Designation: D6011 – 96 (Reapproved 2015)

Standard Test Method for Determining the Performance of a Sonic Anemometer/Thermometer[1]

This standard is issued under the fixed designation D6011; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of the dynamic performance of a sonic anemometer/thermometer which employs the inverse time measurement technique for velocity or speed of sound, or both. Performance criteria include: (*a*) acceptance angle, (*b*) acoustic pathlength, (*c*) system delay, (*d*) system delay mismatch, (*e*) thermal stability range, (*f*) shadow correction, (*g*) velocity calibration range, and (*h*) velocity resolution.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C384 Test Method for Impedance and Absorption of Acoustical Materials by Impedance Tube Method

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

D5527 Practices for Measuring Surface Wind and Temperature by Acoustic Means

IEEE/ASTM SI 10 American National Standard for Metric Practice

3. Terminology

3.1 *Definitions*—For definitions of terms related to this test method, refer to Terminology D1356.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *axial attenuation coefficient*—a ratio of the free stream wind velocity (as defined in a wind tunnel) to velocity along an acoustic propagation path (v_t / v_d) (**1**).[3]

3.2.2 *critical Reynolds number (R_c)*—the Reynolds number at which an abrupt decrease in an object's drag coefficient occurs (**2**).

3.2.2.1 *Discussion*—The transducer shadow corrections are no longer valid above the critical Reynolds number due to a discontinuity in the axial attenuation coefficient.

3.2.3 *Reynolds number (R_e)*—the ratio of inertial to viscous forces on an object immersed in a flowing fluid based on the object's characteristic dimension, the fluid velocity, and viscosity.

3.2.4 *shadow correction (v_{dm}/v_d)*—the ratio of the true along-axis velocity v_{dm}, as measured in a wind tunnel or by another accepted method, to the instrument along-axis wind measurement v_d.

3.2.4.1 *Discussion*—This correction compensates for flow shadowing effects of transducers and their supporting structures. The correction can take the form of an equation (**3**) or a lookup table (**4**).

3.2.5 *speed of sound (c,* (m/s)*)*—the propagation rate of an adiabatic compression wave:

$$c = \left(\gamma \partial P / \partial \rho\right)_s^{0.5} \quad (1)$$

where:

P = pressure
ρ = density,
γ = specific heat ratio, and
s = isentropic (adiabatic) process (**5**).

3.2.5.1 *Discussion*—The velocity of the compression wave defined along each axis of a Cartesian coordinate system is the sum of propagation speed c plus the motion of the gas along that axis. In a perfect gas (**6**):

$$c = \left(\gamma R^* T / M\right)^{0.5} \quad (2)$$

The approximation for propagation in air is:

$$c_{air} = \left[403\, T\, (1 + 0.32\, e/P)\right]^{0.5} = (403\, T_s)^{0.5} \quad (3)$$

[1] This test method is under the jurisdiction of ASTM Committee D22 on Air Quality and is the direct responsibility of Subcommittee D22.11 on Meteorology.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

3.2.6 *system clock*—the clock used for timing acoustic wavefront travel between a transducer pair.

3.2.7 *system delay* (δt, μs)—the time delay through the transducer and electronic circuitry (**7**).

3.2.7.1 *Discussion*—Each path through every sonic array axis can have unique delay characteristics. Delay (on the order of 10 to 20 μs) can vary as a function of temperature and direction of signal travel through the transducers and electronic circuitry. The average system delay for each axis in an acoustic array is the average of the delays measured in each direction along the axis:

$$\delta t = (\delta t_1 + \delta t_2)/2 \tag{4}$$

3.2.8 *system delay mismatch* (δt_t, μs)—the absolute difference in microseconds between total transit times t_t in each direction (t_{t1}, t_{t2}) through the system electronics and transducers.

3.2.8.1 *Discussion*—Due principally to slight differences in transducer performance, the total transit time obtained with the signal originating at one transducer can differ from the total transit time obtained with the signal originating at its paired transducer. The manufacturer should specify the system delay mismatch tolerance.

$$\delta t_t = | t_{t1} - t_{t2} | \tag{5}$$

3.2.9 *thermal stability range* (°C)—a range of temperatures over which the corrected velocity output in a zero wind chamber remains at or below instrument resolution.

