THE MAXIMUM TYPE 40 ANEMOMETER CALIBRATION PROJECT

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ABSTRACT

The consequence of the series of tests in this project is the convergence of the transfer functions, as found by Otech and Second Wind, to a manageable scatter. When 332 tests by Otech and 140 tests by Second Wind using NRG Maximum Type 40 anemometers with the boot attached are combined, a consensus transfer function is found. It is

Meters per second = 0.765Hz + 0.35 or
Miles per hour = 1.711Hz + 0.78.

The uncertainty attached to the use of the linear regression of offset and slope from calibrations by Otech and Second Wind tests is ±0.1 m/s (±0.2 mph) over a range of 5 to 25 m/s (11 to 56 mph). The consensus transfer function is based on 10 Hz representing 8.00 m/s (17.90 mph). The standard deviation of the scatter about the linear regression line is 0.06 m/s (0.13 mph).

INTRODUCTION

For several years there has been controversy in the wind energy community regarding the calibration of Maximum Type 40 anemometers, which are assembled and sold by NRG Systems, Inc. There are many choices of transfer functions available to users of the Maximum anemometer. These choices include the use of generic, manufacturer-recommended transfer functions and sensor-specific functions supplied by Otech Engineering or Second Wind, Inc. When compared, the choices lead to significant differences in reported wind speed under identical wind conditions. Average differences in reported speed can be as large as eight percent [1], but between individual anemometers the difference can be much larger. Because of the cubic relationship between the wind speed and the power content, such measurement differences amplify the uncertainty when estimating a wind turbine's energy output.

In an attempt to resolve or reduce the differences in Maximum anemometer transfer functions, a team of representatives from the resource assessment, anemometer manufacturing, and anemometer calibration industries was formed. Between December 1996 and November 1997, the team conducted a series of tests at the following anemometer calibration facilities: National Institute of Standards and Technology, Massachusetts Institute of Technology, NOAA/NWS Test and Evaluation Laboratory, R.M. Young Company, NOAA/Pacific Marine Environmental Laboratory/University of Washington, and Otech Engineering. All of the calibration facilities employ wind tunnels with the exception of OTECH Engineering, which uses a test rack mounted on a moving vehicle.

These tests were originally designed to address three hypotheses:

1. Cup anemometers have a transfer function sensitive to the amount of turbulence in the flow. Wind tunnel calibrations may be different from calibrations conducted in the open atmosphere. (Rejected at the resolution of the tests.)

2. The use of a single transfer standard anemometer will decrease the difference in transfer functions seen with different calibration methods and facilities. (Accepted.)

3. The use of individually calibrated anemometers will provide more accurate data than the use of a generic transfer function. (Accepted with qualification.)

The tests also investigated a number of related issues: the relative contribution of calibration test uncertainty due to manufacturing variability among anemometers; the impact of a new boot accessory on the Maximum transfer function; and the influence of blockage on wind tunnel testing.

Commonly used in all calibration tests was a helicoid propeller-type reference anemometer. This single transfer standard provided a relative comparison of the different calibration facilities and can be considered authoritative since it has also been used to evaluate several national standards facilities in the United States and Europe. The Maximum transfer standard anemometer (#300), which has been used as the Type 40 standard since 1987, was also tested in every facility.

PROJECT TEAM COMPOSITION

The following individuals participated in the project experiments or provided peer-review comments or advice:

Principal Investigator	**Thomas J. Lockhart, CCM, CMet,** *Meteorological Standards Institute (MSI)*
Project Manager	**Dr. Bruce H. Bailey, CCM,** *AWS Scientific, Inc. (AWS)*
Project Officer	**Marc N. Schwartz,** *National Renewable Energy Laboratory (NREL)*
Investigator	**Dr. Vern Bean,** *National Institute of Standards and Technology (NIST)*
Investigator	**David Blittersdorf,** *NRG Systems, Inc. (NRG)*
Investigator	**Kenneth E. Cohn,** *Second Wind Inc. (Second Wind)*
Investigator	**Professor Eugene E. Covert,** *Massachusetts Institute of Technology (MIT)*
Investigator	**Hal Link,** *National Renewable Energy Laboratory (NREL)*
Investigator	**John Obermeier, P.E.,** *Otech Engineering (Otech)*
Investigator	**Michael C. Sturgeon,** *NOAA/NWS Test and Evaluation Laboratory (NOAA)*
Investigator	**Robert M. Young,** *R.M. Young company (YOUNG)*

All of the investigators donated part or all of their time and facilities to this project.

