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AMERICAN NATIONAL STANDARD

**Measurement Microphones – Part 2:
Primary Method for Pressure Calibration of
Laboratory Standard Microphones by the
Reciprocity Technique**

ANSI S1.15-2005/Part 2

Accredited Standards Committee S1, Acoustics

Standards Secretariat
Acoustical Society of America
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**ANSI S1.15- 2005 /Part 2
(Replaces ANSI S1.10-1966)**

AMERICAN NATIONAL STANDARD

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Primary Method for Pressure Calibration of
Laboratory Standard Microphones by the
Reciprocity Technique**

Secretariat

Acoustical Society of America

Approved by:

**American National Standards Institute, Inc.
9 March 2005**

Abstract

This Standard specifies a primary method for the calibration of microphones by the reciprocity technique. The specifications are intended to ensure that primary calibration with the reciprocity technique can attain the highest accuracy. The technical requirements of this American National Standard is identical to International Standard IEC 61094-2: 1992, "Measurement microphones -- Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique". Various improvements have been made to include recent technical information.

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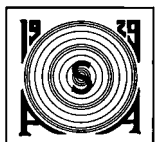
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Foreword

[This Foreword is for information only, and is not a part of the American National Standard ANSI S1.15 - 200X/Part 2 American National Standard American National Standard Measurement Microphones – Part 2: Primary Method for Pressure Calibration of laboratory Standard Microphones by the Reciprocity Technique].

This standard comprises a part of a group of definitions, standards, and specifications for use in acoustics. It was developed and approved by Accredited Standards Committee S1 Acoustics, under its approved operating procedures. Those procedures have been accredited by the American National Standards Institute (ANSI). The Scope of Accredited Standards Committee S1 is as follows:

Standards, specifications, methods of measurement and test, and terminology in the field of physical acoustics, including architectural acoustics, electroacoustics, sonics and ultrasonics, and underwater sound, but excluding those aspects which pertain to biological safety, tolerances, and comfort.

The technical requirements in this American National Standard are identical to the international standard IEC 61094-2 1992-03, *Measurement Microphones – Part 2: Primary Method for Pressure Calibration of Laboratory Standard Microphones by the Reciprocity Technique*. Various improvements have been made to include the latest information on pressure and temperature coefficients for microphone sensitivity correction and physical properties of air.

This standard replaces ANSI S1.10-1966 American National Standard Method for the Calibration of Microphones.

Annexes A and B form an integral part of this standard.

Annexes C, D, E, F, and G are for information only.

At the time this Standard was submitted to Accredited Standards Committee S1, Acoustics for approval, the membership was as follows:

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Working Group S1/WG 1 Standard Microphones, which assisted Accredited Standards Committee S1, Acoustics, in the development of this standard, had the following membership.

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Suggestions for improvements of this standard will be welcomed. They should be sent to Accredited Standards Committee S1, Acoustics, in care of the Standards Secretariat of the Acoustical Society of America, 35 Pinelawn Road, Suite 114E, Melville, New York 11747-3177. Telephone: 631-390-0215; FAX: 631-390-0217; E-mail: asastds@aip.org

American National Standard

Measurement Microphones – Part 2: Primary Method for Pressure Calibration of Laboratory Standard Microphones by the Reciprocity Method

1 Scope

This standard

- is applicable to laboratory standard microphones meeting the requirements of ANSI S1.15-1997/Part 1 (R2001) and other types of condenser microphones having the same mechanical dimensions;
- specifies a primary method of determining the pressure sensitivity to establish a reproducible and accurate basis for the measurement of sound pressure.

2 Normative references

The following referenced documents are indispensable for the application of this standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ANSI S1.1-1994 (R 1999) *American National Standard Acoustical Terminology*.

ANSI S1.15-1997/Part 1 (R2001), *American National Standard Measurement microphones – Part 1: Specifications for Laboratory Standard Microphones*.

ANSI/IEEE 260.4-1996 (R2002) *American National Standard Letter Symbols and Abbreviations for Quantities Used in Acoustics*.