3.2.9.1 *Discussion*—Thermal stability range defines a range of temperatures over which there is no step change in system delay.

3.2.10 *time resolution* (Δt, μs)—resolution of the internal clock used to measure time.

3.2.11 *transit time* (t, μs)—the time required for an acoustic wavefront to travel from the transducer of origin to the receiving transducer.

3.2.11.1 *Discussion*—Transit time (also known as time of flight) is determined by acoustic pathlength d, the speed of sound c, the velocity component along the acoustic propagation path v_d, and cross-path velocity components) v_n (**8**):

$$t = d[(c^2 - v_n^2)^{0.5} \pm V_d]/[c^2 - (v_d^2 + v_n^2)] \tag{6}$$

The transit time difference between acoustic wavefront propagation in one direction (t_1, computed for $+ v_d$) and the other (t_2, computed for $- v_d$) for each transducer pair determines the magnitude of a velocity component. The inverse transit time solution for the along-axis velocity is (**9**):

$$v_d = \frac{d}{2}\left[\frac{1}{t_1} - \frac{1}{t_2}\right] \tag{7}$$

The total transit times t_{t1} and t_{t2}, include the sum of actual transit times plus system delay through the electronics and transducers in each direction along an acoustic path, δ_{t1} and δ_{t2}. System delay must be removed to calculate v_d, that is:

$$t_1 = t_{t1} - \delta_{t1} \tag{8}$$

$$t_2 = t_{t2} - \delta_{t2} \tag{9}$$

3.2.11.2 *Discussion*—Procedures in this test method include a test to determine whether separate determinations of $\delta\, t_1$ and δt_2 are needed, or whether an average δt can be used. The relationship of transit time to speed of sound is:

$$c^2 = \left[\frac{d}{2}\left(\frac{1}{t_1} + \frac{1}{t_2}\right)\right]^2 + v_n^2 \tag{10}$$

and the inverse transit time solution for sonic temperature in air is as follows (**5**):

$$T_s = \left(\frac{d^2}{1612}\right)\left[\frac{1}{t_1} + \frac{1}{t_2}\right]^2 + \frac{v_n^2}{403} \tag{11}$$

3.2.12 *velocity calibration range* (U_c to U_s, (m/s))—the range of velocity between creeping flow and the flow at which a critical Reynolds number is reached.

3.2.12.1 *Discussion*—The shadow correction is valid over a range of velocities where no discontinuities are observed in the axial attenuation coefficient.

3.2.13 *velocity resolution* (δv, (m/s))—the largest change in an along-axis wind component that would cause no change in the pulse arrival time count.

3.2.13.1 *Discussion*—Velocity resolution defines the smallest resolvable wind velocity increment as determined from system clock rate. For some systems, δv defined as the standard deviation of system dither can also be reported.

3.3 *Symbols:*

c = speed of sound, m/s,
C_p = specific heat at constant pressure, J/(kg·K),
C_v = specific heat at constant volume, J/(kg·K),
e = vapor pressure, Pa,
d = acoustic pathlength, m,
f = compressibility factor, dimensionless,
M = molecular weight of a gas, g/mol,
P = pressure, Pa,
R^* = universal gas constant, 8.31436 J/(mol·K),
RH = relative humidity, %,
t = transit time, μs,
t_t = total transit time, μs,
T = absolute temperature, K,
T_s = sonic absolute temperature, K,
U_c = upper limit for creeping flow, m/s,
U_s = critical Reynolds number velocity, m/s,
v_d = velocity component along acoustic propagation path, m/s,
v_{dm} = tunnel velocity component parallel to the array axis (v_t, cos θ), m/s,
v_n = velocity component normal to an acoustic propagation path, m/s,
v_t = free stream wind velocity component (unaffected by the presence of an obstacle such as the acoustic array), m/s,
δt = system delay, μs,
δt_t = system delay mismatch, μs,
Δt = clock pulse resolution, s,
α = acceptance angle, degree,
γ = specific heat ratio (C_p/C_v), dimensionless,
δv = velocity resolution, m/s,
θ = array angle of attack, degree, and
ρ = gas density, kg/m^3.

