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Meteorology — Wind measurements —

Part 1: Wind tunnel test methods for rotating anemometer performance

Météorologie — Mesurages du vent —

Partie 1: Méthodes d'essai en soufflerie pour déterminer les caractéristiques d'un anémomètre tournant

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 17713-1 was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 5, *Meteorology*.

ISO 17713 consists of the following parts, under the general title *Meteorology — Wind measurements*:

— *Part 1: Wind tunnel test methods for rotating anemometer performance*

The following part is planned:

— *Part 2: Wind tunnel test methods for wind vanes*

Introduction

Cup and propeller anemometers are the most frequently used meteorological instruments for the measurement of mean wind speed in the near surface layer, that portion of the atmosphere which lies within a few tens of meters of the earth's surface. Some types of cup and propeller anemometers are available for measuring wind speeds of a few tenths of a meter per second while other types can measure wind speeds approaching 100 $m \cdot s^{-1}$. These general purpose anemometers are used extensively for meteorology, aviation, air pollution, wind energy and numerous other applications.

This part of ISO 17713 was developed in order to have a worldwide uniform set of test methods to define the characteristics of cup and propeller anemometers. This part of ISO 17713 will allow an end user to compare different manufacturers and different models of cup and propeller anemometers to determine the suitability for a particular application.

Meteorology — Wind measurements —

Part 1:
Wind tunnel test methods for rotating anemometer performance

1 Scope

1.1 This part of ISO 17713 describes wind tunnel test methods for determining performance characteristics of rotating anemometers, specifically cup anemometers and propeller anemometers.

1.2 This part of ISO 17713 describes an acceptance test and unambiguous methods for measuring the starting threshold, distance constant, transfer function and off-axis response of a rotating anemometer in a wind tunnel.

Note that when transferring values determined by these methods to atmospheric flow, there is a difference between anemometer performance in the free atmosphere and in the wind tunnel.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document applies.

ISO 5725-1, *Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions*

ISO 5725-2, *Accuracy* (*trueness and precision*) *of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply. See also References [1], [2] and [3].

3.1
distance constant
L_U
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 increase change in air speed

3.2
off-axis response ratio
Q_U
ratio of the indicated wind speed (U_θ) at various angles of attack (θ) to the product of the indicated wind speed (U_i) at zero angle of attack and the cosine of the angle of attack (θ) and thus this ratio (Q_U) compares the actual off-axis response to a true cosine response

3.3
starting threshold
U_0
lowest wind speed at which a rotating anemometer starts and continues to turn and produce a measurable signal when mounted in its normal operating position

NOTE The normal operating position for cup anemometers is with the axis of rotation perpendicular to the direction of air flow and the normal operating position for propeller anemometers is with the axis of rotation aligned parallel with the direction of the air flow.

3.4
transfer function
relationship between predicted wind tunnel air speed and the anemometer rotation rate throughout the specified working range of the anemometer: ($\hat{U} = a + bR + \ldots$)

4 Symbols and abbreviated terms

a zero offset constant (metres per second)

b wind passage (apparent pitch) constant or calibration constant (metres per revolution)

D_{P} wind distance passage (metres) per output pulse for anemometers with pulse output signal

° symbol for directional degrees

e base of natural logarithms

L average of the distance constants (metres) at 5 m·s^{-1} and 10 m·s^{-1}

L_U distance constant (metres) at wind tunnel air speed U (metres per second)

$M_{\mathrm{R}U}$ wind speed measurement resolution, i.e. the smallest reported speed measurement increment (metres per second) for the anemometer

Q_U off-axis response ratio at wind tunnel air speed U (metres per second)

r a shaft revolution

R rate of rotation (revolutions per second, r·s^{-1})

t time (seconds)

t_{f} time (seconds) to reach 74 % of the anemometer equilibrium speed U_{f} (metres per second)

t_{i} time (seconds) to reach 30 % of the anemometer equilibrium speed U_{f} (metres per second)

T measurement time interval (seconds)

T_{R} time resolution of a measurement (seconds)

U wind tunnel air speed (metres per second, m·s^{-1})

$\hat{U}$ predicted wind speed (metres per second) from the anemometer transfer function

U_{f} anemometer indicated wind speed (metres per second) at equilibrium

U_{i} anemometer indicated wind speed (metres per second) in its normal position in the wind tunnel

U_{max} anemometer maximum specified operational speed (metres per second)

U_{min} anemometer minimum specified operational speed (metres per second)

