Anemometer Performance Determined by ASTM Methods

THOMAS J. LOCKHART

Meteorological Standards Institute, Fox Island, WA 98333

(Manuscript received 25 January 1986, in final form 19 August 1986)

ABSTRACT

Standard methods are tested for determining the starting threshold, distance constant, transfer function and off-axis response of an anemometer. This first use of the draft ASTM method provides data on the performance of a unique anemometer and experience with the test method. Consequently, changes in the test method are suggested.

1. Introduction

The purpose of the ASTM program (Hoehne, 1984 and Snow, 1985) is to develop, among other things, standard methods for testing meteorological instruments and standard definitions of performance terms. A standard method for measuring surface wind has been published (ASTM, 1985). Finkelstein (1981) tested a draft version of a standard wind vane performance test. The test reported in this paper is based on a draft version of an ASTM standard anemometer performance test.

When standard tests are recognized or required, it will be possible to make meaningful comparisons of different sensor designs operating in a controlled environment, such as a wind tunnel. Furthermore, it will be possible to estimate errors likely from turbulent flow or off-axis flow in the real atmosphere.

As it is with all ASTM standards, the volunteer effort of many people is merged, without personal recognition, into a consensus draft. The draft is balloted by the subcommittee of experts, then by the general committee and finally by the society as a whole. Only when there are no negative votes extant will the society publish the standard. Once published, the standard must be reaffirmed by the same process every 5 years or dropped. Some of the individuals who contributed to this anemometer draft method are identified in the acknowledgment section.

The opportunity to try the test method was facilitated by Pacific Gas & Electric Company (PG&E), who sponsored the tests and whose Hydro-Tech anemometer was supplied for the test. The wind tunnel facility was made available by the University of Washington and by the Pacific Marine Environmental Laboratory (PMEL) of the National Oceanic & Atmospheric Administration (NOAA). The data and summarizations presented here are solely the responsibility of the author.

The starting threshold, distance constant, transfer function and off-axis response of the anemometer are described separately. The method for determining each characteristic is explained. Test results are given and discussed.

It will help to understand the test designs if one keeps in mind how a cup anemometer works. While the Hydro-Tech design is not really a "cup" anemometer, it operates on similar principles. The rate of rotation, expressed in revolutions per second (rps), results from the torque caused by the aerodynamic forces of lift and drag on the turning shape. When well above threshold speeds, the relationship (transfer function) between the rps and wind speed, expressed in meters per second, is roughly linear and is independent of air density. The density independence applies to both the transfer function determination and the off-axis response test.

The torque available to turn the anemometer shaft increases as the square of the wind speed (Lockhart, 1985). When the torque available from the net wind force is greater than the starting torque required to turn the bearing assembly (including the transducer load, if any), the cup wheel and shaft will turn. This relates to starting threshold. The torque available at speeds beyond the threshold (5 and 10 m s^{-1} in the ASTM method), working on the mass and load which needs to be turned will determine the time it takes to accelerate 63.2% $(1 - 1/e)$ within the step-change from zero to the test speed. That time at that speed helps determine the distance constant. Both of these torque or force-dependent characteristics are sensitive to air density.

2. Description of the wind tunnel

This wind tunnel was originally located in the Atmospheric Sciences department on the campus of the University of Washington (UW). It was moved to a hangar at the NOAA facility at Sand Point, some three

---

miles north of the campus, and placed under the operational control of PMEL. It is a low speed tunnel with capability of achieving speeds of about 25 m s^{-1}. It uses a centrifugal air pump ("squirrel cage") to push the air through straighteners, screens and a nozzle into the test section (0.92 m wide by 1.10 m high) which is several meters long.

Wind speed is determined by a transfer standard anemometer (Beckman & Whitley Model 170-41, s/n E-97 cup on Model X348-2, s/n 110 bearing assembly) which had been calibrated by the National Bureau of Standards (NBS). For these tests, relative speed stability was determined from measurements of the rps of the fan motor so that tests could be conducted with the transfer standard out of the test section.

A further qualification of the wind tunnel results from the two tests conducted with an R. M. Young propeller anemometer used as the transfer standard in a round-robin wind tunnel calibration test program. This program, sponsored by the author, is designed to interrelate the major wind tunnels used for anemometer calibration. The NBS wind tunnel has been tested twice in this program. The UW/PMEL tunnel was tested while the tunnel was on campus and again after it had been moved to its new location. Since it is an open-return design, there needed to be some justification for claiming proper operation in the new environment. No difference was detected in the ability of the tunnel to develop a stable mean wind speed.

During the second round-robin test, a simple vertical profile of the center of the test section was measured in anticipation of the off-axis tests needed in the test reported here. The propeller (0.18 m diameter) was mounted in the center of the tunnel with its hub at various heights above the test section floor. Table 1 lists the results. While the difference seems organized in height, it is also organized in time. The tunnel slowly changes speed as the servo control hunts for a null. If the boundary layer were being felt with the propeller tip only 0.06 m from the floor (No. 5), one would expect a decrease and not an increase in speed. In any case, the profile seems uniform enough for the anticipated tests.

TABLE 1. Vertical profile test.

Test no.	Hub height (m)	Tip height (m)	Rate of rotation (rps)	Wind speed (m s^{-1})	Difference from 6.69 m s^{-1} (m s^{-1})	(%)
1	0.635	0.545	22.20	6.67	−0.02	−0.3
2	0.508	0.418	22.20	6.67	−0.02	−0.3
3	0.381	0.228	22.17	6.67	−0.02	−0.3
4	0.254	0.164	22.32	6.71	0.02	0.3
5	0.152	0.062	22.40	6.73	0.04	0.6

3. The Hydro-Tech Model WS-3

This unique and sturdy anemometer, manufactured by Hydro-Tech (Seattle, Wash.) is designed specifically to operate in hostile environments where freezing water has caused other designs to be either inoperative or inaccurate. It uses electric power to heat the rotor assembly sufficiently to keep it free from ice accumulation under all natural conditions. Figure 1 shows how the anemometer appears.