HYPOTHESIS 1 - TURBULENCE EFFECT ON CUP TRANSFER FUNCTION

Past data [2] led to the speculation that the presence of turbulence might account for the differences in calibration methods. Data from tests at NIST and Otech Engineering supported this hypothesis, but the tests were not as well designed as possible. These tests, employing three anemometers on a single support structure (see Figure 1), were repeated at NIST and Otech and also run at NOAA and PMEL/UW. The resulting data were useful for understanding some wind tunnel testing problems, such as blockage, but no signal above noise confirmed the hypothesis.

The blockage problem became clear when the transfer standard anemometer, Round-Robin 2 (RR2) [3], showed a different pitch in the 3-anemometer assembly than it did in prior RR2 tests. The difference was only 0.9% in the 3.2 m^2 NIST wind tunnel but it was 1.8% in the 1.5 m^2 NOAA wind tunnel. Double the effect in half the area made a strong case for blockage effect. Since RR2 was 40 cm ahead of the mounting structure and the other anemometers, and since the RR2 produces virtually no blockage itself (see Figure 2), RR2 provides a relative transfer standard for the two cup anemometers in different environments. A substantial fraction of this blockage is due to wake blockage from the support structure.

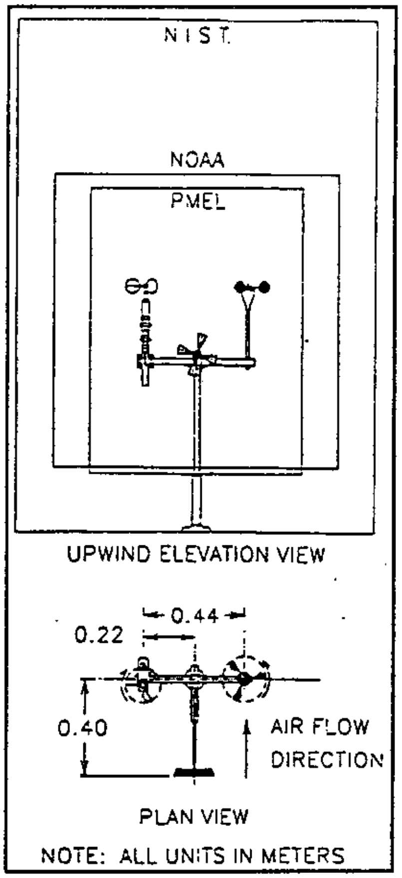


Figure 1
3-Anemometer Configuration

All relative comparisons were made at the speed found from a 10 Hz rate of rotation of #300 with boot. This required finding 259.55 Hz for RR2 and 647.5 mV for the Gill cup to produce zero differences in the NIST wind tunnel. Using these same rates of rotation, #300 was 0.3% faster and the Gill cup was 0.4% slower than RR2 in the NOAA wind tunnel. Is this an edge effect or blockage or the noise of the test uncertainty? In the "free" exposure of the Otech test, #300 was 1.4% slower and the Gill cup was 0.4% slower than RR2. Does this mean that #300 turns 0.7% faster than the Gill cup in a wind tunnel and 1.0% slower than the Gill cup in the "free" environment? There is one other difference. In the wind tunnels, as shown in Figure 1, the cups rotated such that both cups were moving upwind when they are closest together. Unfortunately, in the "free" environment they were reversed where both cups were moving downwind when they are closest together.

