Some Cup Anemometer Testing Methods

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2 November 1984 and 13 May 1985

ABSTRACT

It is necessary to understand, in detail, how an instrument works before methods can be designed or applied for calibration or auditing. This paper describes how a cup anemometer operates in a steady laminar flow and how some devices currently being used for field auditing may be based on erroneous assumptions.

1. Introduction

A cup anemometer has three basic parts. First, there is the cup assembly. This is the structure made up of the cups and the support members holding the cups together into a single unit. The cup assembly or cup wheel, or aerodynamic shape as it is sometimes called, is what reacts to the forces created by the air flow it experiences. The second part is the bearing assembly. This holds the cup wheel rigidly in one plane while allowing it to rotate along an axis perpendicular to that plane. The third part is the transducer which senses the rotational movement of the axis or shaft and provides an output proportional to rate of rotation. The transducer might be a generator providing a voltage output or it might be a device such as a switch, light chopper or other pulse generator that provides a count of revolutions during a time period. In any case, the transducer only reports the rate of rotation because that is how the cup anemometer reacts to flow.

When the anemometer is calibrated in a wind tunnel the rate of rotation (R, rps) can be expressed in units of wind speed (U, m s^{-1}). The wind tunnel must have some basis for being considered a calibrated wind tunnel, capable of generating known average wind speeds (with known error bars) at low turbulence levels. This relationship or transfer function may be linear or not. Usually it is applied, for all practical purposes, as a linear function such as

$$U = a + bR,$$

where the constants a and b are found by the linear regression of the wind tunnel data or by some other useful method. The constant a may be considered to be zero, as is the case with wind run instruments (Lockhart, 1977; Baynton, 1976), or as a fixed "zero wind speed" to compensate for that part of the range lost because of the starting threshold.

Since the force field acts on the cup wheel asymmetrically with respect to the axis of rotation, the cup wheel turns. The resultant rotational force, or moment of force, is expressed as the product of the force and the lever arm. Fundamentally, torque is mass times acceleration times the length of the lever arm and has units of g cm^2 s^{-2}. In practice, weight is used rather than mass and torque is expressed in units of g cm.

The force of air acting on a body increases as the square of the wind speed. The torque provided by the flow to turn the shaft also increases as the square of the wind speed (Lockhart, 1978). For example, a conventional small three conical cup anemometer (Teledyne Geotech 170-42) provides about 0.3 g cm of torque at 0.5 m s^{-1} and about 30 g cm of torque at 5 m s^{-1} when measured by a torque watch restraining the cup wheel from turning. (Torque watches in a series of ranges from 0.2 g cm to 360 g cm are available from Waters Mfg. Inc., Wayland, MA 01778.)

While the force available to turn the shaft increases with the square of the speed, the rate of rotation increases linearly with speed. The cup wheel acts like a wind mill. It turns with the air passing by as a result of the aerodynamic forces (lift and drag) acting on the various shapes of the the cup wheel with respect to their orientation to the flow direction.

Flow through a helicoid propeller is much simpler to visualize, but the principles are the same. The reaction in terms of rate of rotation is linear with wind speed, and torque available increases as the square of the wind speed. Therefore, with either cups or a propeller, those performance characteristics that depend on torque (starting threshold and response distance) are sensitive to air density and that performance characteristic which depends on aerodynamic response (transfer function of wind speed to rate of rotation) is independent of air density.

2. Variables in cup anemometer performance

The only two things that can happen to change the performance of a cup anemometer, leaving aside the

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transducer and any loads it may place on the bearing assembly, are changes in the cup wheel and changes in the bearing assembly performance. Changes in the cup wheel effect the transfer function (linear). Changes in the bearing assembly effect the reaction of the bearing assembly to the torque provided by the forces on the cup wheel (square function), usually causing changes in the starting threshold.

The best method for determining the validity of the transfer function is to use a wind tunnel test. The next best method is to inspect the cup wheel for physical changes which might have changed the transfer function from that determined in an initial wind tunnel test.

The best method for determining the bearing assembly condition is to remove the cup wheel, physically examine the shaft (spin it) and measure its starting torque with a torque watch. Another way to determine the condition of the bearing assembly is to use a device similar to one described by Dilger and Thomas (1975) and compare the anemometer to another identical anemometer with a bearing assembly which has been tested in a wind tunnel. Be careful not to use the transfer function relating rate of rotation to wind speed as determined in laminar flow (wind tunnel) to describe the rate of rotation observed in the gas jet testing device. The torque provided by this gas jet, while causing a rate of rotation to stabilize in the test device, is not likely to be the same as the torque provided when the same rate of rotation is developed by the laminar flow in the wind tunnel.