The rotating aerodynamic shape is a cylinder, 0.203 m in diameter and 0.083 m high, with six vane-cups welded around the edge of the cylinder at 60 deg points. The vane-cups, 180 deg sections of a cylinder with a 0.038 m radius, are 0.05 m long. They are attached with the curvature oriented to "catch the wind." The weight of the rotating assembly is 1.044 kg.

The manufacturer offers a choice between two methods for measuring rate of rotation. One is an electrical tachometer with a voltage output proportional to rate of rotation and speed. The other is a revolution detector providing a switch closure at each revolution. The PG&E unit (serial no. 55) was the latter type, but for one sample of the threshold test and all the response distance tests the switch closure assembly was replaced with a tachometer.

4. Starting threshold

The starting threshold (U_0) is defined as "the lowest wind speed at which a rotating anemometer starts and continues to turn and produce a measurable signal when mounted in its normal position." The procedure does not specify a starting orientation of the cups, although it is recognized (Lockhart, 1978) that with some cup anemometers, the torque varies by a factor of 2 with orientation.

The method requires the tunnel speed to be increased slowly until the threshold is reached, at which time the tunnel speed and the anemometer output are recorded. The method requires ten samples. Only five samples were taken during this test, and these represented three different configurations. Configuration No. 1 used the tachometer for output. The objective of this sample was to find the effect of the tachometer load on the threshold. The at-rest orientation of the cups was not noted for this test. Configuration No. 2 used the switch assembly for output and had the rotor set with two of the six vanes ("cups") aligned along the tunnel center line. Configuration No. 3 used the switch assembly for output and had the rotor set with two vanes aligned perpendicular to the tunnel center line.

Table 2 provides the results of the starting threshold test along with an indication of speed increment used in approaching the threshold. The wind speed (No. 3) is the one during which the rotor began turning. Wind speed No. 4 is the same speed during which a 60-second count of the anemometer rotation was taken. A special sample (Test No. 6) relevant to threshold was run during the transfer function test series, between tests 20

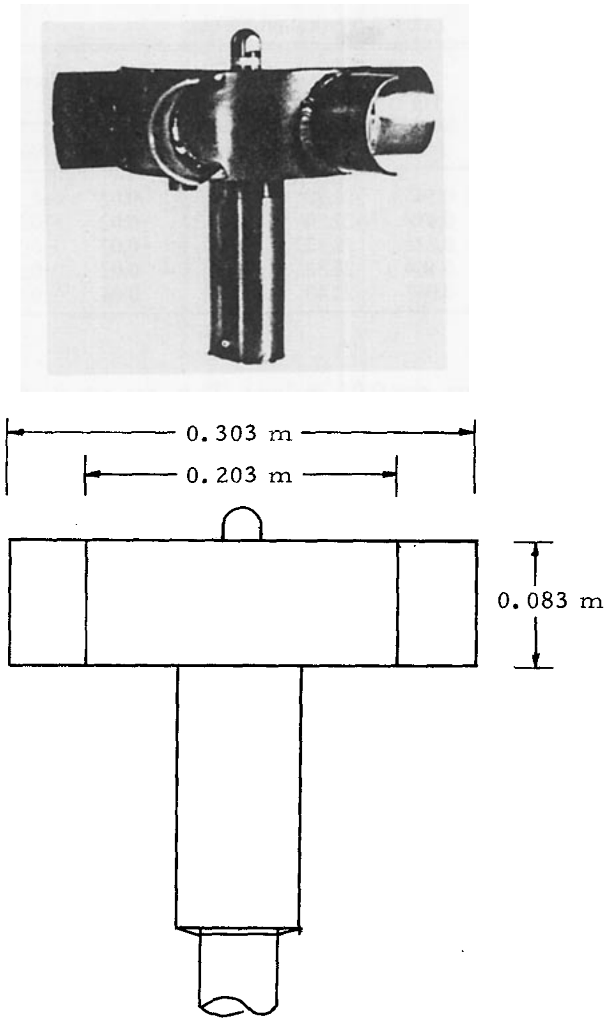

FIG. 1. The Hydro-Tech Model WS-3 Anemometer.

and 21. The tunnel was run at speeds well below the threshold to find the lowest speed at which the rotor continued to turn, i.e., a sort of stopping speed.

Since it is unlikely that the direction of light winds will be steady at the configuration No. 3 and since the stopping speed was so much lower than the starting speed, it was decided by the author to use the average of configuration No. 2 as the starting threshold for this instrument. While this is probably a realistic value, more specific requirements are needed for the method.

$$\text{starting threshold} = 2.2\ \mathrm{m\ s^{-1}}$$

at $1.20\ \mathrm{kg\ m^{-3}}$

5. Distance constant

The distance constant (L) is defined as "the distance the air flows past a rotating anemometer during the time it takes the cup wheel or propeller to reach $(1 - 1/e)$ or 63% of the equilibrium speed after a step change in wind speed." The wind tunnel test procedure uses a steady flow with the anemometer restrained from turning. A quick release from the restraint simulates an increasing step function in wind speed. Since the initial condition is a forced stall, the first 5 or 10% of the response motion is not a good simulation of response to a step function. The ASTM method uses the time in seconds from a 30 to a 74.2% change toward the equilibrium speed, times the wind speed in meters per second to determine L.

The method requires ten samples at about 5 m $\mathrm{s^{-1}}$ and ten more at about 10 m $\mathrm{s^{-1}}$. The average of the 20 samples is the distance constant. The average distance constant at each speed must be within 10% of the average of the 20 samples for the test to be valid.