U_t instantaneous indicated wind speed (metres per second) at time t

U_0 starting threshold (metres per second)

U_θ indicated wind speed (metres per second) of the anemometer at off-axis angle of attack θ

θ off-axis angle of attack (degrees)

θ_s stall angle for fixed-axis propeller anemometers (degrees)

τ anemometer response time (seconds) for the equilibrium speed U_f

5 Summary of test method

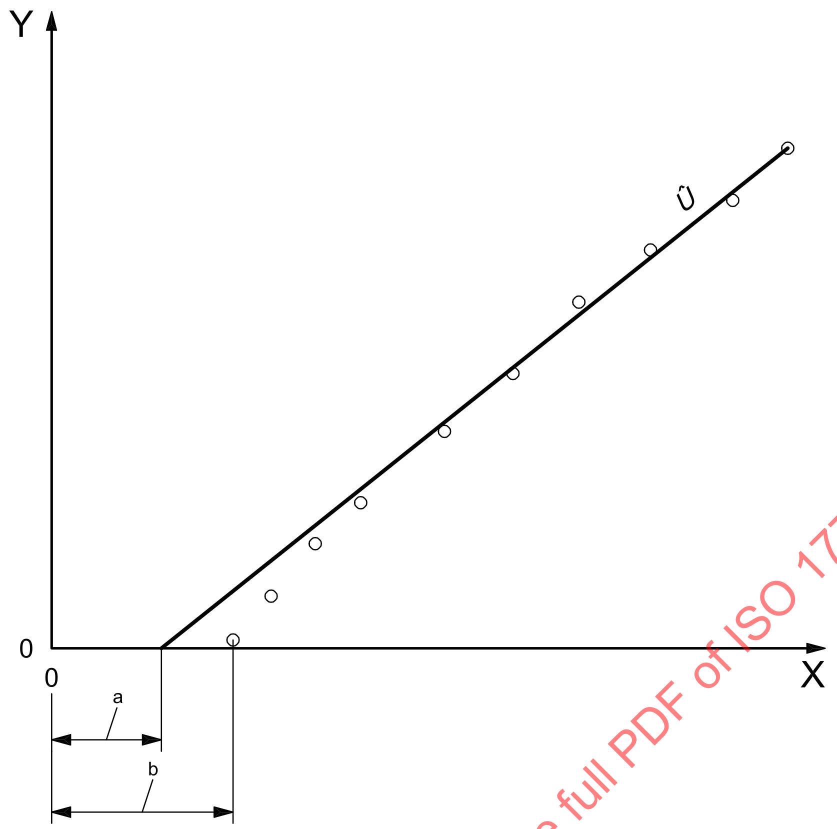
5.1 This test method requires a wind tunnel described in Annex A. Additional information regarding wind tunnel testing is listed in the bibliography [7][10][12][13].

5.2 The starting threshold (U_0) is determined by measuring the lowest speed at which a rotating anemometer starts and continues to turn and produce a measurable signal when mounted in its normal operating position. The anemometer axis is aligned parallel with the direction of air flow for a propeller anemometer. The anemometer axis is aligned perpendicular to the direction of air flow for a cup anemometer.

5.3 The transfer function ($\hat{U} = a + bR + \ldots$) [1][6] is determined by measuring the rate of rotation, or output signal, of the anemometer at a number of wind speeds throughout the working range (range of intended use). In the range of wind speeds where the anemometer response is non-linear (near threshold), measurements at a minimum of five different speeds are recorded. Measurements at a minimum of five additional speeds are recorded within the working range of the anemometer and wind tunnel but above the non-linear threshold region (see Figure 1). If the application working range extends into a further high speed non-linear range, then measurements at additional speeds shall be included in that range, sufficient to enable a suitable polynomial expression to be determined. A minimum of three sets of measurements are to be taken. The values of a and b are determined by least-squares regression using the individual measurements taken at each data point.

The transfer function can be approximated to a linear relationship for certain application ranges and certain anemometer designs. The function can be non-linear at low tunnel speeds (typically two to five times the U_0) and again at higher speeds. $\hat{U}$ is the predicted wind speed in metres per second; a and b are polynomial constants. Constants beyond b would be zero for the linear relationship. For the linear case, the constant a is commonly called zero offset, in metres per second, b is a constant representing the wind passage in metres per revolution for each revolution of the particular anemometer cup wheel or propeller, and R is the rate of rotation in revolutions per second. It should be noted that zero offset is not the same parameter as the starting threshold. In some very sensitive anemometers, the constant a, zero offset, may not be significantly greater than zero. The constants a and b shall be determined by wind tunnel measurement for each type of anemometer. In the case of anemometers that do not directly output a rate of rotation, for example, with an output directly in wind speed (ASCII, hexadecimal, etc.) or electrical units (volts, milliamperes, etc.), R and b can have different units that correspond to those of the output.

