrieus wind turbine. A commercial 10-conductor system was obtained for the rotating boom facility. Figure B.1 provides detailed information on this particular slip-ring assembly. A photograph of the slip ring mounted on the rotating boom shaft is shown in Figure 5.

FIGURE B.1. Slip-Ring Details

Tests of the noise generated by the slip rings indicate extremely low levels. A nominal 1.5-V battery was connected across two of the slip rings. The root-mean-square noise signal was 0.0001 V both when the shaft was rotating and when stopped. The shape of the noise signal changed when the shaft was

rotated, suggesting some pickup from the drive motor. The noise level from the modular anemometers is between 0.0003 and 0.0006 V, root-mean-square. Thus, the noise generated by the slip rings can be neglected for the present application.

Figure B.2 is a sketch of the slip-ring arrangement employed for the Darrieus wind turbine tests. As noted in Figure 12, the junctions required for this assembly produced a noise pulse.

FIGURE B.2. Darrieus Wind Turbine Slip Ring

APPENDIX C

APPENDIX C

SEMIPORTABLE TOWER

A commercially available, semiportable, self-supporting, nested-section, crank-up instrument tower upon which the rotating-boom assembly could be mounted was procured. This tower may be readily placed in both the vertical operating position or in the tilted-over position for storage or instrumentation access. Specifications required that the tower be operated in 50 mph winds and that it withstand 120 mph winds. When mounted on the base designed by the manufacturer, the tower can freestand in a 50 mph wind. When guyed, it can withstand 120 mph winds in the vertical position. Under such conditions, however, it seems safer to take advantage of the tilt-over option used during storage.

MOTOR-BLADE ASSEMBLY MOUNTING

The motor-blade assembly discussed in Appendix A was mounted on the tower by means of either one of two platforms. One of these is designed to accommodate boom rotation in the vertical plane; the other is used when the boom is rotating in the horizontal plane. The former is composed of a base plate above which a motor-boom assembly support plate is bolted in any one of eight positions 45° apart, providing variable orientation with respect to the incident wind. The base plate is mounted horizontally on the innermost (nested) section of the tower (i.e. the uppermost section in the extended configuration) by means of three solid rods fitting into the section legs. Additional rigidity is afforded by a fourth rod welded to the boom-assembly support plate. This rod fits into the central tube included in the top of the tower section, (Figure C.1a). The other platform consists of a flat plate fastened vertically to two legs of the tower section by means of four U-bolts, (Figure C.1b). Vertical motion of these U-bolts is prevented by the lap bracing of the tower section.

FIGURE C.1. Rotating Boom Mounting Plates

APPENDIX D

APPENDIX D

TURBULENCE MEASUREMENTS WITH FILM ANEMOMETERS

VOLTAGE-WIND VELOCITY RELATION

Heat loss from a circular cylinder has been found to be a function of the mean flow velocity. The heat transfer also varies around the circumference of the cylinder, as well as the angle the flow makes with the axis of the cylinder (Sandborn 1972). The heat transfer is also affected to a lesser degree by the flow temperature and density. As shown by Sandborn, the output voltage from a circular cylinder anemometer can be written as

$$e = \frac{dE}{du} u_t + \frac{1}{u} \frac{dE}{d\alpha} u_\alpha \quad (D.1)$$

where the velocities u_t and u_α are defined for the coordinates shown in Figure D.1.

FIGURE D.1. Coordinates for Split-Film and Circular Cylinder Film Probes

The velocity ($Su_t \equiv dE/dU$) and angle ($Su_\alpha \equiv 1/U dE/dU$) sensitivities were introduced and evaluated for yawed hot wires by Sandborn (1972). These sensitivities must be determined by a calibration procedure in order to obtain the linear relation, as in equation (D.1) (the fluctuating velocities need to be small compared to the mean velocity). For the present application the mean velocity is approximately equal to the tangential velocity of the sensor. Figure D.2 is a typical calibration map for a split-film sensor employed on the rotating boom (see next section for details of the calibration). The mean voltage is a measure of the power ($E \propto I^2$ for R constant) required to maintain the particular sensor at a constant temperature (and thus a constant sensor resistance). The sensors were maintained at instantaneous constant temperatures by modular, electronic, constant temperature anemometer circuits. These electronic circuits can maintain the sensor temperature constant under the stress of heat transfer fluctuations to at least 10,000 Hz. From the calibration curves shown on Figure D.2, the sensitivities Su_t and Su_α were obtained by graphic differentiation. The values of Su_t and Su_α in the area of interest for the present rotating boom tests are shown on the insert, Figure D.2.