Since the time between two points on the response curve is being measured, a tachometer providing a voltage was used for the anemometer output. The voltage was recorded on a rectilinear Brush recorder with suitably fast chart speed. The equilibrium speed was found for each test. The 30 and 74.2% points were marked, and the time measured between the marks. The recorder had 1 sec event marks which were necessary since the chart speed was not perfectly constant. Table 3 lists the results of the measurements and Fig. 2 is an example of a recording showing the measurement procedure.

TABLE 2. Starting threshold.

Test no.	Configuration no.	Wind speed No. 1 (m $\mathrm{s^{-1}}$)	Wind speed No. 2 (m $\mathrm{s^{-1}}$)	Wind speed No. 3 (m $\mathrm{s^{-1}}$)	Wind speed No. 4 (m $\mathrm{s^{-1}}$)	Output Speed (rpm)	Output No. 4 (m $\mathrm{s^{-1}}$)	Error Speed (m $\mathrm{s^{-1}}$)	Error No. 4 (%)
1	1	3.50	3.71	3.86	n/a	n/a	n/a	n/a	n/a
2	2	1.88	2.05	2.30	2.28	35	1.75	−0.53	−23
3*	2	1.89	2.07	2.18	2.19	30	1.49	−0.70	−32
4	3	3.30	3.42	3.53	3.52	61	3.14	−0.38	−11
5	3	3.51	3.62	3.72	3.73	66	3.40	−0.33	−9
6	—				1.31	6.5	0.24	−1.07	−82

* Indicates vibration present from passing fork lift.

TABLE 3. Distance constant results.

Test no.	Time (sec)	Wind speed (m s^{-1})	L (m)	Test no.	Time (sec)	Wind speed (m s^{-1})	L (m)
1	11.8	5.06	59.7	11	6.33	9.55	60.4
2	11.4	5.06	57.7	12	6.10	9.55	58.3
3	11.7	5.06	59.2	13	6.16	9.55	58.5
4	11.5	5.07	58.3	14	5.77	9.55	55.1
5	11.5	5.08	58.4	15	6.10	9.54	58.2
6	11.55	5.08	58.7	16	5.85	9.54	55.8
7	11.05	5.08	56.1	17	6.00	9.54	57.2
8	11.00	5.07	55.8	18	5.80	9.55	55.4
9	11.45	5.07	58.0	19	5.95	9.55	56.8
10	11.10	5.07	56.3	20	5.85	9.55	55.9
Average			57.8				57.2
Standard deviation			1.3				1.7

Since the two averages are within 10% of 57.5 m (actually they are within 1%; the 10% was an estimate of what should be acceptable without the test experience upon which to base the expectation), the measurement is valid. The variability between samples is more likely a consequence of the data reduction method than a true variability in L.

Distance constant = 57.5 m at 1.20 kg m^{-3}.

6. Transfer function

The transfer function

$$\hat{U}_f = a + bR,$$

where

$\hat{U}_f$ predicted wind tunnel speed (m s^{-1})
R anemometer rate of rotation (rps)
a and b constants for line of regression of U_f on R

is "the linear relationship between the wind tunnel speed and the rate of rotation of the anemometer throughout the specified working range." The method selects ten target speeds. The five highest speeds, spaced within the operating range and within the wind tunnel capability, define the transfer function. The other five speeds define the low range where the response goes from nonlinear, because of bearing friction near threshold, to linear as the available torque becomes large compared to the torque needed to achieve the aerodynamically determined rate of rotation. A transfer function may be chosen in a variety of ways (Lockhart, 1977). This method intends to isolate the threshold points from influencing the linear regression.

Each speed is used four times, twice in increasing order and twice in decreasing order. No two tests at the same speed are run consecutively (except 10–11 and 30–31; the tunnel was turned off between 20–21). This is to provide independent tests at each speed rather than four samples at the same speed. There have been reports of differences in NBS calibrations depending upon whether the test speeds were reached in increasing

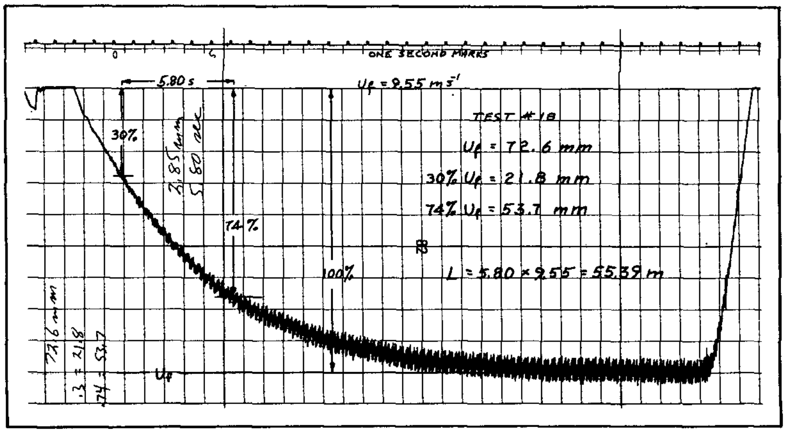

FIG. 2. Distance constant test No. 18 showing how the time constant points were located, measured in millimeters on the chart paper, converted to seconds, and multiplied by the wind tunnel speed to find L.

or decreasing order. The repeat tests are designed to detect this phenomena if it is real.