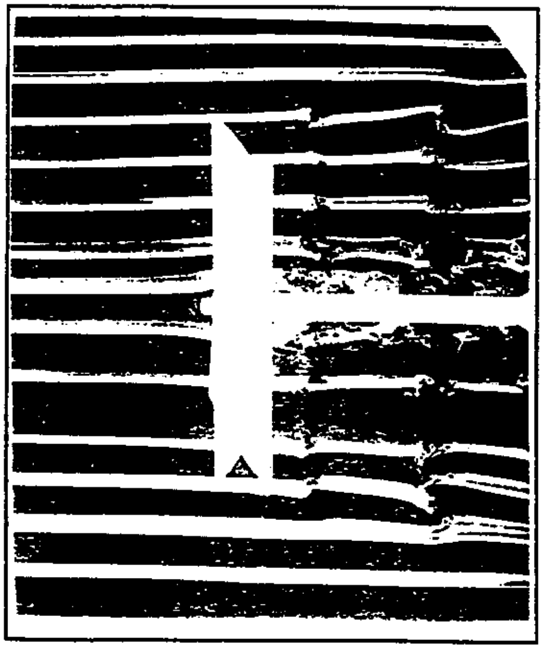


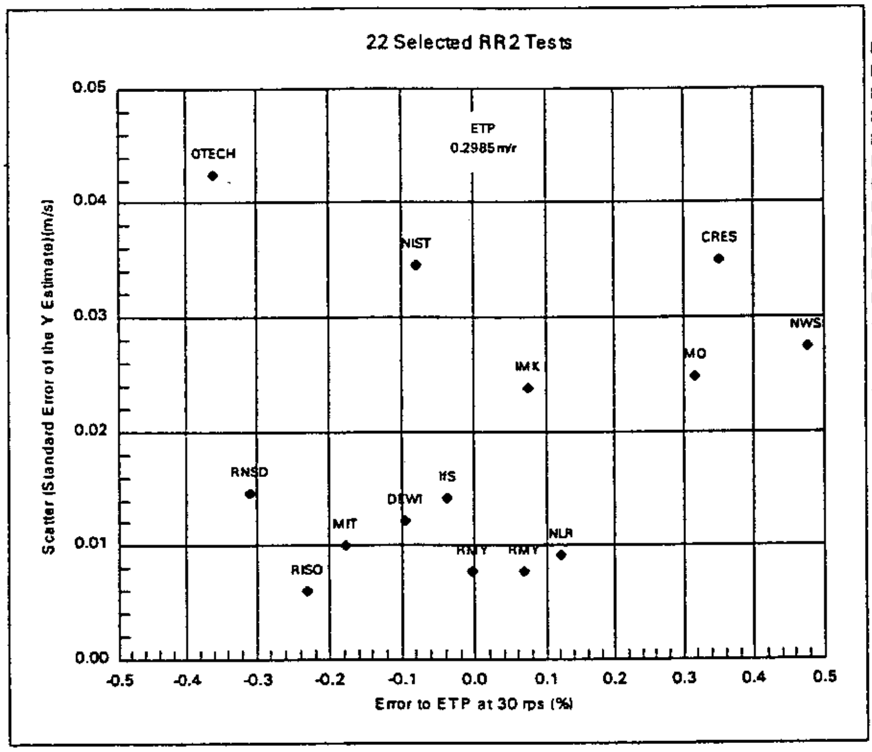
Figure 2
Smoke Streams Through a Helicoid Propeller

The differences are too small and the blockage effects too large to draw any conclusion from these tests, except to warn about blockage in wind tunnels and possible side-by-side influence.

HYPOTHESIS 2 - NORMALIZING TESTS WITH RR2 MINIMIZES DIFFERENCES BETWEEN FACILITIES

When calibration differences exist the first thing to consider is the relative calibration of the facilities. The RR2 experiment provides some background data for estimating calibration facility relative uncertainty. Figure 3 shows 14 of the 22 selected tests which had a difference, at the 30 rps speed, of less than 0.5% from the consensus estimated true pitch (ETP) and a scatter (Standard Error of the Y Estimate) of less than 0.05 m/s. Notice that the MIT value and the Otech value differ by only 0.2%. The difference was 0.8% before the MIT speed was corrected for minor test section variability. A difference of 0.2% at 30 rps or 8.955 m/s is 0.02 m/s.

In addition to ranking these calibration facilities among other commonly used anemometer calibration facilities, the RR2 instrument was used during various tests as a relative transfer standard.



Sorted on scatter (Y est.)