NOTE Although this transfer function model does not completely represent the anemometer response in the non-linear starting portion of the curve, for most applications the additional accuracy provided by more rigorous mathematics is not warranted. These data points in the non-linear starting area can be the basis for a more advanced mathematical model of the transfer function.



Key

X wind tunnel speed, U, in metres per second

Y rotation rate, R, in revolutions per second

a zero offset, a, in metres per second

b starting threshold, U_0, in metres per second

Figure 1 — Typical anemometer calibration curve

5.4 The distance constant (L_U) shall be determined at a number of wind speeds which shall include 5 m·s^{-1} and 10 m·s^{-1}. It is computed from the time required for the anemometer rotor to accelerate (1 – 1/e) or 63 % of a step increase change in rotational speed after release from a restrained, non-rotating condition [4]. The final response, U_f, is the wind speed at equilibrium as indicated by the anemometer (see Figure 2). This response time (τ) is only applicable at the particular test speed. For some applications, additional wind speeds over the operational range can be of interest.

NOTE There is a different distance constant for a decreasing step change of speed. This value will be an indicator of the amount of anemometer over speed (the anemometer reporting a wind speed value higher than the true wind speed) in gusty wind conditions. For specific anemometer applications, this distance constant for decreasing wind speed can be of interest. The determination of the distance constant for decreasing wind speeds is beyond the scope of this part of ISO 17713.

The response of a rotating anemometer to a step change in which the air speed increases instantaneously from $U = 0$ to $U = U_f$ is [5]:

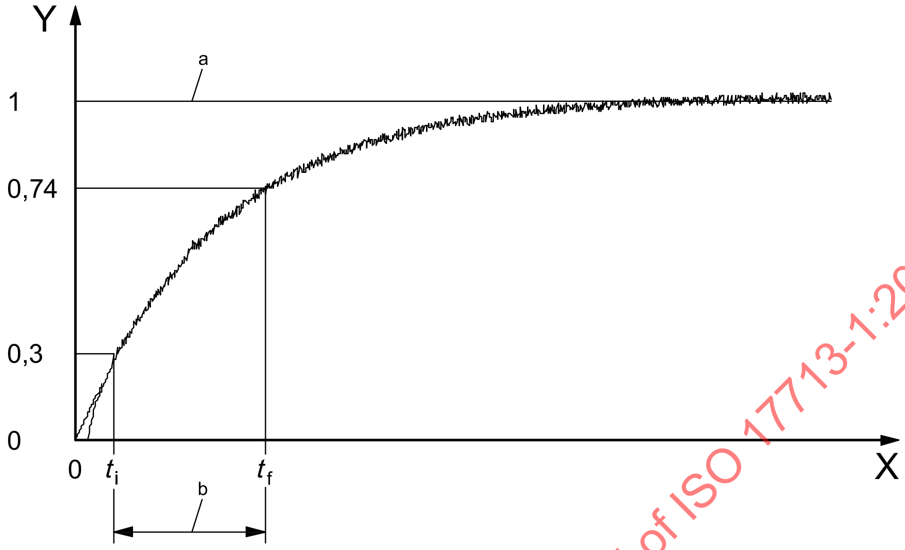
$$U_t = U_f (1 - e^{-(t/\tau)}) \tag{1}$$

The response time is:

$$\tau = t_f - t_i \tag{2}$$

The distance constant is:

$$L_U = U\tau \tag{3}$$



Key

X time, t, in seconds

Y anemometer indicated wind speed, U_i, in metres per second

[a] final response

[b] response time, τ

Figure 2 — Typical anemometer response curve — Increasing wind speed step change

In order to avoid the unrealistic effects of the restrained condition, as shown in Figure 2, the time measurement should be made from 0,30 of U_f to 0,74 of U_f. This calculated response time (τ) interval in seconds is to within 1 % of the theoretical (1 – 1/e) response of the instrument and is converted to the distance constant (L_U) by multiplying by the wind tunnel air speed (U) [1].

5.5 The off-axis response ratio (Q_U) can be a function of speed. The off-axis response ratio shall be measured at a number of wind speeds which shall include 5 m·s^{-1} and 10 m·s^{-1}.