IEC 60050-801:1994 *International electrotechnical vocabulary – Chapter 801: Acoustics and electroacoustics*.

Guide to the expression of uncertainty in measurement, 1995, BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OILM

3 Definitions

For the purposes of this standard, the terms and definitions given in ANSI S1.1:1994, IEC 60050-810:1994, and ANSI/IEEE 260.45-1996 (R2002), and the following apply

NOTE Boldface symbols represents complex quantities.

3.1

reciprocal microphone

A linear passive microphone for which the open-circuit reverse and forward transfer impedances are equal in magnitude.

3.2

phase angle of pressure sensitivity of a microphone

For a given frequency, the phase angle between the open-circuit voltage and the uniform sound pressure acting on the diaphragm.

Unit: degree or radian ($^{\circ}$ or rad).

3.3

electrical transfer impedance

For a system of two acoustically coupled microphones the quotient of the open-circuit voltage of the microphone used as a receiver by the input current through the electrical terminals of the microphone used as a transmitter.

Unit: ohm (Ω).

NOTE This impedance is defined for the ground-shield configuration given in 7.2 of ANSI S1.15-1997/Part 1 (R2001).

3.4

acoustic transfer impedance

For a system of two acoustically coupled microphones the quotient of the sound pressure acting on the diaphragm of the microphone used as a receiver by the short-circuit volume velocity produced by the microphone used as a transmitter.

Unit: pascal-second per cubic metre ($\text{Pa}\cdot\text{s}\cdot\text{m}^{-3}$).

3.5

coupler

A device which, when fitted with microphones, forms a cavity of predetermined shape and dimensions acting as an acoustic coupling element between the microphones.

4 Reference environmental conditions

The reference environmental conditions are:

Temperature: $t_r = 23.0\text{ }^{\circ}\text{C}$

Static pressure: $p_{s,r} = 101.325\text{ kPa}$

Relative humidity: $H_r = 50\%$

5 Principles of pressure calibration by reciprocity

5.1 General principle

A reciprocity calibration of microphones may be carried out by means of three microphones, two of which shall be reciprocal, or by means of an auxiliary sound source and two microphones, one of which must be reciprocal.

NOTE If one of the microphones is not reciprocal it can only be used as a sound receiver.

5.1.1 General principles using three microphones

Let two of the microphones be connected acoustically by a coupler. Using one of them as a sound source and the other as a sound receiver, the electrical transfer impedance is measured. When the acoustic transfer impedance of the system is known, the product of the pressure sensitivities of the two coupled microphones can be determined. Using pair-wise combinations of microphones (1), (2) and (3), three such mutually independent products are available, from which an expression for the pressure sensitivity of each of the three microphones can be derived.

5.1.2 General principles using two microphones and an auxiliary sound source

First, let the two microphones be connected acoustically by a coupler, and the product of the pressure sensitivities of the two microphones be determined, see 5.1.1. Next, let the two microphones be presented to the same sound pressure, set up by the auxiliary sound source. The ratio of the two output voltages will then equal the ratio of the two pressure sensitivities. Thus, from the product and the ratio of the pressure sensitivities of the two microphones, an expression for the pressure sensitivity of each of the two microphones can be derived.

NOTE In order to obtain the ratio of pressure sensitivities, a direct comparison method may be used, and the auxiliary sound source may be a third microphone having mechanical or acoustical characteristics which differ from those of the microphones being calibrated.