3.4 *Units*—Units of measurement are in accordance with IEEE/ASTM SI 10.

4. Summary of Test Method

4.1 Acoustic pathlength, system delay, and system delay mismatch are determined using the dual gas or zero wind chamber method. The acoustic pathlength and system clock rate are used to calculate the velocity resolution. Thermal sensitivity range is defined using a zero wind chamber. The axial attenuation coefficient, velocity calibration range, and transducer shadow effects are defined in a wind tunnel. Wind tunnel results are used to compute shadow corrections and to define acceptance angles.

5. Significance and Use

5.1 This test method provides a standard method for evaluating the performance of sonic anemometer/thermometers that use inverse time solutions to measure wind velocity components and the speed of sound. It provides an unambiguous determination of instrument performance criteria. The test method is applicable to manufacturers for the purpose of describing the performance of their products, to instrumentation test facilities for the purpose of verifying instrument performance, and to users for specifying performance requirements. The acoustic pathlength procedure is also applicable for calibration purposes prior to data collection. Procedures for operating a sonic anemometer/thermometer are described in Practices D5527.

5.2 The sonic anemometer/thermometer array is assumed to have a sufficiently high structural rigidity and a sufficiently low coefficient of thermal expansion to maintain an internal alignment to within the manufacturer's specifications over its designed operating range. Consult with the manufacturer for an internal alignment verification procedure and verify the alignment before proceeding with this test method.

5.3 This test method is designed to characterize the performance of an array model or probe design. Transducer shadow data obtained from a single array is applicable for all instruments having the same array model or probe design. Some non-orthogonal arrays may not require specification of transducer shadow corrections or the velocity calibration range.

6. Apparatus

6.1 *Zero Wind Chamber,* sized to fit the array and accommodate a temperature probe (Fig. 1) used to calibrate the sonic anemometer/thermometer. Line the chamber with acoustic foam with a sound absorption coefficient of 0.8 or better (Test Method C384) to minimize internal air motions caused by thermal gradients and to minimize acoustic reflections. Install a small fan within the chamber to establish thermal equilibrium before a zero wind calibration is made.

6.2 *Pathlength Chamber*—See Fig. 2.

6.2.1 Design the pathlength chamber to fit and seal an axis of the array for acoustic pathlength determination. Construct the chamber components using non-expanding, non-outgassing materials. Employ O-ring seals made of non-outgassing materials to prevent pressure loss and contamination. Design the chamber for quick and thorough purging. The basic pathlength chamber components are illustrated in Fig. 2.