5.5.1 For *cup anemometers*, a measurement is made of the output signal when the anemometer is inclined into the wind (representing a down-draft) and away from the wind (representing an updraft), while the wind tunnel is running at a steady speed. The output signal is measured with the anemometer axis at 5° intervals from vertical to ± 30° from vertical. The measured signal is then converted to a ratio for each interval by dividing by the product of cosine of the angle and the signal measured with the anemometer axis in the normal (vertical) position.

5.5.2 For *vane-mounted propeller anemometers*, a measurement is made of the output signal when the anemometer's axis of rotation is inclined downward into the wind (representing a down-draft) and inclined upward into the wind (representing an updraft), while the wind tunnel is running at a steady speed. The output signal is measured as 5° intervals from a horizontal axis of rotation to ± 30° from the horizontal. The measured signal is then converted to a ratio for each interval by dividing by the product of the cosine of the angle and the signal measured with the anemometer axis in the normal (horizontal) position. This test may be conducted either with the vane in place or with the vane removed. In either case, the axis of rotation shall be fixed in the down-tunnel direction.

5.5.3 For *fixed-axis propeller anemometers*, a measurement is made of the output signal when the anemometer is rotated in the air stream throughout the complete 360° angle of attack. The signal is measured at a number of angles but shall include 10° intervals from 0° to 360° except for 90° and 270°. Additional measurements at 85°, 95°, 265° and 275° are also required. The measured signal for each angle of attack is then converted to a ratio by dividing each measurement by the product of the measurement along the axis of the tunnel at 0° angle of attack (axial flow) and the cosine of the test angle. Additionally, the stall angle (θ_s) of the propeller is measured by orienting the anemometer propeller axis of rotation at 90° to the tunnel air flow and slowly rotating into and away from the air flow until the propeller starts rotating continuously. The stall angle is the total contained angle within which the propeller does not continuously rotate. The procedure is repeated at 270°.

6 Documentation

Data for all runs should be recorded in a format similar to the examples shown in Annex B. The minimum content of the test report shall include the following.

— Date, time, name of the wind tunnel and location; identification of wind tunnel air speed measurement apparatus with serial numbers and calibration dates; the model and serial number of the anemometer under test and if applicable, the anemometer firmware version. Include unique equipment identification where possible. Photographs of the test anemometer mounted on the various test fixtures in the wind tunnel are recommended.

— Description of the testing environmental conditions and corrections to standard conditions (A.2). At a minimum, the range of the environmental parameters shall be listed in the test report. It is recommended that the individual values of the environmental parameters for each measurement be listed in the test report.

— Tabulation of the data used to determine the results of the test method (Annex B).

— The application speed range for which the anemometer was tested.

— The measurement uncertainty of the wind tunnel shall be documented at the wind tunnel facility and be related to measurements at a national laboratory by a national laboratory report on the transfer standard. The demonstrated wind tunnel measurement uncertainty shall be stated in each anemometer calibration report.

7 Apparatus

7.1 Measuring system

7.1.1 Rotation

The resolution of the anemometer transducer can limit the measurement repeatability. The resolution of the measuring or recording system shall represent the indicated wind speed with a resolution of 0,02 m·s^{-1} or better.

7.1.2 Time

The resolution of time (T_R) shall be consistent with the distance accuracy required. For this reason, the time resolution may be changed as the wind tunnel speed is changed. A distance constant measurement to 0,1 m resolution (M_R) requires a time resolution of 0,05 s at 2 m·s^{-1} and 0,01 s at 10 m·s^{-1}.

$$T_R = M_R / U \qquad (4)$$

7.1.3 Angle of attack

The resolution of the angle of attack (θ) shall be within 0,5°. An ordinary protractor of adequate size with 0,5° markings will permit measurements with sufficient resolution. A fixture should be constructed to permit alignment of the anemometer to the off-axis angles while the wind tunnel is running at a steady speed.

7.1.4 Distance constant

A mechanical method is required to hold the anemometer in its normal test position and to enable it to be released from a restrained, or non-rotating condition, while the wind tunnel is running at the test speed. The release mechanism shall not move the anemometer rotor when activated with the wind tunnel off.

7.2 Recording techniques

7.2.1 For the wind tunnel environment, the temperature, pressure and relative humidity (or dew point) of the environment within the wind tunnel test section shall be recorded for each independent measurement.