The output of the two split-film sensors may be written as

$$\begin{aligned} e_1 &= Su_{t_1} u_t + Su_{\alpha_1} u_\alpha \\ e_2 &= Su_{t_2} u_t + Su_{\alpha_2} u_\alpha \end{aligned} \quad (D.2)$$

Whether u_α or u_r is sensed by the probe depends on the particular orientation of the sensor, as indicated in Figure D.1. The present evaluation of the turbulent velocities was made with analog instrumentation, since the digital system was not available. The instantaneous voltages can be rewritten in terms of the statistical mean square values (for the axis of the sensors in the t - r plane) as follows

$$\overline{e_1^2} \equiv \frac{1}{T} \int_0^T e_1^2 dt = Su_{t_1}^2 \overline{u_t^2} + 2 Su_{t_1} Su_{\alpha_1} \overline{u_t u_\alpha} + Su_{\alpha_1}^2 \overline{u_\alpha^2}$$

and

$$\overline{e_2^2} = Su_2^2 \overline{u_t^2} + 2 Su_{t_2} Su_{\alpha_2} \overline{u_t u_\alpha} + Su_{\alpha_2}^2 \overline{u_\alpha^2} \quad (D.3)$$

FIGURE D.2. Calibration of a Split-Film Sensor

The squaring process produces three unknown velocity terms, so a third voltage-velocity relation among them is needed. Two voltage-velocity relations can be obtained by computing the mean square of the instantaneous sum and difference of the sensor voltages

$$\overline{(e_1 + e_2)^2} = (Su_{t_1} + Su_{t_2})^2 \overline{u_t^2} + 2(Su_{t_1} + Su_{t_2})(Su_{\alpha_1} + Su_{\alpha_2}) \overline{u_t u_\alpha}$$

$$+ \left(Su_{\alpha_1} + Su_{\alpha_2} \right)^2 \overline{u_{\alpha}^2} ,$$

$$\begin{aligned} \overline{(e_1 - e_2)^2} &= \left(Su_{t_1} - Su_{t_2} \right)^2 \overline{u_t^2} + 2 \left(Su_{t_1} - Su_{t_2} \right) \left(Su_{\alpha_1} - Su_{\alpha_2} \right) \overline{u_t u_{\alpha}} \\ &+ \left(Su_{\alpha_1} - Su_{\alpha_2} \right)^2 \overline{u_{\alpha}^2} . \end{aligned} \quad (D.4)$$

Obviously, all four equations are not necessary to obtain the three unknowns. As can be seen from the calibration curves in Figure D.2, the angle sensitivities for sensor 1 is of an opposite sign to that of sensor 2. If the sensitivities of the two sensors were identical, the instantaneous sum would be directly proportional to the u_t component and the difference would be proportional to the u_{α} component.

For the particular split-film sensor calibration shown in Figure D.2, the sensitivities obtained for the calibration are listed in Table D.1.

TABLE D.1. Split-Film Sensitivities and Corresponding Mean Squared Voltage-Wind Velocity Correlation Relations