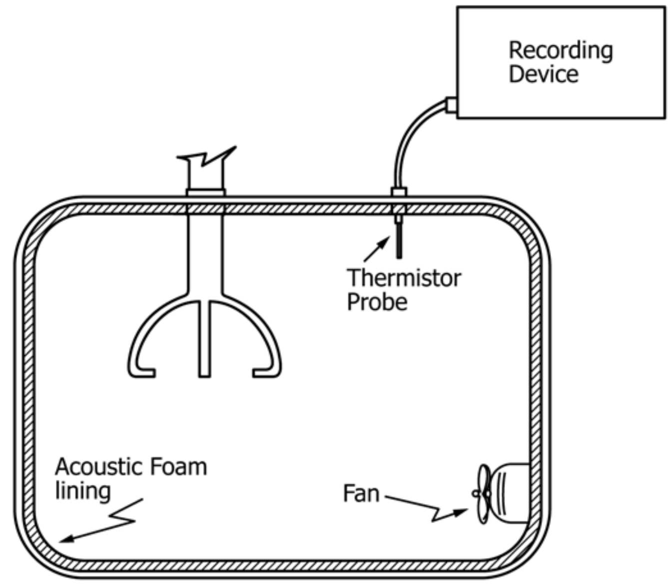

FIG. 1 Sonic Anemometer Array in a Zero Wind Chamber

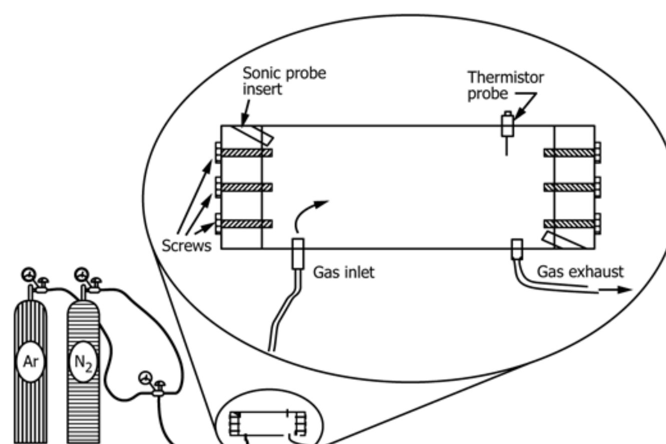

FIG. 2 Pathlength Chamber for Acoustic Pathlength Determination

6.2.2 *Gas Source and Plumbing,* to connect the pathlength chamber to one of two pressurized gas sources (nitrogen or argon). Employ a purge pump to draw off used gases. Required purity of the gas is 99.999 %.

6.3 *Temperature Transducer* (two required), with minimum temperature measurement precision and accuracy of ±0.1°C and ±0.2°C, respectively, and with recording readout. One is required for the zero wind chamber and one for the pathlength chamber.

6.4 *Wind Tunnel:*

6.4.1 *Size,* large enough to fit the entire instrument array within the test section at all required orientation angles. Design the tunnel so that the maximum projected area of the sonic array is less than 5 % of tunnel cross-sectional area.

6.4.2 *Speed Control,* to vary the flow rate over a range of at least 1.0 to 10 m/s within ±0.1 m/s or better throughout the test section.

6.4.3 *Calibration*—Calibrate the mean flow rate using transfer standards traceable to the National Institute of Standards and Technology (NIST), or by an equivalent fundamental physical method.

6.4.4 *Turbulence,* with a uniform velocity profile with a minimum of swirl at all speeds, and known uniform turbulence scale and intensity throughout the test section.

6.4.5 *Rotating Plate,* to hold the sonic transducer array in varying orientations to achieve angular exposures up to 360°, as needed. The minimum plate rotation requirements are ±60° in the horizontal and ±15° in the vertical, with an angular alignment resolution of 0.5°.

NOTE 1—Design the plate to hold the array at chosen angles without disturbing the test section wind velocity profile or changing its turbulence level.

6.5 *Measuring System:*

6.5.1 *Counter,* to log the anemometer velocity component readings, with a count resolution equaling or exceeding the clock rate of the sonic anemometer/thermometer.

6.5.2 *Recorder,* with at least a 10 Hz rate and a resolution comparable to instrument resolution, for recording onto magnetic or optical media the anemometer velocity component readings.

6.6 *Calipers,* for transducer separation distance measurements, with minimum tolerance of 0.1 mm.

6.7 *Ancillary Measurements*—Ancillary pressure (±0.5 hPa) and relative humidity measurements (±10 %) are needed for sonic temperature and acoustic pathlength determination if the ambient vapor pressure is greater than 20 Pa. These measurements can be obtained from on-site instruments or estimated from nearby data sources.

7. Precautions

7.1 Exercise care while using gas pressurized containers. Procedures for handling pressurized gas cylinders shall be posted and observed. Perform all testing with pressurized gases in a well-ventilated room. Use of the buddy system is recommended.

7.2 Maintain chamber temperatures and pressures close to laboratory temperature and pressure to minimize gradients that could cause convection within the chamber, but use sufficient over-pressure to prevent contamination from extraneous gases.

7.3 Ascertain that acoustic reflections and apparatus vibrations are not contaminating results.

NOTE 2—Noise and vibrations generated during wind tunnel operation are potential interferents. Isolate the array from extraneous noise and vibration.

7.4 Ensure that the transducer array geometry is not altered when mounted in the test chambers.

NOTE 3—Array support should not protrude into the wind tunnel.

8. Sampling

8.1 *Acoustic Pathlength, System Delay, and System Delay Mismatch*—If the dual gas procedure is used, repeat the procedures used to determine d and δ_t in argon and nitrogen gases for a minimum of ten times, or until consistent results are achieved. If the caliper method is used, measure and verify the transducer spacing to a tolerance of 0.1 mm. Independently determine d and δ_t for each axis of the acoustic array for each instrument.