Table 4 lists the 40 2-min average runs and the five 1-min off-axis runs when the anemometer was vertical (OA1, 8, 15, 16 and 30). The 22 values between 9.88 and 20.25 m s^{-1} were used in a least-squares linear regression analysis (Taylor, 1982). The constants from this analysis are

$$a = -0.010 \pm 0.366 \, \mathrm{m\,s^{-1}}$$
$$b = 3.163 \pm 0.008 \, \mathrm{mpr}$$

and the transfer function is therefore

$$\hat{U}_f = (-0.010 + 3.163R) \pm 0.04 \, \mathrm{m\,s^{-1}}.$$

The error estimates are one standard deviation, calculated by the method described by Taylor (1982). The predicted ($\hat{U}_f$) values in Table 4 are calculated from this expression (carrying the usual computer precision) using the measured rates of rotation for R. The error (E) is then calculated by subtracting the measured speed (of the wind tunnel) from the predicted speed,

TABLE 4. Transfer function data.

Test no.	Target speed (m s^{-1})	U_f tunnel speed (m s^{-1})	$\hat{U}'_f$ est. speed (m s^{-1})	$\hat{E}'$ est. error (m s^{-1})	R Sensor revolutions (no.)	R Sensor revolutions (rps)	$\hat{U}_f$ est. speed (m s^{-1})	E est. error (m s^{-1})
1	2	1.97	1.99	0.02	56	0.47	1.47	−0.50
20	2	1.99	1.99	0.00	56	0.47	1.47	−0.52
21	2	1.94	1.99	0.05	56	0.47	1.47	−0.47
40	2	1.97	1.93	−0.04	53	0.44	1.39	−0.58
2	3	2.96	2.92	−0.04	98	0.82	2.57	−0.39
19	3	3.01	3.04	0.03	103	0.86	2.71	−0.30
22	3	2.96	2.99	0.03	101	0.84	2.65	−0.31
39	3	3.02	3.02	0.00	102	0.85	2.68	−0.34
3	4	3.97	3.90	−0.07	139	1.16	3.65	−0.32
18	4	4.06	4.07	0.01	146	1.22	3.84	−0.22
23	4	3.98	3.99	0.01	143	1.19	3.76	−0.22
38	4	4.05	4.04	−0.01	145	1.21	3.81	−0.24
OA1	5	4.98	4.95	−0.03	182	1.52	4.79	−0.19
OA8	5	4.94	4.95	0.01	182	1.52	4.79	−0.15
OA15	5	4.94	4.95	0.01	182	1.52	4.79	−0.15
4	6	5.90	5.89	−0.01	220	1.83	5.79	−0.11
17	6	6.01	6.04	0.03	226	1.88	5.95	−0.06
24	6	5.99	5.99	0.00	224	1.87	5.89	−0.10
37	6	6.04	6.07	0.03	227	1.89	5.97	−0.07
$N = 19$								
			$\hat{U}_f$	E				
5	8	8.02	7.98	−0.04	303	2.53		
16	8	8.03	8.00	−0.03	304	2.53		
25	8	8.01	7.95	−0.06	302	2.52		
36	8	8.08	8.03	−0.05	305	2.54		
6	10	9.93	9.90	−0.03	376	3.13		
15	10	9.97	10.01	0.04	380	3.17		
26	10	9.88	9.90	0.02	376	3.13		
35	10	10.01	10.03	0.02	381	3.18		
OA16	10	10.10	10.06	−0.04	382	3.18		
OA30	10	10.01	10.01	0.00	380	3.17		
7	12.5	12.60	12.56	−0.04	477	3.98		
14	12.5	12.54	12.48	−0.06	474	3.95		
27	12.5	12.52	12.48	−0.04	474	3.95		
34	12.5	12.45	12.43	−0.02	472	3.93		
8	15	14.98	15.07	0.09	572	4.77		
13	15	15.05	15.04	−0.01	571	4.76		
28	15	15.01	15.12	0.11	574	4.78		
33	15	14.98	14.99	0.01	569	4.74		
9	17.5	17.66	17.70	0.04	672	5.60		
12	17.5	17.47	17.47	0.00	663	5.53		
29	17.5	17.48	17.49	0.01	664	5.53		
32	17.5	17.53	17.52	−0.01	665	5.54		
10	20	20.17	20.15	−0.02	765	6.38		
11	20	20.25	20.23	−0.02	768	6.40		
30	20	20.12	20.10	−0.02	763	6.36		
31	20	20.14	20.10	−0.04	763	6.36		
$N = 22$								

KEY:

$\hat{U}_f = a + bR$

$E = \hat{U}_f - U_f$

$\hat{E} = a' + b'[\ln \hat{U}_f]$

$\hat{U}'_f = \hat{U}_f - \hat{E}$

$\hat{E}' = \hat{U}'_f - U_f$

$a = -0.010 \pm 0.366$

$b = 3.163 \pm 0.008$

$a' = -0.638 \pm 0.019$

$b' = 0.305 \pm 0.014$

assuming the measured speed to be the true value. The column in Table 4 headed "E" describes how well the transfer function fits the nonthreshold speeds and what errors are found at threshold speeds.

When considering how to graph these data, U_f vs E, the curve of the threshold errors suggested an exponential function. When the data were plotted as $\ln(U_f)$ vs E, the threshold errors looked linear. This seemed reasonable since the torque developed from the force of the air on the aerodynamic shape increases as the square of the wind speed. To test this hypothesis, another least-squares linear regression analysis was tried. This time a conditional transfer function

$$\hat{E} = a' + b' \ln(\hat{U}_f)$$

where

$\hat{E}$	the predicted error (m s^{-1})
$\hat{U}_f$	$a + bR$ (m s^{-1})
a' and b'	constants for line of regression of E on $\ln(\hat{U}_f)$

was found. The condition for application is for speeds lower than where E is zero. The data used for this second analysis were the 16 tests between 1.94 and 6.04 m s^{-1} and the three off-axis tests at about 5 m s^{-1} when the sensor was vertical. The 8 m s^{-1} samples were not used because it was not originally clear which side of the transition point that speed would fall.