RR2-22	Risoe, Denmark
RR2-1a	R.M. Young (s/n 56341)
RR2-10	R.M. Young (s/n 56341)
RR2-15b	DNW-LST, The Netherlands (NLR)
RR2-14c	MIT Wright Brothers Wind Tunnel
RR2-5	DEWI, Oldenburg, Germany
RR2-18b	WINDTEST - IfS, U of Hamburg
RR2-9b	R.N.S.D. Exeter, UK
RR2-3a	IMK Karlsruhe, Germany
RR2-8b	Met Office, Bracknel, UK
RR2-2	NOAA/NWS, Sterling, VA
RR2-11b	NOAA/NWS, Sterling, VA
RR2-12	NIST, Gaithersburg, MD
RR2-23	CRES, Pikermi/Athens, Greece
RR2-20	Met One, Dallas, Texas
RR2-16a	OTECH Engineering, Davis, CA
RR2-7	DWD, Hamburg, Germany
RR2-6b	DWD, Munich, Germany
RR2-4	ZMK, Hamburg U , Germany
RR2-13b	Meteo France, Saint-Cyr
RR2-17	NEL, Glasgow, Scotland
RR2-19b	CIEMAT - U. Politecnia de Madrid

Figure 3
Round-Robin 2 Analysis

HYPOTHESIS 3 - INDIVIDUAL CALIBRATION IS MORE ACCURATE THAN GENERIC CALIBRATION

The first test for this hypothesis was a single speed calibration of 99 new NRG Maximum Type 40 anemometers with boots. The wind tunnel was set at about 7.6 m/s. The RR2 anemometer and a fan motor counter were used to normalize the 106 30-second tests. The distribution of the total 30-second counts, normalized with the total RR2 count, is shown in Figure 4. The total range for the cups was ±1.5% of the average, nearly full scale on the graph. The total range for RR2 was ±1.2% of the average. There is always a larger range when cups measure speed than when helicoid propellers measure the same flow. The cause is the turbulent wake generated by the cup wheel through which the cup wheel must travel. But, since there were 100 different cups used (#300 was used six times) and since the RR2 was always the same anemometer, the 0.3% difference in the ranges could be interpreted as product variability for the cups. This test showed a very small product variability when compared to the variability of calibration tests by all participants.

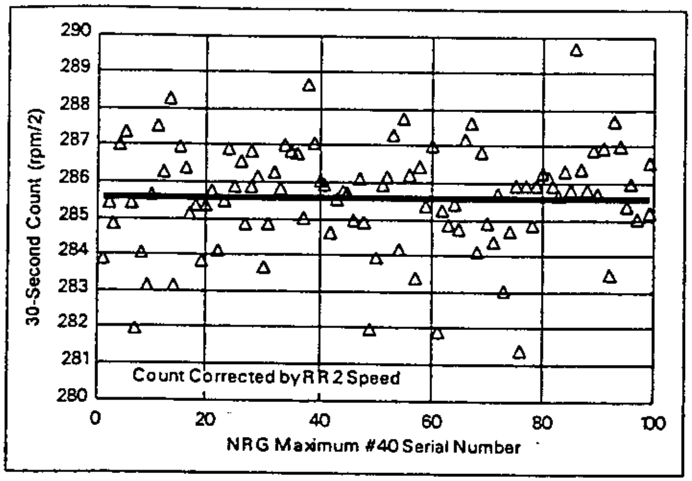


Figure 4

Distribution of 99 Cups at 7.7 m/s

A series of recent calibrations were provided by Otech and Second Wind. The Second Wind calibrations used four speeds in the range of 4.5 or 6.7 m/s to 17.9 m/s (10 or 15, 20, 30, and 40 mph). The Otech Engineering calibrations use ten speeds in the range of 4.5 to 24.6 m/s (10 to 55 mph). Their plan is 10, 20, 30, 40, 50, 55, 45, 35, 25, and 15 mph. A second analysis of the Otech Engineering calibrations using only the first four points was run to provide a range equal to the Second Wind range. A summary of these data are in Table 1.