8.2 *Thermal Stability Range*—Obtain a zero velocity reading over a period of at least one minute at room temperature. Repeat the procedure over the instrument's expected temperature operating range. Repeat the test for each transducer axis for each instrument.

8.3 *Axial Attenuation and Angular Shadow Effects*—After the wind tunnel test section velocity has stabilized, obtain the velocity readings at each position for a measurement period of 30 s. Obtain at least three consecutive measurements at each angle and tunnel velocity settings. Calculate the average and range of each of these readings.

8.4 *Shadow Correction*—Select a low velocity setting (at or below 2.0 m/s) and take one head-on (0°) reading, followed by one reading at each 10° interval to + 60° or beyond, as the apparatus permits. Reverse the process, going back through 0° to − 60°, and return to 0°. Average the results to a single value for each angular position. Use a measurement period of 30 s at each angle, and begin measurements only when the tunnel velocity is stable at the selected velocity. Repeat the procedure for an intermediate velocity (5 to 6 m/s) and high velocity (10 m/s or greater), but not exceeding U_s. Repeat the sequence for vertical angle orientations over a range of at least ±15°.

NOTE 4—Positions may be found where the flow across the array is not unambiguously defined, or where consistent results cannot be obtained due to flow blockage. The locations of these positions should be noted. For non-orthogonal axis sonic anemometers, refer to procedures described in (**4**) and (**10**).

9. Procedure

9.1 *Velocity Resolution* (δv)—The zero wind chamber procedure and the clock rate procedure are available to compute the velocity resolution.

NOTE 5—The clock rate procedure is applicable to all systems. The zero wind chamber procedure may also be applicable for systems that use synchronous phase angle detection or similar methods.

9.1.1 *Velocity Resolution by the Zero Wind Chamber Procedure*—Place the array in a zero wind chamber and wait approximately 20 min for the internal chamber temperature and air movement to stabilize. Note signal variation due to electronic dither and small scale turbulent motions within the chamber. If the signal variation over a 10 s sampling period does not exceed five quantization units, terminate the procedure and proceed to 9.1.2. Sample chamber velocities along each axis for 1 min and calculate the mean and standard deviation of this sample.

9.1.2 *Velocity Resolution by the Clock Rate Procedure: Increment of Resolution* (δv)—Calculate the clock pulse resolution (Δt) as the inverse of the clock rate in Hz. Use a nominal speed of sound (340 m/s) and acoustic pathlength (d) to calculate a nominal transit time (t) between transducer pairs in a zero wind field. The velocity resolution (δv) is given by

$$\delta v = \frac{d\Delta t}{2t^2} \quad (12)$$

9.2 *Acoustic Pathlength (d), System Delay (δt), and System Delay Mismatch (δt_t)*—The dual gas procedure (9.2.1) and the zero wind chamber procedure (9.2.2) are available. Use either method to determine *d*, δ*t*, andδ t_t. Perform the chosen procedure for each array axis.

NOTE 6—Conduct these procedures at room temperature (~25°C) unless other temperatures are specified.

9.2.1 *The Dual Gas Procedure:*

9.2.1.1 Mount one axis of the anemometer array in a gas chamber, purge the chamber, and fill with nitrogen (N_2) gas. Check the seals for leaks. Wait for motions and temperature within the chamber to stabilize. Record the temperature and total transit times in each direction (t_{t1} and t_{t2}) for 1 min. Calculate the system delay mismatch (Eq 5). If the mismatch exceeds the manufacturer tolerance, replace the transducers until a matched pair is found. Define the total transit time t_t as the average of t_{t1} and t_{t2}.

9.2.1.2 Solve for speed of sound in nitrogen c_{N_2}

$$c_{n_2} = [\gamma f R^* T/M]^{0.5} \quad (13)$$

See Table 1 for values of the specific heat ratios ($\gamma = c_p/c_v$), the compressibility factor, *f*, and the molecular weight, *M* (**11**).

9.2.1.3 Use the speed of sound for nitrogen and the t_t summations (or their equivalents in counts) to solve for *d*. For *n* summations *d* is determined by

$$d_{N_2} = c_{N_2} \sum t_t/n \quad (14)$$

Repeat the procedure until a consistent sample is obtained.