The constants from this second analysis are

$$a' = -0.638 \pm 0.019 \text{ m s}^{-1}$$

$$b' = 0.305 \pm 0.014 \text{ m s}^{-1},$$

and the conditional transfer function is therefore

$$\hat{E} = (-0.638 + 0.305 \ln(\hat{U}_f) \pm 0.031 \text{ m s}^{-1}.$$

The speed at which the predicted error is zero is

$$\hat{U}_f = \exp(0.638/0.305) = 8.1 \text{ m s}^{-1}.$$

Given these two expressions and the condition for the use of the second one, a new transfer function covering the entire range can be written as follows:

$$\text{if} \quad (a + bR) > 8.1, \quad \hat{U}_f = a + bR$$

if not,

$$\hat{U}'_f = (a + bR) - [a' + b' \ln(a + bR)].$$

The results of this conditional expression are listed in Table 4 and plotted in Fig. 3 with error bars at one standard deviation.

7. Off-axis response

The ASTM draft method requires a cup anemometer to be tested with its normally vertical axis of rotation tilted over a range of ±30 deg, into (minus) and away from (plus) the flow. The definition is "$(U/U_f\cos\theta)$—the ratio of the indicated wind speed (U) at various angles of attack (θ) to the indicated wind speed at zero

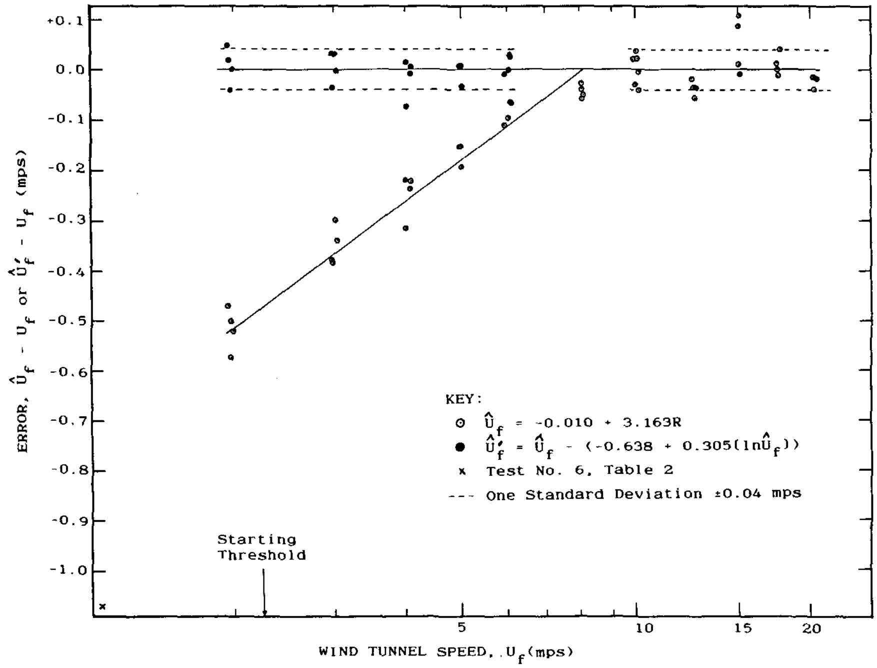

FIG. 3. The transfer function, defining the relationship between rate of rotation and wind speed, is shown along with the error encountered using this function in the threshold range. A two-step transfer function correcting for the threshold error is also shown.

angle of attack (U_f), multiplied by the cosine of the angle of attack." This definition compares the instrument response to a cosine response or, put another way, compares the instrument response to the horizontal component of the mean flow. It is an arbitrary choice based on the presumed belief that cup anemometers measure the horizontal component of the wind when they are rotating in a horizontal plane. The data are shown in Fig. 4 with respect to the horizontal component, with the contribution of the cosine of the angle also shown.

A fixture in the UW/PMEL wind tunnel provides a rigid mount which can be tilted through the range required. The resolution of the indicator marks is 1 deg. The degree marks are about 0.2 cm apart, allowing for easy interpolation to 0.1 deg. (The index lines are finely engraved so that setting to even-degree positions can be made to much better than 0.1 deg.) Even at 20 m s^{-1} there was no detectable change in tilt angle from wind force. The zero position was set and verified with a level.

There are two concerns with the off-axis test. Since the fixture tilts forward and back, the sensor mounted on its top senses air from lower in the test section as the angle increases. It is necessary to be sure that the test section profile is uniform so that the same speed is found no matter what the height of the test sensor is above the tunnel floor. The profile test in Table 1 satisfies this requirement.

The conventional practice utilized to find the tunnel wind speed is to use the transfer standard (cup anemometer; see section 2) during the test or use it before and after the test, assuming the tunnel speed is constant during the test. This was the practice during the transfer function test since there was no detectable wake from the small cup on the subject anemometer. A different strategy was necessary for the off-axis test because the wake from the transfer standard would surely affect the subject anemometer at the larger tilt angles.