7.2.2 For the measurement of the distance constant (L_U), digital recording systems and appropriate reduction programs will be satisfactory if the sampling rate is at least 100 samples per second. Care shall be taken to avoid electronic circuits with time constants which limit the proper recording of anemometer performance. Oscilloscopes with memory and hard copy capability may also be used.

Another simple technique is to use a fast-response strip chart recorder (flat frequency response to 10 Hz or better) with enough gain so that the signal produced by the anemometer when the wind tunnel is running at 2 m·s^{-1} is sufficient to provide full scale pen deflection on the recorder. The recorder chart drive shall have a fast speed of 50 mm·s^{-1} or more.

With anemometers that have a pulse output, care shall be taken to ensure that the pulses are frequent enough to provide a satisfactory measurement resolution. Where the measurement resolution is limited, interpolation techniques can be necessary to accurately measure the distance constant. Some anemometers perform internal wind speed averaging and do not provide instantaneous wind speed. For example, those anemometers with a serial data output message can have this resolution problem. In these cases, internal anemometer modifications either in hardware or firmware can be required in order to provide a method to make measurements directly related to the rate of rotation of the cups or propeller. The anemometer manufacturer should be consulted to determine the required modifications.

8 Test procedures

8.1 Starting threshold (U_0)

8.1.1 Set the wind tunnel to a speed to zero. Slowly increase the wind tunnel speed until the cup wheel or propeller starts moving and continues to rotate while producing a measurable output signal.

Validate the lowest stable air speed in the wind tunnel prior to starting this test. See Annex A.1.3. Due to the large variation (up to 300 %) of torque produced by a cup anemometer, change the cup positions by approximately 12° for each run in order to obtain a more representative average for the starting threshold of the anemometer.

8.1.2 Repeat the procedure of 8.1.1 ten times and record the results. Calculate and record the arithmetic mean ($\overline{U}_0$) of the ten runs.

Vibration caused by the wind tunnel or by other sources can cause erroneous measurements of starting threshold. Care shall be exercised to eliminate any vibration in the wind tunnel test section during threshold measurements.

8.2 Transfer function ($\hat{U} = a + bR + \ldots$)

8.2.1 Set the wind tunnel speed at approximately two times threshold (U_0) as determined in 8.1. After the wind tunnel air speed has reached equilibrium, measure the anemometer output for a fixed measurement time interval (T) of between 30 s and 100 s. This measurement time interval (T) will provide a wind speed measurement resolution ($M_{\mathrm{R}U}$) of 0,1 m·s^{-1} or better for most anemometers. Some low resolution anemometers with a pulse output signal can require a much longer measurement time interval (T) to achieve a wind speed measurement resolution ($M_{\mathrm{R}U}$) of at least a 0,1 m·s^{-1}. The wind speed measurement resolution ($M_{\mathrm{R}U}$) in meters per second for an anemometer with a pulse output signal is the product of the wind distance passage per output pulse (D_p) in meters divided by the measurement time interval (T) in seconds.

$$M_{\mathrm{R}U} = D_\mathrm{p} / T \qquad (5)$$

If the anemometer wind speed measurement resolution ($M_{\mathrm{R}U}$) is too large, the least squares regression coefficients determined in 8.2.4 will be invalid.

Record the wind tunnel speed and the anemometer rotation rate (R) or equivalent output. Increase the wind tunnel speed to approximately three times U_0 and record the measurements. Repeat at four times U_0, five times U_0 and six times U_0.

8.2.2 Set the wind tunnel air speed at approximately 10 % of the specified anemometer maximum operational speed (U_{max}). After the wind tunnel speed has reached equilibrium, measure the anemometer output for the same fixed measurement time interval (T) used in 8.2.1. Record the mean wind tunnel air speed and the anemometer rotation rate (R) or equivalent output. Increase the wind tunnel air speed to approximately 20 % of U_{max} and, after it has reached equilibrium, record the measurements as before over the same fixed measurement interval. Repeat at approximately 30 % of U_{max}, 40 % of U_{max} and 50 % of U_{max}. A complete determination of the transfer function requires at least five additional measurements at approximately evenly spaced speeds up to U_{max}. A complete determination of transfer function is necessary for a new design or a major design modification.

Where air speed measurements are limited to part of the application range, for example due to wind tunnel speed constraints, then extrapolation of the data beyond the range of actual measurements can result in an increase in measurement uncertainty. If it is not possible to test to U_{max}, then the test report shall state that the anemometer was not tested to U_{max}, and the highest test speed shall be stated in the test report.