9.2.1.4 Purge the chamber, fill with Argon (Ar), and repeat the procedure.

9.2.1.5 Calculate the system delay (δ*t*) using the averaged values of speed of sound and acoustic pathlength determined for N_2, and Ar. The average delay in µs is given by

$$\delta t = \left| \frac{d_{N_2} - d_{Ar}}{c_{N_2} - c_{Ar}} \right| \quad (15)$$

This delay time in µs multiplied by the clock rate (12×10^6 for a 12 Mhz clock) is a count number that is subtracted from counts in the system software or programmable memory. Subtract δ*t* from t_t and calculate the true acoustic pathlength *d*. If consistent results cannot be obtained, terminate this procedure.

9.2.1.6 While the axis is still mounted in the chamber, record at least ten transit times for each direction through the axis and calculate the average t_1 and t_2. Assume zero wind in the chamber (v_n, $v_d = 0$) and calculate the acoustic pathlengths d_1 and d_2 using (Eq 6). Calculate velocities v_{d^1} and v_{d^2} using (Eq 7) and subtract v_{d^1} and v_{d^2}. If the v_d difference exceeds δ*v*, either change transducers and repeat the procedure, or repeat 9.2.1 separately for each direction through each axis. If acceptable results cannot be obtained, terminate the procedure.

9.2.1.7 Repeat 9.2.1.1 – 9.2.1.6 for each anemometer axis.

9.2.2 *The Zero Wind Chamber Procedure:*

9.2.2.1 Place the array in a zero wind chamber and monitor the chamber temperature. When the chamber temperature has stabilized (varies by 0.2°C or less over a period of 1 min), measure the chamber temperature to within ±0.2°C.

NOTE 7—A small fan may be used to mix the chamber air prior to measurement.

9.2.2.2 Determine the zero wind chamber relative humidity (RH). A desiccant can be used to stabilize chamber RH at a known value. Alternatively, a humidity measurement in the room can be assumed valid for the chamber.

NOTE 8—Humidity has a second order effect on this procedure, so estimations to within ±10 % are adequate. A common method for converting RH to vapor pressure (*e*) is the Tetens (**12**) equation

$$e = 0.0611\, RH \left[10^{7.5\, T/(237.3+T)}\right] \quad (16)$$

where *T* is given in °C.

9.2.2.3 Obtain a sonic temperature, T_s, using chamber temperature and vapor pressure with the approximation (**6**)

$$T_s \simeq T + 0.1e \quad (17)$$

9.2.2.4 Apply the result from 9.2.2.3 with the thermodynamic quantities presented in Table 1 to the speed of sound calculation

$$c_{air}[\gamma f R^* T_s/M]^{0.5} \quad (18)$$

9.2.2.5 Use results from 9.2.2.4 with summations of *n* total transit times in each direction through the acoustic array to calculate d_1 and d_2.

$$d_1 = c_{air} \sum t_{t1}/n \quad (19)$$

$$d_2 = c_{air} \sum t_{t2}/n \quad (20)$$

9.2.2.6 Measure the transducer spacing (*d*) on each axis of the array to a tolerance of 0.1 mm. System delay is the difference (converted to µs using c_{air}) between the pathlengths calculated in procedure 9.2.2.5 and caliper measurements. Record d_1, d_2, δt_1, δt_2, and δt_t and enter *d* and δ*t* corrections into the system software.

NOTE 9—The caliper measurement *d* should be less than the calculated pathlengths (d_1, d_2). If the caliper measurements exceed either calculated pathlength, repeat the caliper measurement. If the error persists, recalculate the pathlengths. If the error remains unresolved or δt_t exceeds the manufacturer's mismatch tolerance, terminate the procedure.

9.2.2.7 With *d* and δ*t* corrections installed, record transit times for each direction through the acoustic path to obtain new t_1 and t_2. Calculate v_d and compare it with δ*v*. If v_d exceeds δ*v* or the manufacturer's designated resolution threshold, change transducers and repeat the procedure.

