INTERNATIONAL

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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~~SI 10 ~~Use of the International System of Units (SI): The Modern Metric System~~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**).

[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.

3.2.2.1 *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~~ wave:

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

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**):

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

The approximation for propagation in air is:

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

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~~axis:

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

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.

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

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**):

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

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):

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

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,~~is:

$$t_1 = t_{t1} - \delta_{t1} \quad (8)$$

$$t_2 = t_{t2} - \delta_{t2} \quad (9)$$

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~~is:

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

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

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

3.2.12 *velocity calibration range (U_c* toU_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~~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 ~~Practice~~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.

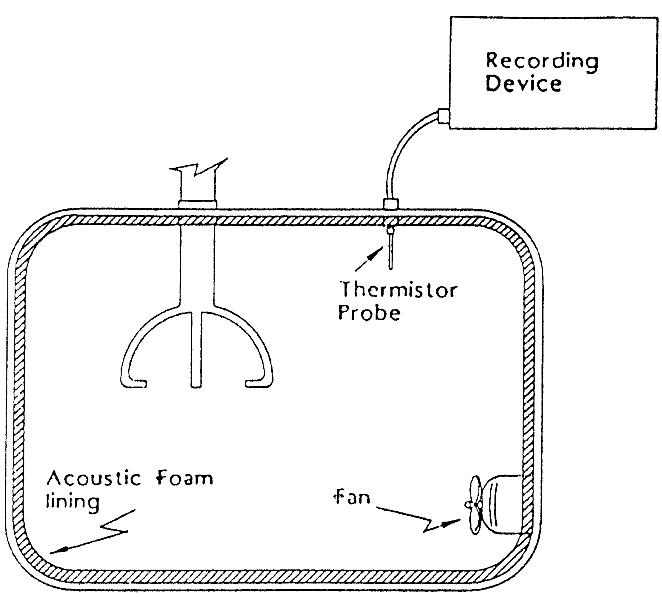

FIG. 1 Sonic Anemometer Array in a Zero Wind Chamber

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.

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.

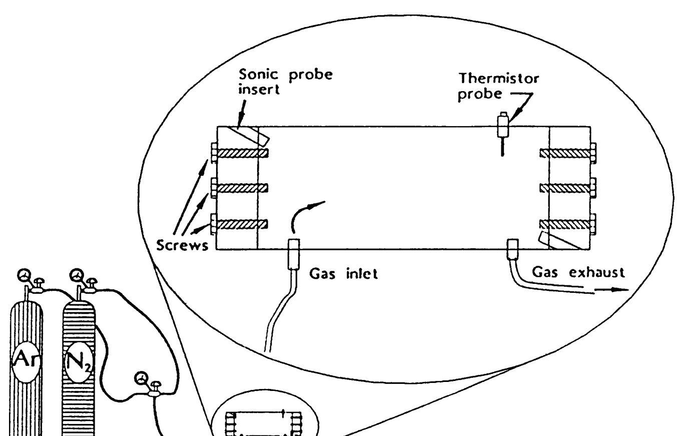

FIG. 2 Pathlength Chamber for Acoustic Pathlength Determination

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

$$\delta v = \frac{d \Delta t}{2t^2} \tag{12}$$

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, δt, and$\delta\, t_t$. 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}

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

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