5.2 Basic expressions

Laboratory standard microphones and similar microphones are considered reciprocal and thus the two-port equations of the microphones can be written as:

$$\underline{z}_{11}\underline{i} + \underline{z}_{12}\underline{q} = \underline{U} \quad (1)$$

$$\underline{z}_{21}\underline{i} + \underline{z}_{22}\underline{q} = \underline{p}$$

where

$\underline{p}$ is the sound pressure, uniformly applied, at the acoustical terminals (diaphragm) of the microphone;

$\underline{U}$ is the signal voltage at the electrical terminals of the microphone;

$\underline{q}$ is the volume velocity through the acoustical terminals (diaphragm) of the microphone;

$\underline{i}$ is the current through the electrical terminals of the microphone;

$\underline{Z}_{11} = \underline{Z}_e$ is the electrical impedance of the microphone when the diaphragm is blocked;

$\underline{Z}_{22} = \underline{Z}_a$ is the acoustic impedance of the microphone when the electrical terminals are unloaded;

$\underline{Z}_{12} = \underline{Z}_{21} = \underline{M}_p \underline{Z}_a$ is equal to the reverse and forward transfer impedances, $\underline{M}_p$ being the pressure sensitivity of the microphone.

Equations (1) may then be rewritten as:

$$\underline{Z}_e \underline{i} + \underline{M}_p \underline{Z}_a \underline{q} = \underline{U} \quad (1a)$$

$$\underline{M}_p \underline{Z}_a \underline{i} + \underline{Z}_a \underline{q} = \underline{p}$$

which constitute the equations of reciprocity for the microphone.

Let microphones (1) and (2) with the pressure sensitivities $\underline{M}_{p,1}$ and $\underline{M}_{p,2}$ be connected acoustically by a coupler. From equations (1a) it is seen that a current $\underline{i}_1$ through the electrical terminals of microphone (1) will produce a short-circuit volume velocity (where the term "short circuit" describes the condition for which $\underline{p}=0$ at the diaphragm) of $\underline{M}_{p,1} \underline{i}_1$ and thus a sound pressure $\underline{p}_2 = \underline{Z}_{a,12} \underline{M}_{p,1} \underline{i}_1$ at the acoustical terminals of microphone (2), where $\underline{Z}_{a,12}$ is the acoustic transfer impedance of the system.

The open-circuit voltage of microphone (2) will then be:

$$\underline{U}_2 = \underline{M}_{p,2} \underline{p}_2 = \underline{M}_{p,1} \underline{M}_{p,2} \underline{Z}_{a,12} \underline{i}_1$$

Thus the product of the pressure sensitivities is given by:

$$\underline{M}_{p,1} \underline{M}_{p,2} = \frac{1}{\underline{Z}_{a,12}} \frac{\underline{U}_2}{\underline{i}_1} \quad (2)$$

5.3 Insert voltage technique

The insert voltage technique is used to determine the open-circuit voltage of a microphone when it is electrically loaded.

Let the microphone having a certain open-circuit voltage and internal impedance be connected to a load impedance. To measure the open-circuit voltage, an impedance, small compared to the load impedance, is connected in series to the microphone and a calibrating voltage applied across it.

Let a sound pressure and a calibrating voltage of the same frequency be applied alternately. When the calibrating voltage is adjusted until it gives the same voltage drop across the load impedance as results from the sound pressure on the microphone, the open-circuit voltage will be equal in magnitude to the calibrating voltage.

5.4 Evaluation of the acoustic transfer impedance

The acoustic transfer impedance $\underline{Z}_{a,12} = p_2/(M_{p,1}\dot{I}_1)$ can be evaluated from the equivalent circuit in Figure 1, where $\underline{Z}_{a,1}$ and $\underline{Z}_{a,2}$ are the acoustic impedances of microphones (1) and (2) respectively.

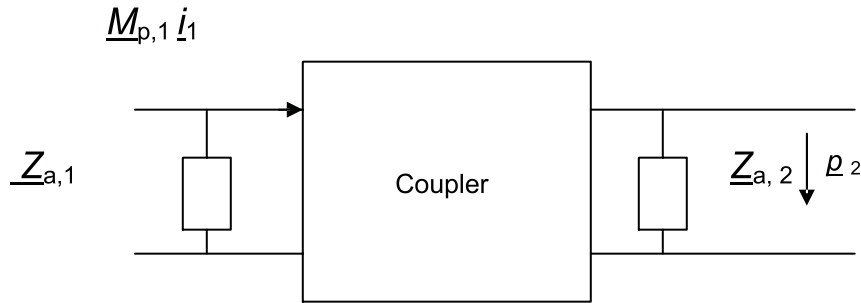


Figure 1 — Equivalent circuit for evaluating the acoustic transfer impedance $\underline{Z}_{a,12}$