9.2.2.8 Repeat procedures 9.2.2.1 – 9.2.2.7 for each anemometer axis.

NOTE 10—If the zero wind chamber is large enough to enclose the whole acoustic array, pathlength for each axis may be obtained simultaneously.

TABLE 1 Nominal Values of Specific Heat Ratio (γ), Compressibility Factor (*f*), and Molecular Weight (*M*) for Nitrogen, Argon, and Dry Air, and Their Respective Uncertainties (11)

Variable	Units	Nominal Value			Uncertainty
		Nitrogen	Argon	Air	
γ	dimensionless	1.4	1.67	1.4	±0.01
f	dimensionless	0.99997	0.99925	0.9997	±0.00005
M	g/mol	28.01	39.95	28.97	±0.02

9.3 *Thermal Stability-Range:*

9.3.1 Use the system calibration procedure to obtain a zero mean wind velocity reading along each axis in a zero wind chamber at room temperature. Record the mean velocities, the standard deviations, and the speed of sound.

9.3.2 Cool the entire apparatus to – 20°C or to the coldest desired operating temperature. Observe the wind reading and the speed of sound as the chamber and array temperature decreases. After the chamber temperature stabilizes and the chamber motion subsides, record the mean wind, standard deviations, and speed of sound after the chamber temperature stabilizes. Thermal sensitivity due to changes in wave train amplitude or phase lock are revealed as spikes or as an apparent increase in the chamber turbulence level. Bias in velocity readings during this procedure indicate a temperature dependence in system delay.

9.3.3 Repeat procedure 9.3.2 with the apparatus heated to 40°C or the warmest desired operating temperature. Record the temperature(s) at which thermal instability effects are first observed or note the absence of this phenomenon.

9.3.4 Subtract the velocity offset obtained in 9.3.2 from the velocity offset obtained in 9.3.3. If the offset difference exceedsδ v or the manufacturer's velocity resolution alternative, apply a manufacturer specified correction factor and repeat 9.3, or replace the transducers and repeat 9.2 and 9.3.

9.3.5 Repeat 9.3 for each axis on each instrument. If acceptable results cannot be obtained, terminate the procedure.

9.4 *Shadow Correction:*

9.4.1 This procedure is applicable to each array type or model where the measured wind might be affected by the presence of the array and supports that lie within the acceptance angle. For non-orthogonal arrays, refer also to (**4**) and (**10**).

9.4.2 Mount the array on a rotating plate in a wind tunnel with zero angle of attack (aligned to array center or u-axis) and zero elevation angle. Select a tunnel wind speed and obtain a wind tunnel velocity measurement (v_t) and an along-axis velocity measurement (v_d). Record the v_t/v_d ratio-as the first guess axial attenuation coefficient.

9.4.3 Adjust the angle of attack (θ) a maximum of 10°. Obtain a v_t reading and calculate the velocity component parallel to the array axis ($v_{dm} = v_t \cos\theta$). Record the v_{dm}/v_d ratio. Repeat this procedure for each angular increment of 10° or less between ±60° or until a known acceptance angle limit is reached.

9.4.4 Return the array to zero angle of attack and adjust the elevation angle 5°. Measure v_t, v_d, and record the v_t/v_d ratio. Repeat for angular increments of 5° over at least ±15° (or to the maximum desired vertical angle) and for at least one tunnel velocity in each range (low, intermediate, and high, see 8.4).

9.4.5 Repeat procedure 9.4.3 and 9.4.4 for the other horizontal array axis. If consistent results are obtained, proceed to 9.5. Otherwise, terminate the procedure.

9.5 *Velocity Calibration Range:*

9.5.1 Mount the array in the wind tunnel with zero angle of attack (aligned to one of the horizontal axes). Set the wind tunnel velocity to its lowest setting and obtain v_t and v_d. Record the v_t/v_d ratio for this tunnel velocity. If this v_t/v_d ratio is within 5 % of the v_t/v_d ratio obtained in procedure 9.4.2, this tunnel velocity is U_c. If the ratio differs by more than 5 %, incrementally adjust the tunnel velocity and recalculate v_t/v_d until intolerance results are obtained. This velocity is U_c.