Sensitivity Values	Corresponding Set of Voltage, Wind Speed Relations
$Su_{t_1} = 0.0348$ volts/m/s	$\overline{e_1^2} = 1.21 \times 10^{-3} \overline{u_t^2} + 0.277 \overline{u_t u_{\alpha}} + 1.75 \times 10^{-3} \overline{u_{\alpha}^2}$
$Su_{t_2} = 0.0407$ volts/m/s	$\overline{e_2^2} = 1.65 \times 10^{-3} \overline{u_t^2} - 0.272 \overline{u_t u_{\alpha}} + 1.71 \times 10^{-3} \overline{u_{\alpha}^2}$
$Su_{\alpha_1} = 0.0421$ volts/m/s	$\overline{e_1 + e_2^2} = 5.69 \times 10^{-3} \overline{u_t^2} + 1.92 \times 10^{-3} \overline{u_t u_{\alpha}} + 3.41 \times 10^{-7} \overline{u_{\alpha}^2}$
$Su_{\alpha_2} = 0.0413$ volts/m/s	$\overline{e_1 - e_2^2} = 3.49 \times 10^{-5} \overline{u_t^2} - 9.84 \times 10^{-4} \overline{u_t u_{\alpha}} + 6.99 \times 10^{-3} \overline{u_{\alpha}^2}$

For the spectra data plotted on Figure 7, the following relative values of the turbulent term were obtained:

$$G \overline{u_t^2} = 2.24 \text{ (m/s)}$$

$$G \overline{u_\alpha^2} = 1.83 \text{ (m/s)}^2$$

$$G \overline{u_r^2} = 2.42 \text{ (m/s)}^2$$

$$G \overline{u_t u_\alpha} = -0.00142 \text{ (m/s)}^2$$

$$G \overline{u_t u_r} = -0.00428 \text{ (m/s)}^2$$

where G is a gain factor for the amplification associated with the analog instrumentation. It appears that the cross-correlation terms are nearly two orders of magnitude smaller than the velocity components. The velocity components are of the same order of magnitude. For the case considered, the following approximations may be employed:

$$G \overline{u_t^2} \cong \frac{(e_1 + e_2)^2}{5.69 \times 10^{-3}} ; \quad G \overline{u_\alpha^2} \text{ or } G \overline{u_r^2} \cong \frac{(e_1 - e_2)^2}{6.99 \times 10^{-3}} . \quad (D.5)$$

The constants will vary from sensor to sensor. An analysis given by Sandborn (1981) demonstrated that experimental determination of the sensitivities Su_t and Su_α or Su_r had an uncertainty of approximately 15%. Improvements in sensitivity estimates may be expected with improvements in instrumentation and technique.

SENSOR CALIBRATION

A portable calibrator was employed for direct evaluation of the sensors at the site. Figure D.3 is a schematic diagram of the calibrator developed for use in the field. It was desirable to use a calibrator that supplies a

flow identical to that encountered by the sensor. Commercial calibrators employ compressed air supplies that could cause problems with the composition and temperature of the air. Thus, a blower system was built which can supply a steady flow with velocities greater than 60 m/s. The calibrator consists of a small, high-pressure blower that is controlled by a 28-V variable power

FIGURE D.3. Split-Film Calibrator

supply. The velocity in the test section can be controlled by step-switches on the power supply and monitored by measuring the power applied to the blower. The velocity can also be monitored by the static pressure drop along the nozzle.

A special mount is provided for the use of either a split-film or three-dimensional probe, so that variation of the voltage with angle, as well as velocity, can be obtained. It is desirable to calibrate the sensor at the same air temperature as the test conditions. If it is necessary to calibrate

for a widely varying temperature condition, a more detailed calibration is required. In that case, the sensor resistance may be varied, according to Sandborn (1972, page 307), so that the variation in the sensitivities as a function of temperature difference between the sensor and the air is obtained. An independent measure of the air temperature during the actual measurements of wind velocity would be required to correct for the change in sensitivity due to air temperature change. The present tests were for a relatively short boom, so that temperature variations of only a few degrees were observed. For the larger wind turbine tests, a fast response resistance thermometer may be a necessary part of the recorded data.

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APPENDIX E

APPENDIX E

SENSOR MOUNTING AND CONSTANT TEMPERATURE ANEMOMETER PODS

The film probes were mounted on the rotating boom and the Darrieus wind turbine by the mechanisms shown in in Figure E.1. The split-film probes can be adjusted to different distances in front of the rotating blade. For the small rotating boom blade, no difference in the measured turbulent velocity components were observed for a distance from 15 to 35 cm in front of the blade. The three-dimensional probes have a large connection box, which posed a problem in mounting.