In several cases, $\underline{Z}_{a,12}$ can be evaluated theoretically. Assume the sound pressure to be the same at any point inside the coupler (this will take place when the physical dimensions of the coupler are very small compared to the wavelength). The gas in the coupler then behaves as a pure compliance and, from the equivalent circuit in Figure 2, $\underline{Z}_{a,12}$ is given by $\underline{Z}'_{a,12}$ (assuming adiabatic compression and expansion of the gas):

$$\frac{1}{\underline{Z}'_{a,12}} = \frac{1}{\underline{Z}_{a,V}} + \frac{1}{\underline{Z}_{a,1}} + \frac{1}{\underline{Z}_{a,2}} = j\omega \left(\frac{V}{\kappa p_s} + \frac{V_{e,1}}{\kappa_r p_{s,r}} + \frac{V_{e,2}}{\kappa_r p_{s,r}} \right) \quad (3)$$

where

V is the total geometrical volume of the coupler, m^3 ;

$V_{e,1}$ is the equivalent volume of microphone (1), m^3 ;

$V_{e,2}$ is the equivalent volume of microphone (2), m^3 ;

$\underline{Z}_{a,V} = \frac{\kappa p_s}{j\omega V}$ is the acoustic impedance of the gas enclosed in the coupler, $\text{Pa} \cdot \text{s} \cdot \text{m}^{-3}$;

ω is the angular frequency, $\text{rad} \cdot \text{s}^{-1}$;

p_s is the static pressure, Pa;

κ is the ratio of the specific heat capacities at measurement conditions;

κ_r is κ at reference conditions.

Values for κ and κ_r can be derived from equations given in Annex F.

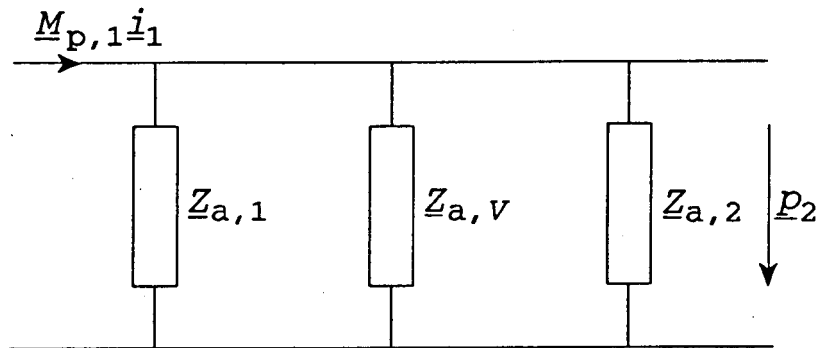


Figure 2 — Equivalent circuit for evaluating $Z_{a,12}$ when coupler dimensions are small compared with wavelength

At higher frequencies, when the dimensions are not sufficiently small compared with the wavelength, the evaluation of $Z_{a,12}$ generally becomes complicated. However, if the shape of the coupler is cylindrical and the diameter d is the same as that of the microphone diaphragms, then, at frequencies (f) where plane wave transmission can be assumed, (typically below $f = 0.586 c/d$) the whole system can be considered as a homogeneous transmission line (see Figure 3). $Z_{a,12}$ is then given by $Z'_{a,12}$ (assuming adiabatic compression and expansion of the gas):

$$\frac{1}{Z'_{a,12}} = \frac{1}{Z_{a,0}} \left[\left(\frac{Z_{a,0}}{Z_{a,1}} + \frac{Z_{a,0}}{Z_{a,2}} \right) \cosh \underline{\gamma} \ell_o + \left(1 + \frac{Z_{a,0}}{Z_{a,1}} \frac{Z_{a,0}}{Z_{a,2}} \right) \sinh \underline{\gamma} \ell_o \right] \quad (4)$$

where

$$Z_{a,0} = \rho c / S_o$$

ρ is the density of the gas enclosed, $\text{kg} \cdot \text{m}^{-3}$

c is the free-space speed of sound in the gas, $\text{m} \cdot \text{s}^{-1}$;