The tunnel speed was monitored by measuring the rate of rotation of the motor which drives the air through the tunnel. Each revolution of the motor shaft was detected by a counter, called FAN. During the transfer function tests, data were collected from FAN during the same 120 sec used for counting the revolutions of the subject anemometer and the transfer standard anemometer. A least-squares linear regression analysis was done for the 28 samples between 4.94 and 17.66 m s^{-1}. The FAN counts, expressed as Rf (rps), were used to estimate the wind tunnel speed $\hat{U}_f$ (m s^{-1}) without the presence of the transfer standard. The constants from this analysis are

$$a'' = -0.3127 \pm 0.016\,\mathrm{m\,s^{-1}},$$

$$b'' = 0.2724 \pm 0.0004\,\mathrm{m\,s^{-1}},$$

and the transfer function is therefore

$$\hat{U}_f = (-0.3127 + 0.2724Rf) \pm 0.03\,\mathrm{m\,s^{-1}}.$$

Note that either transfer function (using R from the test anemometer or using Rf from the fan rotation) estimates the tunnel speed to better than 0.1 m s^{-1} based on the same NBS calibrated transfer standard. The speed used as $\hat{U}_f$ during the off-axis test was that calculated by this expression using Rf (FAN rate) as input. During the six 0-deg samples, the transfer standard was in the tunnel. The average of the three low speed samples was 5.00 m s^{-1} from the transfer standard and 4.95 m s^{-1} calculated from FAN. At the higher speed, the average was 10.10 m s^{-1} from the transfer standard and 10.08 m s^{-1} from FAN.

The regular off-axis tests, 15 samples taken at each of two speeds, requires about 30 min at each speed.

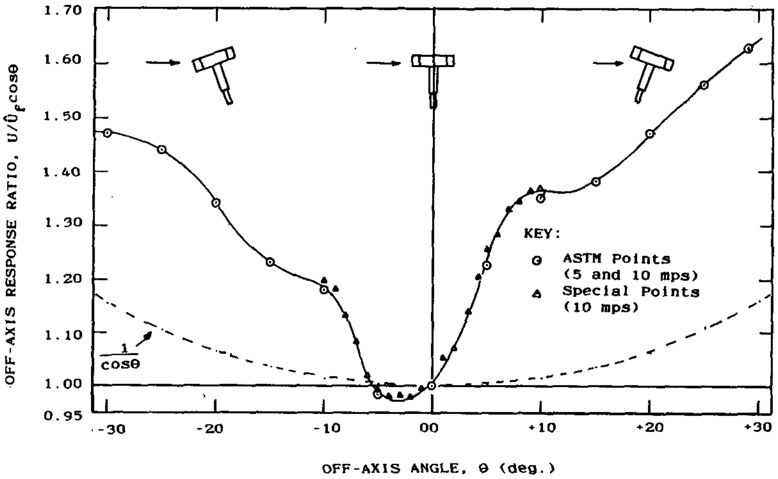

FIG. 4. The off-axis response is the ratio of the sensor output to the horizontal component of the wind when the mean wind direction is not horizontal. The contribution of cosine θ to the over-estimation of the speed is also shown.

During the 30 min, the tunnel speed controls are untouched and the data are taken for 60 sec every other minute. This provides two measures of tunnel speed stability. The mean at the low speed was 4.96 m s^{-1} with a standard deviation of 0.02 m s^{-1} (14 samples with a range of 4.93 to 4.99, or 0.06 m s^{-1}). At the higher speed, the mean was 10.07 m s^{-1} with a standard deviation of 0.08 m s^{-1} (15 samples with a range of 9.98 to 10.23, or 0.25 m s^{-1}).

The results of the off-axis test are listed in Table 5. It was clear during the test that the off-axis ratios were both large and asymmetrical. For this reason a series of short tests (approximately 30 sec per 10 sec recording) were made at 10 m s^{-1} for each one-deg position within ±10 deg from vertical. At this speed, 30 sec represents at least five distance constants.

The ASTM method chooses 5 and 10 m s^{-1} as test speeds above the nonlinearity of the threshold of anemometers. For this anemometer, however, there is still a 3.5% underestimation from the linear regression

TABLE 5. Off-axis response.

Test no.	θ angle (deg)	FAN (no.)	Rf revs. (rps)	$\hat{U}_f$ speed (m s^{-1})	R sensor (rps)	U speed (m s^{-1})	$U'/\hat{U}_f$ ratio	$U'/\hat{U}_f\cos\theta$ ratio
OA1	00	1167	19.45	4.99	1.517	4.79	0.99	0.99
OA2	−05	1164	19.40	4.97	1.467	4.63	0.96	0.96
OA3	−10	1165	19.42	4.98	1.783	5.63	1.16	1.18
OA4	−15	1167	19.45	4.99	1.800	5.68	1.17	1.21
OA5	−20	1154	19.23	4.93	1.883	5.95	1.24	1.32
OA6	−25	1156	19.27	4.94	1.950	6.16	1.28	1.41
OA7	−30	1159	19.32	4.95	1.883	5.95	1.23	1.42
OA8	00	1157	19.28	4.94	1.517	4.79	1.00	1.00
OA9	+05	1162	19.37	4.96	1.933	6.10	1.26	1.26
OA10	+10	1164	19.40	4.97	2.017	6.37	1.31	1.33
OA11	+15	M		4.96*	2.017	6.37	1.32	1.37
OA12	+20	1168	19.47	4.99	2.083	6.58	1.35	1.44
OA13	+25	1167	19.45	4.99	2.117	6.69	1.37	1.51
OA14	+29	1161	19.35	4.96	2.133	6.74	1.39	1.59
OA15	00	1158	19.30	4.94	1.517	4.79	1.00	1.00
							$U/\hat{U}_f$	$U/\hat{U}_f\cos\theta$
OA16	00	2295	38.25	10.11	3.183	10.05	1.00	1.00
OA17	−05	2300	38.33	10.13	3.167	10.00	0.99	0.99
OA18	−10	2308	38.47	10.17	3.750	11.85	1.17	1.19
OA19	−15	2300	38.33	10.13	3.817	12.06	1.19	1.23
OA20	−20	2305	38.42	10.15	4.083	12.90	1.27	1.35
OA21	−25	2291	38.18	10.09	4.200	13.27	1.32	1.46
OA22	−30	2323	38.72	10.23	4.200	13.27	1.30	1.50
OA23	00	2301	38.35	10.13	3.217	10.16	1.00	1.00
OA24	+05	2271	37.85	10.00	3.883	12.27	1.23	1.23
OA25	+10	2268	37.80	9.98	4.200	13.27	1.33	1.35
OA26	+15	2269	37.82	9.99	4.200	13.27	1.33	1.38
OA27	+20	2275	37.92	10.02	4.433	14.01	1.40	1.49
OA28	+25	2288	38.13	10.07	4.567	14.43	1.43	1.58
OA29	+29	2268	37.80	9.98	4.533	14.32	1.44	1.65
OA30	00	2276	37.93	10.02	3.167	10.00	1.00	1.00