All one can say when finding in the gas jet device that the subject anemometer performs identically to the "standard" anemometer (with wind tunnel calibration papers) is that the two bearing assemblies performed identically in that test device and that the subject anemometer would *probably* also perform identically in the atmosphere in terms of bearing condition. It is possible that the torque provided by the gas jet which turned both anemometers at what would be the rate of rotation at threshold speed in the wind tunnel was greater than the torque provided at that speed in the wind tunnel, and that the subject anemometer could fail the wind tunnel threshold speed test while the "standard" anemometer would pass. This uncertainty is not the case with a torque watch test.

3. The gas jet field testing device

In October 1984, there was a specialty conference on Quality Assurance sponsored by the Air Pollution Control Association (APCA, 1984) and the American Society for Quality Control. The session on meteorological monitoring included a demonstration of an audit device used to challenge (a word used by auditors when measurement systems are required to respond to a known input) cup anemometers in the field. The device was alleged to provide "NBS traceability" by exposing identical cup anemometers, sequentially, to the same gas jet. Several gas flow rates would provide several rates of rotation. Since one of the cup anemometers had been calibrated in the NBS wind tunnel, it was called a "transfer standard." A comment was made at the session that the method was not valid.

A day or so later during a discussion of this device between the author and A. Morris and D. Street of Ambient Analysis in Boulder, Colorado, D. Street recalled seeing a paper on the subject. It was Cup Anemometer Testing Device for Low Wind Speeds (Dilger and Thomas, 1975). The method described in that paper is also not valid. Philosophically speaking, the appearance of a paper or note in the refereed journals does not certify the material to be correct, although every effort is expended to be sure it is correct. When errors are found they should be corrected. Manufacturers and buyers still must make their own determination of validity.

The cup wheel turns as a result of the differential lift and drag forces applied to the right and left (with respect to the effective mean wind direction) of the axis of rotation of the cup wheel. These differential forces can be described by an equivalent torque on the bearing shaft. The torque will cause the shaft to turn if it is greater than the starting torque of the bearing assembly and transducer load, if any. The maximum torque at any wind speed is not found when the open side of one cup is facing upwind. For some cup wheels it is found when the closed side of one cup is facing upwind (Lockhart, 1978).

Figure 1 restates the data for a Teledyne Geotech Model 170-42 (stainless steel) cup wheel from this reference. Figure 2 shows the position of the cup wheel with respect to the wind direction at six points on Fig. 1. Follow the C cup through the 120 degrees represented by positions 1–6. Note that the maximum torque was found when the open end of cup C was at about 45 deg to the incoming wind (see also Brock, 1984). Less than half the maximum torque was found at position 4 when the open cup faced directly upwind. Of course, this kind of nonlinearity should be expected from the classic data showing force versus angle of attack for single cups (Slade, 1968). It becomes clear, as one visualizes the wind pushing on each of the three cups in the various orientations, why a single gas jet cannot simulate a flow immersing the whole cup wheel.

The authors describe a device which is well-designed to turn a cup wheel and measure rate of rotation. The measurement error of less than ±5 pulses out of 180 pulses per revolution of the shaft (3%) is reasonable but there is no basis for relating the rate of rotation, as generated in this device, to wind speed. The cup anemometer calibrated at Aerodynamische Versuchsanstalt Gottingen wind tunnel may turn at a rate of 0.03 revolutions per second (or 5.7 cps) at 0.6 m s^{-1}.

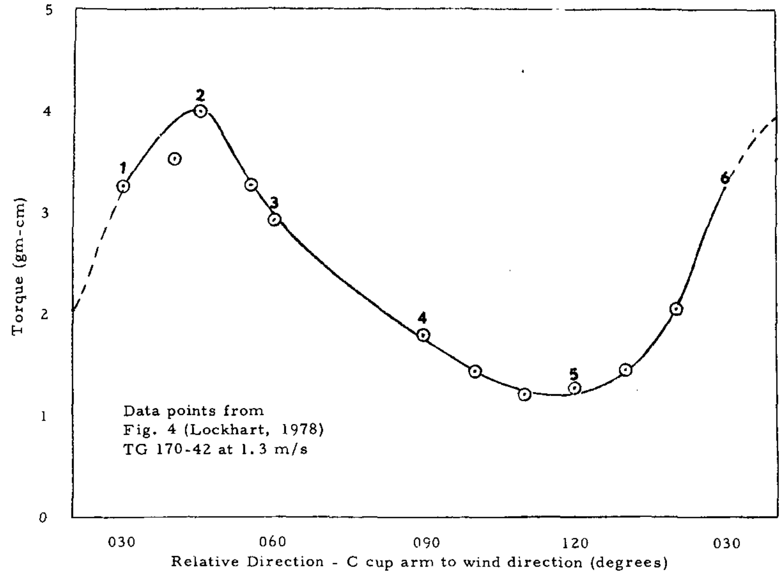

FIG. 1.