S_o is the cross-sectional area of the coupler, m^2 ;

ℓ_o is the length of the coupler, i.e. the distance between the two diaphragms, m ;

$\underline{\gamma} = \alpha + j\beta$ is the complex propagation coefficient, m^{-1} .

When used in Equation (4), $\underline{\gamma}$ may be approximated by putting α equal to zero and β equal to ω/c .

Allowance shall be made for any air volume associated with the microphones that is not enclosed by the circumference of the coupler and the two diaphragms (see 7.3.3).

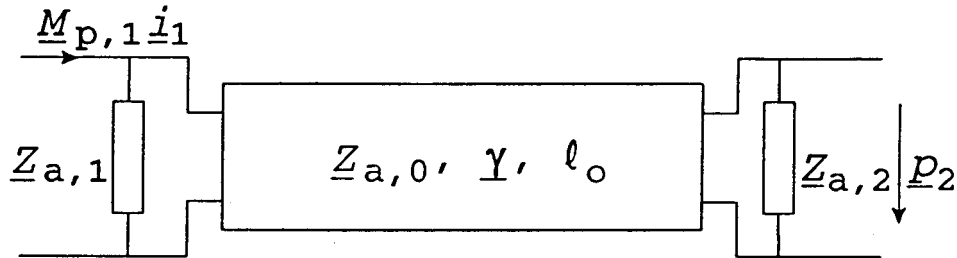


Figure 3 — Equivalent circuit for evaluating $\underline{Z}_{a,12}$, when plane wave transmission in the coupler can be assumed

5.5 Heat-conduction correction

The evaluation of $\underline{Z}'_{a,12}$ in 5.4 assumes adiabatic conditions in the coupler. However, in practice, the influence of heat conduction at the walls of the coupler causes departure from purely adiabatic conditions, especially for small couplers and low frequencies. For a coupler of simple shape and under the assumption that the walls remain at a constant temperature, the influence of the heat conduction losses can be calculated and expressed in terms of a complex correction factor $\underline{\Delta}_H$ to the geometrical volume V in Equation (3) or to the cross-sectional area S_0 in Equation (4).

Expressions for the correction factor $\underline{\Delta}_H$ are given in Annex A.

5.6 Capillary tube correction

The coupler is usually fitted with capillary tubes in order to equalize the static pressure inside and outside the coupler. Two such capillary tubes also permit the introduction of a gas other than air.

The acoustic input impedance of an open capillary tube is given by:

$$\underline{Z}_{a,C} = \underline{Z}_{a,t} \tanh \gamma \ell_c \quad (5)$$

where

$\underline{Z}_{a,t}$ is the complex acoustic wave impedance of an infinite tube, $\text{Pa} \cdot \text{s} \cdot \text{m}^{-3}$;

ℓ_c is the length of the tube, m.

The shunting effect of the capillary tubes can be taken into account by introducing a complex correction factor $\underline{\Delta}_C$ to the acoustic transfer impedances given in equations (3) and (4):

$$\Delta_{C,12} = 1 + n \frac{Z''_{a,12}}{Z_{a,C}} \quad (6)$$

where

n is the number of identical capillary tubes used;

$Z''_{a,12}$ is the acoustic transfer impedance $Z'_{a,12}$ corrected for heat conduction according to 5.5.

An expression for the acoustic input impedance $Z_{a,C}$ of an open capillary tube is given in Annex B.

5.7 Final expressions for the pressure sensitivity

5.7.1 Method using three microphones

Let the electrical transfer impedance U_2/i_1 (see 5.2) be denoted by $Z_{e,12}$ with similar expressions for other pairs of microphones.