Table 1

Summary Statistics for Recent Tests

	Test Speeds	Number of cups	Sort on R	Slope (m/pulse)	Offset (m/s)	Speed at 10Hz (m/s)	Relative Percentages (%)	(%)	(%)	Speed Range (m/s)	Speed Range (%)
Otech	10	616	all	0.7528	0.43	7.958	-0.30			0.75	9.4
Otech	10	547	0.99990	0.7530	0.44	7.970	-0.15			0.52	6.5
Otech	10	332	0.99995	0.7532	0.45	7.982	0	0		0.46	5.8
Otech	10	117	all	0.7581	0.46	8.037				0.38	4.7
Otech	4	616	all	0.7565	0.36	7.922	-0.18			1.06	13.4
Otech	4	544	0.99990	0.7570	0.37	7.937	0.01			0.61	7.7
Otech	4	408	0.99995	0.7575	0.36	7.936	0	-0.58	0	0.61	7.7
SWI	4	140	all	0.7704	0.344	8.047	0.04			0.33	4.1
SWI	4	137	graph	0.7707	0.338	8.044	0	0.78	1.36	0.29	3.6

The Otech Engineering tests took place between May 1997 and February 1998. There were 616 cups calibrated. An average of all the slopes and offsets for the original 10-speed calibration was calculated. The resulting speeds at 10 Hz were calculated for each cup. The total range of speeds was measured in m/s and also expressed as a percent of the average speed. The next step was to look at the correlation coefficient (R) for each linear regression. The NEL [4] criteria is that the linear regression should be 0.99995 or greater for the calibration to be accepted. The data were sorted for two select levels of R and the same calculations made. The differences among different amounts of scatter are small. The R=0.99990 seems as good as the NEL value and in this case, only 11% of the cups are rejected for retest if 0.99990 is used while 46% would need retesting if 0.99995 were used. Actually, all the cups are within a reasonable 0.3% of the average of them all.

The 117 cups are those calibrated after a two degree adjustment was made to align the cups with the average angle of the flow distorted by the bow wake. Otech Engineering, following its strategy of quality control, tested the angle of the flow at the point where the cup wheels are exposed. The angle varies with speed but the average angle at the average speed was two degrees. The fact that this subset with a corrected vertical component agrees with the Second Wind calibration (at 10 Hz speed) explains part of the differences seen over the years. During the past year, Otech Engineering redesigned the mounting on the vehicle by placing the anemometers higher and farther in front of the vehicle. This change decreases the vertical component caused by the flow around the vehicle. This would also account for some of the improving comparison between Otech Engineering and Second Wind calibrations.

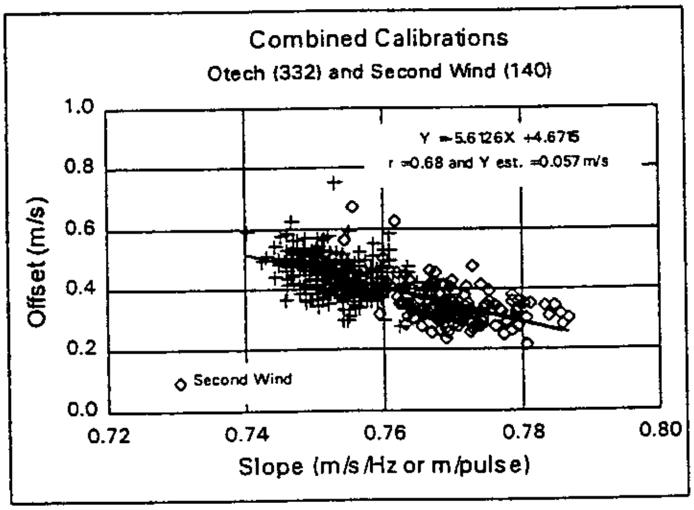


Figure 5
Selected Recent Calibrations

The recent data from Otech which met the NRL criteria and the corrected data from Second Wind with RR2 as the transfer standard are combined in Figure 5. The linear regression formula for calculating offset given the slope is in the figure. An analysis of the sensitivity of the consensus function standard is shown in Figure 6. The zero line is the consensus transfer function, 0.765Hz + 0.35, assumed to be correct for all speeds. The numbers came from the consensus speed at 10 Hz of 8 m/s. One can also get 8 m/s from 0.760Hz + 0.40 and from 0.770Hz + 0.30. Speeds were calculated at frequencies from 5 Hz (4.2 m/s) to 40 Hz (31.0 m/s) and the difference found from the consensus transfer function. These are plotted as straight lines in Figure 6. Note that at high speeds, such as 30 Hz (23.3 m/s or 52.1 mph), the difference rises only to 0.1 m/s. If the offset is calculated, using the formula for the linear regression of the recent data shown in Figure 5, for multipliers of 0.760 Hz/m/s and 0.770 Hz/m/s, the diamonds in Figure 6 result.