8.2.3 Repeat the procedure of 8.2.1 and 8.2.2 three times.

8.2.4 Use the data recorded in 8.2.2 and 8.2.3 to determine the value of transfer function constants (a, b, etc.) in the equation ($\hat{U} = a + bR + \ldots$) by least squares regression. Do not use the data near the threshold (U_0) recorded in 8.2.1 for this calculation.

NOTE For most well-designed cup and propeller anemometers, a linear regression should provide a good approximation of the transfer function over the working range of the anemometer. However, this part of ISO 17713 does not exclude the use of a higher order regression equation to model the anemometer transfer function.

8.2.5 Using the values of the transfer function constants (a, b, etc.) calculated in 8.2.4, find the predicted $\hat{U}$ for each R measured in 8.2.1 and 8.2.2. Subtract the predicted $\hat{U}$ from the measured U. Report the differences in metres per second for each tunnel speed used in 8.2.1 and 8.2.2.

NOTE These residual data can be used to determine the non-linear portion of the transfer function and the outliers.

8.3 Distance constant (L_U)

8.3.1 Set the wind tunnel speed to 5 m·s^{-1}. Stop the rotation of the cup wheel or propeller and release by method of 7.1.4. Record ten measurements for L_5.

8.3.2 Repeat the procedures of 8.3.1 at 10 m·s^{-1} for L_{10}.

8.3.3 From the recorded data, measure the time (t_i) in seconds from the point when the rotor speed reaches 0,30 of final equilibrium speed (U_f) to the time (t_f) where the rotor speed reaches 0,74 of the final equilibrium speed (U_f) (see Figure 2). A trial run will be necessary to determine the final equilibrium speed (U_f). When $t \geqslant 7\tau$, the rotor speed will have reached 99,9 % of the equilibrium speed (U_f). This speed will be within 0,01⋅m⋅s^{-1} of the theoretical equilibrium speed (U_f) at a 10 m⋅s^{-1} test speed.

The response time (τ) is:

$$\tau = t_f - t_i \tag{6}$$

The distance constant (L_U) is determined by multiplying the tunnel speed (U) by the response time (τ). The distance constant is:

$$L_U = U\,\tau \tag{7}$$

This shall be done for each of the ten measurements at 5 m⋅s^{-1} and at 10 m⋅s^{-1}. The average of the ten measurements at 5 m⋅s^{-1} and the ten measurements at 10 m⋅s^{-1} should produce distance constants that are within 10 % of the overall average of the combined twenty measurements at 5 m⋅s^{-1} and 10 m⋅s^{-1}.

8.4 Off-axis response ratio (Q_U) — Cup anemometers

8.4.1 Set up the off-axis angle fixture for the cup anemometer described in 7.1.3 and align the cup anemometer to its normal (vertical axis of rotation) position. Set the wind tunnel speed to 5 m⋅s^{-1}. Take one sample with the anemometer vertical and one sample at each 5° interval inclined into the air flow, up to 30°. Take one additional sample with the anemometer vertical and one sample at each of the 5° intervals inclined away from the air flow, up to 30° from the vertical. Divide each value by the product of the value in the normal position and the cosine of the tilt angle to obtain the off-axis response ratio.

$$Q_U = U_\theta / (U_i \cos\theta) \tag{8}$$

8.4.2 Repeat the procedure of 8.4.1 at 10 m⋅s^{-1}. Tabulate the results by averaging the ratios at each speed for each 5° interval.

8.5 Off-axis response ratio (Q_U) — Vane-mounted propeller anemometers

8.5.1 Set up the off-axis angle fixture, described in 7.1.3, for the vane-mounted propeller anemometer and align the propeller axis of rotation to its normal (horizontal) position. Set the wind tunnel speed to 5 m⋅s^{-1}. Take one sample with the propeller axis horizontal and one sample at each of the 5° intervals for down draft (propeller tilted downward to the wind tunnel floor), up to 30°. Take one additional measurement in the normal (horizontal) position and one measurement at each of the 5° intervals for updraft (propeller tilted upward to the wind tunnel ceiling) up to 30°. Divide each value by the product of the value in the normal position and the cosine of the tilt angle to obtain the off-axis response ratio. See Equation (8).

8.5.2 Repeat the procedure of 8.5.1 at 10 m⋅s^{-1}. Tabulate the results by averaging the ratios at each speed for each 5° interval.

