Designation: D 6011 – 96

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

This standard is issued under the fixed designation D 6011; 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 *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:*

C 384 Test Method for Impedance and Absorption of Acoustical Materials by the Impedance Tube Method[2]

D 1356 Terminology Relating to Sampling and Analysis of Atmospheres[3]

D 5527 Practice for Measuring Surface Wind and Temperature by Acoustic Means[3]

E 380 Practice for Use of the International System of Units (SI) (the Modernized Metric System)[4]

3. Terminology

3.1 *Definitions*—For definitions of terms related to this test method, refer to Terminology D 1356.

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)**.[5]

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3.2.2.1 *Discussion*—The transducer shadow corrections are no longer valid above the critical Reynolds number due to a discontinuity in the axial attenuation coefficient.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

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

where:

ρ = density,
γ = specific heat ratio, and
s = isentropic (adiabatic) process **(6)**.

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 **(5)**:

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

The approximation for propagation in air is:

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

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

3.2.7 *system delay* (δ*t*, 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

[1] This test method is under the jurisdiction of ASTM Committee D-22 on Sampling and Analysis of Atmospheresand is the direct responsibility of Subcommittee D22.11on Meteorology.

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[2] *Annual Book of ASTM Standards*, Vol 04.06.

[3] *Annual Book of ASTM Standards*, Vol 11.03.

[4] *Annual Book of ASTM Standards*, Vol 14.02.

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

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

$$\delta t = (\delta t_1 + \delta t_2)/2 \quad (4)$$

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.

$$\delta t_t = |t_{t1} - t_{t2}| \quad (5)$$

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)**

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

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,

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

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

3.2.11.2 *Discussion*—Procedures in this test method include a test to determine whether separate determinations of δt_1 and δt_2 are needed, or whether an average δt can be used. The relationship of transit time to speed of sound is

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

and the inverse transit time solution for sonic temperature in air is as follows **(6)**:

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

3.2.12 *velocity calibration range* (U_c 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 *Abbreviations:Units*—Units of measurement are in accordance with Practice E 380.

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 D 5527.

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 C 384) 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.

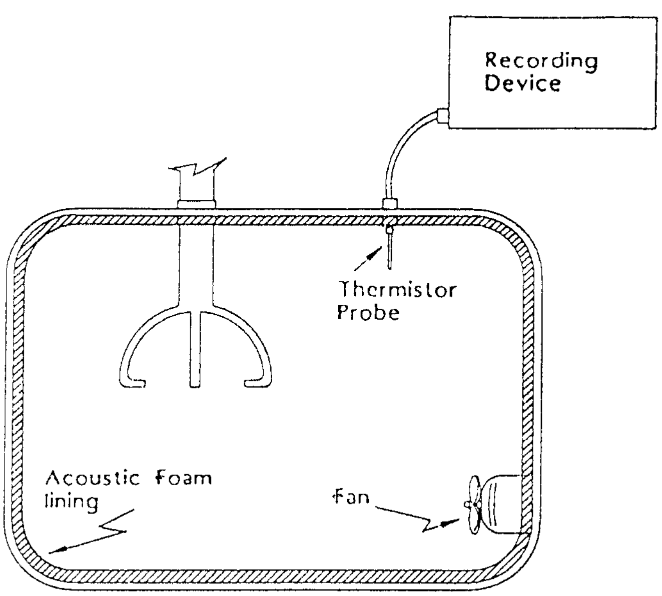

FIG. 1 Sonic Anemometer Array in a Zero Wind Chamber

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*:

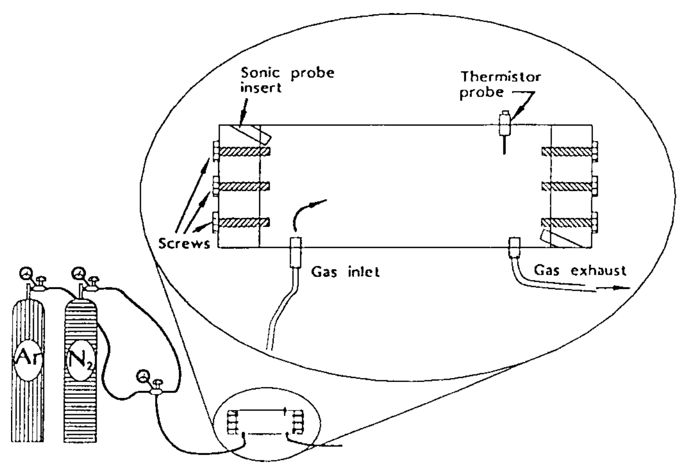

FIG. 2 Pathlength Chamber for Acoustic Pathlength Determination