9.5.2 Repeat the sequence described in 9.5.1 starting at 10 m/s or the highest desired anemometer calibration velocity. The highest velocity at which consistent results are found is U_s. If v_t/v_d is invariant over the desired range of velocities, this ratio is the axial attenuation coefficient. If v_t/ v_d varies, describe the axial attenuation coefficient as a function of velocity over the range of velocities where no discontinuities are observed.

9.6 *Transducer Shadow Correction and Acceptance Angle*—Use the information recorded in 9.4 and 9.5 to generate a transducer shadow correction algorithm or lookup table. With this algorithm or table installed in the instrument's microprocessor, repeat 9.4.2 and 9.4.3 at velocity settings near U_c and U_s, recording the v_{dm} /v_d ratios. The acceptance angle is the maximum angle from the array axis of symmetry over which the following conditions are met: (*a*) wind velocity components are unambiguously defined, (*b*) corrections adequately compensate for transducer array shadow effects.

10. Report

10.1 Report the internal alignment measurement results and manufacturer's specifications.

10.2 Report the velocity resolution and procedure used (9.1.2 or 9.1.1 and 9.1.2), the fundamental instrument sampling rate, clock rate, and number of samples averaged to produce each individual wind component reading.

10.3 Report the acoustic pathlength, system delay (average δt along each path or along each direction, as applicable), system delay mismatch, and the manufacturer's system delay mismatch tolerance. Include in the report the procedure used (9.2.1 or 9.2.2) and the temperatures and humidities at which these measurements were made.

10.4 Report the range of temperatures over which thermal stability was determined. Report the maximum high and low temperature deviations in velocity offset and speed of sound, and the temperatures at which they were measured. Include any observed bias in velocity readings and whether or not compensating corrections were applied.

10.5 Report the shadow correction algorithm (if applicable and the average residual v_{dm}/v_d ratio as percent dedition from unity.

NOTE 11—Items reported in 10.3 and 10.5 may be included in system algorithms for wind component calculations. Report whether or not this has been done.

10.6 Report the range of angles (±α) and velocities (U_c to U_s, if applicable) over which traceable wind component readings can be obtained. Indicate whether α, U_c, or U_s were defined by instrument performance or apparatus limitations. Include ambient temperatures and pressures at which these determinations were made.

11. Precision and Bias

11.1 The contributions of temperature measurement and thermodynamic constant uncertainties to electronic delay determination arise through the speed of sound equation. These uncertainties, expressed in percent of c, are presented in Table 2 for both the pathlength chamber and caliper measurement procedures. These figures were obtained with assumptions of a pressure near 101.3 kPa and temperature near 25°C. The assumed temperature measurement precision is ±0.2°C, with moisture controlled using desiccant.

11.2 System delay affects velocity and speed of sound readings by increasing t_1 and t_2 in (Eq 7) and (Eq 10) by the uncompensated system delay mismatch. Use these equations with typical transit times (t_1, t_2) and transit times plus mismatch ($t_1 + \delta t_1$, $t_2 + \delta t_2$) to determine measurement bias.

TABLE 2 Estimated Uncertainties in Speed of Sound *c* due to Uncertainties in *M*, γ, *f*, and *T*

Type of Pathlength Determination	Uncertainty in c, %			
	M	γ	f	T
Pathlength chamber	0.01	0.1	0.01	0.03
Caliper measurement	0.5	0.5	0.02	0.01

11.3 Caliper measurement uncertainties affect velocity readings (Eq 7) and speed of sound readings (Eq 10) by a factor of δd. This creates a velocity error of 0.67 % and a 2.2 m/s error in speed of sound for each millimetre of error on a 150 mm path. In practice, transducer spacing can vary by several tenths of a millimetre due to thermal expansion, handling, and wind loading effects. Changing or adjusting transducers can generate even larger spacing differences and should be followed by determination of a new acoustic pathlength.

11.4 The bias and stability of velocities in the wind tunnel test section determine the precision and bias of v_{dm}/v_d ratios. Tunnel vibrations also contribute to uncertainties. Estimated precisions are between 1 and 3 %.

12. Keywords

12.1 acceptance angle; acoustic pathlength; shadow correction; sonic anemometer; sonic temperature; sonic thermometer; speed of sound; system delay

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