8.6 Off-axis response ratio (Q_U) — Fixed-axis propeller anemometers

8.6.1 Set up the off-axis fixture described in 7.1.3 for the propeller anemometer and align the propeller anemometer to its normal (horizontal) position with the axis of the propeller at 0° (align directly into the air flow). Set the wind tunnel speed to 5 m⋅s^{-1}. The signal is measured at a number of angles but shall include 10° intervals from 0° to 360° except for 90° and 270°. Additional measurements at 85°, 95°, 265°, and 275° are also required. The measured signal for each angle of attack is then converted to a ratio by dividing each measurement by the product of the measurement along the axis of the tunnel at 0° angle of attack (axial flow) and the cosine of the test angle. See Equation (8).

8.6.2 Additionally, the stall angle (θ_s) of the propeller is measured by orienting the anemometer at 90° and slowly rotating into and away from the air flow until the propeller starts rotating continuously. The stall angle is the total contained angle within which the propeller does not continuously rotate. The procedure is repeated at 270°.

8.6.3 Repeat the procedure of 8.6.1 and 8.6.2 at 10 m·s^{-1}. Tabulate the results by averaging the ratios for each speed for each interval.

8.7 Acceptance testing

Portions of this test method may be performed to evaluate the performance characteristics of an anemometer. The results may be used for such purposes as determining if the characteristics have changed over time. The recommended minimum content of an acceptance test includes determining the starting threshold (U_0) according to 8.1 and measuring at least five separate speeds over a stated range suitable for the intended application using the techniques given for the transfer function determination in 8.2. Compare the results using the predicted anemometer speeds ($\hat{U}$) from the existing transfer function with the measured wind tunnel air speeds (U).

9 Quality of the test method

9.1 General

The determination of the measurement uncertainty for this method shall be in accordance with ISO 5725-1 and ISO 5725-2.

9.2 Wind tunnel

The measurement quality of the wind tunnel limits the measurement uncertainty of this test method. A wind tunnel measurement uncertainty of 0,2 m·s^{-1} or better is recommended.

9.3 Repeatability

9.3.1 General

Using this equipment and procedure, an estimate of the repeatability of the method follows.

9.3.2 Starting threshold

The repeatability of the speed reported as the threshold relates to the wind tunnel used for this method and the precision of the fundamental time and distance technique employed. The estimated repeatability of this method is 0,1 m·s^{-1}.

9.3.3 Distance constant

The estimated repeatability by this method is 0,2 m or better.

9.3.4 Transfer function

The estimated repeatability of this method is 0,15 m·s^{-1} or better.

9.3.5 Off-axis response ratio

The estimated repeatability by this method is 0,02 or better.

9.4 Uncertainty

9.4.1 Starting threshold

The measurement uncertainty of this method is estimated to be no greater than 0,2 $m \cdot s^{-1}$. Documentation of the time and distance measurements for speeds below 2 $m \cdot s^{-1}$ is required.

9.4.2 Distance constant

The measurement uncertainty of this method is estimated to be no greater than 0,3 m.

9.4.3 Transfer function

The measurement uncertainty of this method is estimated to be no greater than 0,2 $m \cdot s^{-1}$.

9.4.4 Off-axis response ratio

The measurement uncertainty of this method is estimated to be no greater than 3 % of the off-axis response ratio (Q_U).

Annex A
(normative)

Wind tunnel standard test conditions

A.1 Wind tunnel

A.1.1 Size

A.1.1.1 The solid blockage in the wind tunnel test section consists of the projected cross-sectional area of the cup wheel or propeller, sensor and support apparatus. It is preferable that the blockage caused by the complete test anemometer set-up be less than 10 % for a wind tunnel with an open test section and 5 % for a wind tunnel with a closed test section. It is desirable to have the blockage closer to 1 % or less, of the cross-sectional area of the wind tunnel test section to minimize measurement uncertainty.

A.1.1.2 It can be necessary to use two wind tunnels for full range calibration tests and starting threshold tests. Wind tunnels designed for the higher air speeds can have significant non-uniform air flow in the test section at the lower air speeds.

A.1.1.3 Care shall be taken to keep the effective blockage area constant throughout the test. Unless the substitution method (see A.1.1.4) is being used for the anemometer calibration, the blockage effect of the anemometer in the test section of the wind tunnel shall be determined in order to determine the true wind speed experienced by the anemometer under test [7].