This does not mean that any device which causes the shaft to turn at that rate is producing an equivalent wind speed.

As stated in the introduction, the rate of rotation to wind speed transfer function is dependent upon the aerodynamic shape and is empirically determined in the laminar flow of a wind tunnel. One could also find a transfer function in the Dilger and Thomas (D-T) device for rate of rotation to gas jet flow rate (mass or volume?). One cannot "solve" for a relationship between wind speed and gas jet flow rate because the aerodynamic shape being used in the wind tunnel (all of the cup wheel) is different from that being used in the D-T device (a part of a moving cup).

The gas jet device may be useful for testing bearing condition, a critical attribute for low wind-speed accuracy. An experienced instrument technician can remove the cup assembly from an anemometer and spin the shaft and feel the shaft turn between his or her fingers and know whether or not the bearings need attention. It is impossible to quantitatively document such a test (inspection). The gas jet comparison to an anemometer of known condition removes the need for experience since it is objective. The problem is how to

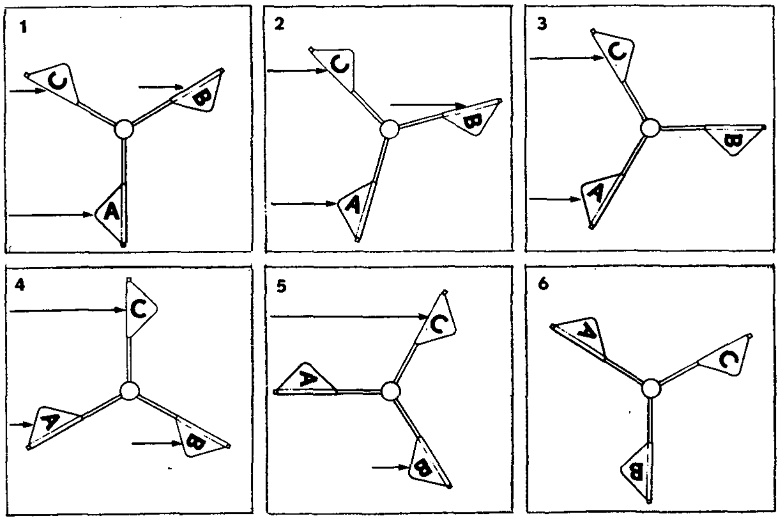

FIG. 2.

quantitatively document the test in meaningful units. The rate of rotation induced by the gas jet cannot be described in units of wind speed. The lowest rate of rotation induced in the "standard" anemometer cannot be called the threshold. All one can say is that the subject anemometer performed exactly like the standard anemometer and therefore is presumed to be in good condition—a subjective conclusion.

In the concluding paragraph the authors claim the device to be ". . . a simple and reliable system for quickly checking anemometer response characteristics at low speeds. . . ." It does not, since it does not check the anemometer at low wind speeds but at jet flow rates. They claim the device is ". . . superior to a wind tunnel. . . ." Since it in no way, meaningful to the performance of a cup anemometer, resembles a wind tunnel, it should not be compared to one.

4. Conclusions and recommendations

The anemometer reports rate of rotation expressed in wind speed units. The signal conditioning, averaging and output recording parts of the instrument may be completely challenged or tested by impressing a known rate of rotation on the bearing assembly. Using the transfer function given by the manufacturer or found from a previous wind tunnel test, the wind speed which should result from the impressed rate of rotation can be compared to that which is reported as the output of the instrument.

The transfer function is not likely to change unless there has been a physical modification to the aerodynamic shape or a change in the performance of the bearing assembly. Degradation of ball bearings appears first as an increase in starting threshold. The bearing assembly can be objectively challenged or tested with a torque watch (Lockhart, 1978).

Other methods may provide useful information. These include

- walking through a still room at a speed near threshold and observing the cup performance, or;
- collocating a "transfer standard" anemometer for operational comparison (functional precision or comparability), or;
- using a gas jet device.

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