The other interesting observation in Figure 5 is the scatter of the calibration points about the best fit straight line. The Standard Error of the Y Estimate from the linear regression calculation is 0.057 m/s. This characterizes the scatter in the Y direction of the closest 68% of the points about the best fit straight line. The speed range column in Table 1 shows that, for the Otech 117 tests, all of the calibrations fall within ±0.19 m/s at 10 Hz. The Second Wind data with three outliers removed show all calibrations are within a range of ±0.15 m/s at 10 Hz. Table 1 shows that both calibration methods find the same average speed at 10 Hz, 8.04 m/s for the last 117 Otech calibrations and 8.04 m/s for the last 137 Second Wind calibrations. The total range of scatter is slightly larger from Otech, which is not surprising from testing in an environment with larger speed variation.

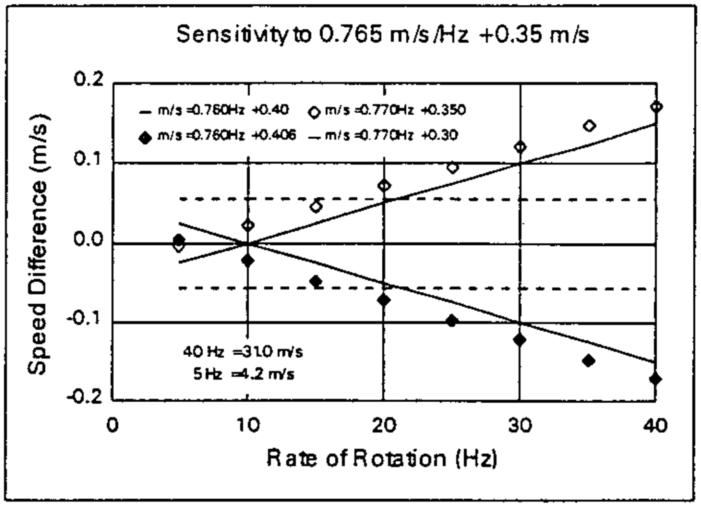


Figure 6
Sensitivity Analysis

DISCUSSION

The use of individually calibrated anemometers may not provide more accurate data than the use of a consensus mean transfer function. If significant differences between calibration results and the consensus transfer function are found at the 8 m/s speed of a 10 Hz rate of rotation, the cause should be investigated. It will most likely be found in the calibration method or facility. The calibration of new anemometers, apart from identifying outliers, can only quantify where within a very small range (0% to 0.5%) of product variability a particular anemometer lies. It is unlikely that the uncertainty of a calibration facility is small enough to provide important accuracy improvement. It is a sound practice, however, to use calibrated sensors in applications where accuracy of the sensor may be questioned for legal or regulatory conformance. Calibration is an effective quality assurance procedure for both new and used anemometers.

The boot accessory decreases the Maximum anemometer's transfer function slope by about 2% compared to an anemometer without the boot. This means that if the boot is added to an anemometer calibrated without the boot, the transfer function will indicate a wind speed 2% higher than the actual speed.

Blockage effects on measured wind speeds in wind tunnel tests are significant and must be taken into account. For a given set of test equipment, the blockage effect is inversely proportional to the tunnel's test section area. The methods used to transfer authority in calibration wind tunnels may be sensitive to blockage effects. When authority is transfered to the wind tunnel through the fan motor speed, as is done in the YOUNG facility, the transfer standard calibrated by the authority must be the identical design as the anemometers being calibrated. Blockage effects will be minimized or completely compensated by measuring the static pressure in the plane of the instrument being calibrated. This automatic correction process is effectively achieved in the Second Wind MIT wind tunnel calibrations.

ACKNOWLEDGMENT

The authors are grateful for the support of the National Renewable Energy Laboratory, through Subcontract TAT-5-15208-01, which made this work possible. The donation of facilities and staff by NIST, NOAA, PMEL/UW, and YOUNG also made this project possible. Special thanks are due John Obermeier for his prompt and professional performance during this project. The unsupported contributions of David Blittersdorf, Professor Eugene Covert, Ken Cohn and his crew from Second Wind and Bob Young are gratefully appreciated.

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