A.1.1.4 Verification of the anemometer transfer function by the substitution method. In smaller wind tunnels, the effect of blockage can cause unacceptable errors in the determination of transfer function. This problem can be overcome by substituting an identical transfer standard in place of the test instrument to establish the relationship of wind tunnel air speed to wind tunnel fan revolutions per minute (rpm). The transfer standard is then replaced with the test instrument and its output is measured relative to the wind tunnel air speed as determined from fan rpm. The transfer anemometer is run again after the test anemometer to validate the wind tunnel calibration for this particular calibration test. Since this method requires the availability of an identical transfer standard, which has been calibrated at a national laboratory, or recognized calibration facility, it is only applicable to production testing or acceptance testing of identical sensors.

A.1.1.5 In all cases, it is necessary to understand the effect of blockage caused by the complete test anemometer set-up in the wind tunnel test section can affect the test results. However, to compensate for these effects will require specific methods beyond the scope of this part of ISO 17713.

A.1.2 Speed range

The wind tunnel shall have a speed control, which will allow the flow rate to be varied from 0 to a minimum of 50 % of the application range of the anemometer under test. The speed control should maintain the flow rate within $\pm$ 0,2 $m \cdot s^{-1}$.

A.1.3 Calibration

The mean flow rate shall be verified at the mandatory speeds by use of transfer standards, which have been calibrated at a national laboratory, or by a fundamental physical method. A sensitive anemometer, such as a hot wire anemometer, a laser Doppler anemometer or other equally sensitive air flow measurement instrument, shall be used to verify speeds below 2 $m \cdot s^{-1}$ for the threshold determination. Other air flow measurement techniques can use some fundamental time and distance techniques, such as measuring the transition time of smoke puffs, soap bubbles or heat puffs between two points separated by known distance.

A table of wind tunnel blower revolutions per minute (rpm) or some other index relating method of control to flow rate should be established by this technique for speeds of 2 m·s^{-1} and below [12][13].

A.1.4 Velocity profile

The wind tunnel shall have a relatively flat velocity profile. The air flow in the wind tunnel shall be uniform to within ± 1 % across the test section volume occupied by the cups or propeller of the anemometer under test. At air speeds greater than 10 m·s^{-1}, the wind tunnel shall have an axial turbulence intensity level of less than 2 % as measured at the anemometer test location[3]. The axial turbulence intensity level is equal to the standard deviation of the mean wind tunnel air speed divided by the mean wind tunnel air speed. Flow uniformity and turbulence intensity can be measured by a hot wire anemometer, a laser Doppler anemometer or other equally sensitive air flow measurement instrument.

A.2 Test environment

A.2.1 Differences of greater than 3 % in the density of the air within the test environment can result in poor intercomparability of independent measurements of starting threshold (U_0) and distance constant (L) since these values are density dependent [8][9][10][13].

A.2.2 Record the wind tunnel environmental parameters required for air density for all test runs. Air density may either be calculated or determined by the use of tables such as those in Reference [11].

A.2.3 Pitot-static tube measurements are to be corrected to standard conditions for dry air at 15°C ambient temperature, 1 013,250 hPa barometric pressure and a compressibility factor of 0,999 58. This corresponds to an air density of 1,225 0 kg/m^3 [11].

A.2.4 Barometric pressure, air temperature and relative humidity shall be measured in the test section of the wind tunnel for the correct air density calculations. The size and location of the temperature probe(s) should be carefully selected to minimize the effect on the air flow in the anemometer test location.

A 10 hPa error in the barometric pressure measurement results in an error in the air density calculation of approximately 1 % at 1 013,250 hPa. Errors in the air temperature measurement have an even greater effect on the air density calculation. A 3 °C error in the air temperature measurement causes the calculated air density to change by over 1 % at 15 °C. The test section air temperature in a closed return wind tunnel can increase by 10 °C or more during anemometer tests. A temperature measurement error of this magnitude will cause a significant error in the air density calculation and a corresponding error in the indicated wind tunnel air speed when the air speed measurement is made by means of a pitot static tube or other density dependent measurement system. Therefore, it is critical to accurately measure the average air temperature in the test section air stream. Due to possible temperature stratification in the test section, it can be necessary to use multiple temperature probes in the air stream to accurately determine the average test section air temperature. Table A.1 summarizes the effect of the environmental parameter measurement error in the calculation of the air density.

Table A.1 — Effect of environmental parameter measurement error on air density calculation

Environmental parameter	Parameter measurement error	∆ air density %
Pressure	1 hPa	0,10
Temperature	1 K	0,34
Dew point	1 K	0,02
Relative humidity	3,5 %	0,02

A.2.5 Data for all runs should be recorded in a format similar to the examples shown in Annex B.