θ (deg)	U (m s^{-1})	$U/\hat{U}_f$	$U/\hat{U}_f\cos\theta$	θ (deg)	U (m s^{-1})	$U/\hat{U}_f$	$U/\hat{U}_f\cos\theta$
−01	9.94	0.99	0.99	+01	10.50	1.05	1.05
−02	9.76	0.98	0.98	+02	10.67	1.07	1.07
−03	9.80	0.98	0.98	+03	11.37	1.14	1.14
−04	9.77	0.98	0.98	+04	12.00	1.20	1.20
−05	9.86	0.99	0.99	+05	12.49	1.25	1.25
−06	10.11	1.01	1.02	+06	12.75	1.28	1.28
−07	10.73	1.07	1.08	+07	13.19	1.32	1.33
−08	11.26	1.13	1.14	+08	13.31	1.33	1.34
−09	11.66	1.17	1.18	+09	13.45	1.34	1.36
−10	11.79	1.18	1.20	+10	13.45	1.34	1.37

KEY:

$U' = U + 0.16$

$\hat{U}_f = a'' + b''Rf$

$a'' = -0.3127$

$b'' = 0.2724$

$\sigma_{a''} = 0.0157$

$\sigma_{b''} = 0.0004$

* estimated speed

curve at 5 m s^{-1}. To separate this threshold effect from the off-axis response, the indicated speed U was increased at all off-axis angles by 0.16 m s^{-1}. This corrects for the threshold underestimation and forces the ratio to 1.00 at 0 deg, as it should be. At 10 m s^{-1}, $\hat{U}_f$ is used as the ASTM method requires.

8. Summary and conclusions

a. The ASTM test report

The draft ASTM method, modified for practical purposes, provided the following performance characteristics for the Hydro-Tech sensor tested (Model WS-3, s/n 55):

STARTING THRESHOLD

$$U_0 = 2.2\,(+1.5\,\&\,-0.9)\ \mathrm{m\,s^{-1}} \quad (\text{at } 1.20\ \mathrm{kg\,m^{-3}})$$

DISTANCE CONSTANT

$$L = 57.5 \pm 1.5\ \mathrm{m} \quad (\text{at } 1.20\ \mathrm{kg\,m^{-3}})$$

TRANSFER FUNCTION

$$\hat{U}_f = (-0.010 + 3.163R) \pm 0.04\ \mathrm{m\,s^{-1}}$$

$$\hat{U}_f - U_f = 1.45 - 1.97 = -0.52 \pm 0.05\ \mathrm{m\,s^{-1}}$$

$$\hat{U}_f - U_f = 2.65 - 2.99 = -0.34 \pm 0.05\ \mathrm{m\,s^{-1}}$$

$$\hat{U}_f - U_f = 3.77 - 4.01 = -0.25 \pm 0.05\ \mathrm{m\,s^{-1}}$$

$$\hat{U}_f - U_f = 5.90 - 5.98 = -0.08 \pm 0.05\ \mathrm{m\,s^{-1}}$$

$$\hat{U}_f - U_f = 7.99 - 8.03 = -0.04 \pm 0.05\ \mathrm{m\,s^{-1}}$$

OFF-AXIS RESPONSE:

down draft	up draft
−05° = 0.98	+05° = 1.25
−10° = 1.19	+10° = 1.34
−15° = 1.22	+15° = 1.38
−20° = 1.34	+20° = 1.47
−25° = 1.44	+25° = 1.55
−30° = 1.46	+29° = 1.62

This body of information defines the performance of an anemometer in a way that can be duplicated by anyone with a suitable wind tunnel. Numbers resulting from standard tests may be used to compare the sensor performance characteristics of different designs.

b. Response distance constant considerations

There is a second way to simulate a step function change in speed, a decreasing step from some rate of rotation to zero. This distance-constant test is not required in the ASTM method, but there is reason to consider its addition. The difference between L_i determined from an increasing step function and L_d determined from a decreasing step function is caused by the inertia of the rotating shape. When the manufacturer of the Hydro-Tech anemometer performed tests on 18 April 1982 to determine the performance characteristics, both types of step functions were used. An analysis of the curves supplied by Hydro-Tech to customers on request shows the following values:

$$L_i(\text{increasing}) = (5.7\ \mathrm{s})(8.5\ \mathrm{m\,s^{-1}}) = 48.4\ \mathrm{m}$$

$$L_d(\text{decreasing}) = (21.3\ \mathrm{s})(8.5\ \mathrm{m\,s^{-1}}) = 181.0\ \mathrm{m}.$$

The ratio of L_i/L_d, 0.27 in this example, should relate to the potential dynamic overspeeding of the anemometer. The potential dynamic overspeeding is defined here as that overestimation of average wind speed (from arithmetically averaged samples) caused by the inertia of the rotating aerodynamic shape as it reacts to turbulent flow in the atmosphere. This is not to be confused with what is misleadingly called overspeeding in the literature, which combines the effect of sensor dynamics with the difference between scalar and vector averaging in describing the joint overestimation of measured scalar average to a desired resultant vector averaged speed (Izumi and Barad, 1970).