FIGURE E.1. Probe Mounting Units

Figure E.2 is a photograph of the anemometer electronics mounted on the rotating boom. The Lucite® box contains three independent anemometer systems.

® Lucite is a trademark of DuPont

FIGURE E.2. Anemometer Pods

The anemometers require 15-V, 1-amp power for each channel. The power is supplied by either independent rechargeable battery packs, which can be mounted directly on the blade, or by an electronic power supply. The rotating boom facility was operated with the power supplied through the slip rings.

Operation of the sensors with the anemometers requires the adjustment of the independent control resistors to establish the hot resistance of the film. The control resistance is set at

$$\text{Control resistance} = 5X (\text{Sensor Operating Res.} + \text{Lead Resistance}) \quad (\text{E.1})$$

The control resistances have scales for setting values directly, although for accurate adjustments it may be desirable to check their values with an ohm meter.

The preliminary instruction manual for the anemometers is included here. No approval or assessment by the U.S. Government is implied by the inclusion of this data.

I. INTRODUCTION

The Model 1750 and 1755 are constant temperature anemometers intended for multichannel applications where cost is a primary concern. The contents of the enclosure are potted in epoxy and are not repairable.

The 1750 and the 1755 are basically the same except the 1750 has a "Trim" control, which allows the frequency response to be optimized for a given cable length.

Both units have a "Gain" control, which is set at the factory for the sensor type (film or wire). The 1755 should require no adjustment of the "Gain" control; however, with the 1750 the "Gain" control and the "Trim" control will probably have to be adjusted slightly to obtain maximum frequency response.

The Model 1750/1755 has protective circuitry to protect the sensor against removal of the control resistor and loss of power. Both units have comparable noise and temperature drift specifications with our bench type anemometers.

II. POWER SUPPLY REQUIREMENTS

The 1750/1755 needs only one power supply: +15 V at 0.7 amp with less than 0.05 V RMS of 120 Hz ripple. If more sensor current is needed, a maximum of 25 V at 1 amp can be used.

If a maximum of 12 V is needed on the bridge voltage output with the normal 15-V power supply, a sensor with an operating resistance of less than 10Ω must be used. With a 25-V supply, to get a maximum of 22 V bridge voltage a sensor less than 13Ω operating resistance must be used.

NOTE: If your power supply has a variable voltage selector, set the power at 15V before turning it on. DO NOT OPERATE AT VOLTAGES BELOW 15V.

III. PROBE AND CONTROL RESISTOR

The bridge resistor in series with the sensor is $20\Omega \pm 0.2\%$ and the bridge ratio is $5:1 \pm 0.1\%$.

The probe and control resistor represent two legs of the anemometer bridge (Figure E.3). The probe is the active sensor and the control resistor sets the operating temperature of the probe. Matching probes and control resistors are often furnished by the vendor and these need only be connected to the proper terminal of the anemometer. Likewise, if the "control resistor" is in fact another temperature sensitive element for temperature compensation, the leads for temperature compensation are simply connected to the control resistor terminal (D and E).

FIGURE E.3. Block Diagram of 1750/1755

Probes purchased from the vendor give the recommended operating resistance on the cover of the box (OP. RES.). To determine the value of the control resistance, this number (plus lead resistance) is multiplied by 5. For example, if

$$\text{OP RES} = 8.3 \text{ ohms} ,$$

$$\text{CONTROL RES} = 5 (8.3 + \text{lead resistance}) \text{ ohms} .$$

The "Trim" control on the 1750 has a finite amount of resistance; the longer the probe cable, the more the resistance. This resistance should be included in the control resistor and can be measured by connecting an ohm meter across B and C on the terminal block with the control resistor removed. This value should be subtracted from the control value needed.

The control resistor used should have a low temperature coefficient and have a 1-W or greater rating for optimum stability.

For customer-furnished probes, the correct operating resistance must be established first:

$$R_H = R_O [1 + \alpha (t_h - t_o)] \quad (\text{E.1})$$

where:

R_H = resistance at operating temperature, t_h

R_O = resistance at ice point temperature, t_o

α = temperature coefficient of resistance.