Taking into account the corrections given in 5.5 and 5.6, the final expression for the modulus of the pressure sensitivity of microphone (1) is:

$$|M_{p,1}| = \left\{ \frac{Z_{e,12} Z_{e,31}}{Z_{e,23}} \left\| \frac{Z''_{a,23}}{Z''_{a,12} Z''_{a,31}} \left\| \frac{\Delta_{C,12} \Delta_{C,31}}{\Delta_{C,23}} \right\| \right\} \right\}^{1/2} \quad (7)$$

Similar expressions apply for microphones (2) and (3).

The phase angle of the pressure sensitivity for each microphone is determined by a similar procedure from the phase angle of each term in the above expression.

5.7.2 Method using two microphones and an auxiliary sound source

If only two microphones and an auxiliary sound source are used, the final expression for the modulus of the pressure sensitivity is:

$$|M_{p,1}| = \left\{ \frac{M_{p,1}}{M_{p,2}} \frac{Z_{e,12}}{Z''_{a,12}} \Delta_C \right\}^{1/2} \quad (8)$$

where the ratio of the two pressure sensitivities is measured by comparison against the auxiliary source, see 5.1.2.

6 Factors influencing the pressure sensitivity

6.1 General

The pressure sensitivity of a condenser microphone depends on polarizing voltage and environmental conditions. Further, the definition of the pressure sensitivity implies that certain requirements be

fulfilled by the measurements. It is essential during a calibration that these conditions are controlled sufficiently well so that the resulting uncertainty components are small.

6.2 Polarizing voltage

The sensitivity of a condenser microphone is approximately proportional to the polarizing voltage, and thus the polarizing voltage actually used during the calibration shall be reported.

To conform to ANSI S1.15-1997/Part 1 (R2001) a polarizing voltage of 200.0 V is recommended.

6.3 Ground shield reference configuration

According to 3.3 of ANSI S1.15-1997/Part 1 (R2001), the open-circuit voltage shall be measured at the electrical terminals of the microphone when it is attached to a specified ground-shield configuration using the insert voltage technique described in 5.3. Specifications for ground-shield configurations for laboratory standard microphones are given in ANSI S1.15-1997/Part 1 (R2001).

The appropriate ground-shield configuration shall apply to both transmitter and receiver microphones during the calibration, and the shield shall be connected to ground potential.

If any other arrangement is used, the results of a calibration shall be referred to the reference ground-shield configuration.

If the manufacturer specifies a maximum mechanical force to be applied to the central electrical contact of the microphone, this limit shall not be exceeded.

6.4 Pressure distribution over the diaphragm

The definition of the pressure sensitivity assumes that the sound pressure over the diaphragm is applied uniformly. The output voltage of a microphone presented with a non-uniform pressure distribution over the surface of the diaphragm will differ from the output voltage of the microphone when presented with a uniform pressure distribution having the same mean value, because usually the microphone is more sensitive to a sound pressure at the centre of the diaphragm.

For cylindrical couplers, as described in Annex C, both longitudinal and radial wave motions will be present. The radial wave motion will result in a non-uniform pressure distribution over the diaphragm. It will be generated when the source differs from a true piston source covering the whole end surface of the coupler or when the combined microphone/coupler geometry is not a perfect right angle cylinder.

It is recommended that the sound pressure distribution during a calibration should be uniform to better than ± 0.1 dB over the surface of the diaphragm. However, it is difficult to control this condition in an actual calibration set-up due to the geometrical imperfection of a real microphone. Although radial wave motion can never be avoided because the velocity distribution of the transmitter microphone differs from that of a true piston, couplers having the same diameter as that of the microphone diaphragm will exhibit the smallest amount of radial wave motion and be less sensitive to geometrical imperfections than couplers with larger diameters.

However, when a calibration at high frequencies with a high accuracy is necessary, it may be preferable to use more than one coupler with different dimensions to assess the true sensitivity of the microphones.