It is suggested that a test for L_d be added to the ASTM method. The proposed method for this additional test is to mechanically rotate the aerodynamic shape at a rate equivalent to the speed used for the determination of L_d, quickly remove the cause of rotation (motor or finger), and record the deceleration of the anemometer in a still environment. The difference in time between the 30 and 74.2% response to the decreasing step change times the equivalent speed is L_d. This test could be conducted in a wind tunnel operating at about 0.3 m s^{-1} to remove the vortex caused by the mechanically driven cups.

c. Transfer function considerations

A further examination of Fig. 3 suggests a different method for expressing the transfer function. The data at the five lower speeds fit a linear relationship between the underestimation error of speed and the logarithm of the true speed. This is consistent with the expectation that the square function is dominant in the starting threshold range.

Section 6 describes the two-step conditional expression. There are two advantages of this method over the ASTM listing of the errors at threshold speeds. One, it is more objective and comprehensive. The ASTM method requires doing something additional with table data to compare anemometers at threshold speeds. The second advantage is that the conditional transfer function can be used operationally to find the wind speed from the anemometer rate of rotation (which is what is really measured) at all speeds. This requires a measurement system with computational capability, an increasingly simple and common capability.

d. Starting threshold considerations

Notice in Fig. 3 that the 2 m s^{-1} test points, while below the "starting threshold" as determined by the method, are still on the straight line. The true threshold may be lower than the 2.2 m s^{-1} yielded by the test. The one point at 1.3 m s^{-1} (Table 2) is well below the straight line, suggesting that the rotor would have stopped at that speed if enough time had been allowed.

e. Other testing considerations

Stability of test conditions is critical. The first value to determine for this method is the distance constant, or perhaps, distance constants. They should represent both increasing and decreasing step functions. No data should be taken before equilibrium is achieved. This condition can be defined as the equivalent time for at least five distance constants of stable wind tunnel flow passing the sensor.

When the method was being written, a report was made of different transfer functions derived from NBS calibrations depending upon whether the test was a series of increasing speeds or a series of decreasing speeds. For this reason both were required in the ASTM method. No physical explanation could be found for such an observation. The author speculates that the cause might have been that a constant period of time was used between wind tunnel speed changes. The time could have been long enough for five distance constants to pass the sensor for increasing speeds but not long enough for five of the longer distance constants to pass the sensor for decreasing speeds. Hence, the sensor could have been at equilibrium for increasing speeds but not quite slowed down enough when data were taken at decreasing speeds.

It would be reasonable for manufacturers to obtain a complete evaluation by the ASTM method on a sample of each configuration intended for sale. Further units of that configuration could be considered to have the same starting threshold (given equal bearing condition and output load), the same distance constant and the same off-axis response. A generic transfer function may be used if a large enough sample of aerodynamic shapes (cup wheels or propellers) is tested to estimate the variation possible within the manufacturing process. Otherwise, a transfer function should be considered a description only of the sensor tested.

Acknowledgments. The test described in this paper was supported by Pacific Gas and Electric Company of San Francisco, California. The wind tunnel was made available by the University of Washington and the NOAA Pacific Marine Environmental Laboratory. The author was assisted by Janet Lockhart at the wind tunnel. Philip L. Taylor of Hydro-Tech was very cooperative and helpful during the tests. The quality of wind tunnel testing that was given the instrument in 1982 by the manufacturer demonstrates a professional attitude and capability.

The ASTM subcommittee D-22.11 developed the draft standard used. Those who contributed to this document include

C. Bruce Baker, Climatronics Corporation
Robert F. Brown, Jr., Teledyne Geotech
Peter L. Finkelstein, EPA (NOAA)/EMSL
Gerald C. Gill, University of Michigan, Professor Emeritus
Saburo Hasegawa, National Bureau of Standards
Walter E. Hoehne, NOAA/NWS, retired
Thomas J. Lockhart, Meteorological Standards Institute
Daniel A. Mazzarella, Science Associates
John T. Snow, Purdue University
Robert N. Swanson, PG&E
Robert M. Young, R. M. Young Co. (author).

Many more contributed by reading the drafts and making informal comments. The first draft of this method is dated September 1980.

REFERENCES

ASTM, 1985: Standard method for measuring wind by means of wind vanes and rotating anemometers, D4480-85. *Amer. Soc. for Testing and Materials,* Philadelphia, 5 pp.

——, 1985a: Standard test method for determining the performance of a cup anemometer or propeller anemometer. Draft No. 6. Subcommittee D-22.11.

Finkelstein, P. L., 1981: Measuring the dynamic performance of wind vanes. *J. Appl. Meteor.,* **20,** 588–594.

Hoehne, W. E., 1984: Development of meteorological standards. *Bull. Amer. Meteor. Soc.,* **65,** 1209–1210.

Izumi, Y., and M. L. Barad, 1970: Wind speeds as measured by cup and sonic anemometers and influenced by tower structure. *J. Appl. Meteor.,* **9,** 851–856.

Lockhart, T. J., 1977: Evaluation of rotational anemometer errors. *Bull. Amer. Meteor. Soc.,* **58,** 962–964.

——, 1978: A field calibration strategy for rotating anemometers and wind vanes. *Proc. Fourth Symp. on Meteorological Observations and Instrumentation,* Denver, 57–60.

——, 1985: Some cup anemometer testing methods. *J. Atmos. Oceanic Technol.,* **2,** 680–683.

Snow, J. T., 1985: Meeting of ASTM Subcommittee D-22.11: Meteorology. *Bull. Amer. Meteor. Soc.,* **66,** 1432.

Taylor, J. R., 1982: An introduction to error analysis, the study of uncertainties in physical measurements. *University Science Books.* [ISBN: 0-935702-07-5].