To use equation (E.1), the sensor resistance, R_O , at the ice point, t_o , must be known as well as the temperature coefficient of resistance, α . Some typical values are given in Table E.1. For an accurate value of t_h , α and R_O must both be measured. It is even better if R_H can be determined directly by exposing the sensor to temperature t_h .

Often the exact temperature is not necessary. Then a simple "overheat ratio" can be decided on and set, where the overheat ratio is:

$$O.H. = R_H/R_C$$

and R_C is the sensor resistance at the temperature of the fluid. In air, typical O.H. ratios are 1.5 for film sensors and 1.8 for tungsten wires. These will give the wire temperature of about 250°C if fluid temperature is about 20°C. Since the sensors normally have to be calibrated anyway, in many applications the precise temperature of the sensor is not important.

TABLE E.1. Approximate Temperature Coefficients of Typical Sensor

	<u>α(ohms/ohm - °C)</u>
Platinum Film Sensors	0.002
Tungsten Wire	0.0042
Platinum Wire	0.0039
Platinum-Iridium Wire	0.0009

IV. MEASURING SENSOR RESISTANCE

Thermal anemometer sensors, particularly fine hot wires, will often heat excessively when measuring their resistance with a standard ohm-meter. If a bench-type anemometer is available, it is best to use that to measure sensor resistance. If not, then the specifications of the ohm meter being used should be checked carefully. A good 5-place digital-voltmeter with resistance-measuring capability is often satisfactory - particularly if the sensor is put in water to increase the rate of heat transfer to its environment.

Two results can happen if too much current is used:

- 1) The sensor heats so the measured resistance is significantly higher than the ambient temperature.
- 2) In the case of a fine wire, actual burnout can occur when some ohm-meters are used.

A rough check on amount of heating is to simply "move" the sensor in the fluid to see if there is a change in measured resistance.

V. OPERATION

Connect the cable for the probe to A and B of the terminal block. If coax cable is used, connect the center conductor to A and shield to B. The type of terminal block that is used allows the wires to be connected without any kind of terminal; slip the wire in and tighten. Connect the control resistor across terminals C and D. The output cable is connected to E and F. (If coax cable is used, connect shield of coax to F.) Connect power supply terminals G and H and turn the power supply on.

NOTE: If your power supply has a variable voltage selector, set the power at 15V before turning it on. DO NOT OPERATE AT VOLTAGES BELOW 15V.

The bridge voltage now should vary with velocity past the sensor. Observe bridge output with oscilloscope to be certain unit is operating in a stable manner at the maximum velocity.

VI. CHECKING FREQUENCY RESPONSE

To check response on a thermal anemometer, putting a current into one side of the bridge has become an accepted technique - especially for hot wires. Figure E.4 shows the electrical connections using a standard signal generator. A square wave at about 1 kHz to 10 kHz will give a suitable step change that repeats for easy viewing on an oscilloscope. The output will be as shown on the simulated trace on Figure E.5. Amplitude of pulse for a wire should be less than 50 mV, and for a film approximately 100 mV. The effective frequency for wires is:

$$f = \frac{1}{1.5 \tau}$$

where τ = time to recover within 3% of the initial value.

For hot films, the proper adjustment is less clear, since the pulse does not immediately return all the way to the initial value. Even so, recent evidence suggests that if τ is taken as the pulse width, the following equation gives reasonable results:

$$f = \frac{1}{\tau}$$

FIGURE E.4. Frequency Response Test Connections

WIRE SENSOR

FILM SENSOR

FIGURE E.5. Signal Outputs for Square Wave Test

APPENDIX F

APPENDIX F

MICROCOMPUTER-BASED DATA ACQUISITION SYSTEM

The requirement for a system to digitize and store hot-film anemometer data obtained from the rotating boom facility was met by a digital computer system interfaced with a 9-track digital recorder. Original specifications called for a system to digitize data at a rate of 100, 12-or-more bit samples per second for each of six channels. Record lengths of about 30 minutes were required.

A schematic outline of the 1/10 system is provided in the user's guide supplied with the unit.

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