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Acoustic metrology – an overview of calibration methods and their uncertainties

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Abstract. The paper gives a brief description of the principles and the uncertainty of the acoustic calibration methods that today are applied by National Metrology Institutes and calibration service centers. Even if some of the calibration principles have been applied over more than half a century, the methods and the instrumentation are still being refined in order to minimize their uncertainty, to extend their frequency ranges, to include extra parameters and to speed up slow processes. In addition to the traditional methods for microphone sensitivity and frequency response calibration, new development areas, like for example wind power, has created needs for low-frequency and infra-sound calibration, down to 0.1 Hz. Other high-tech areas have lead to the development of methods for phase response comparison calibration of microphones for large arrays, for sound intensity measurement and for verification of dynamic linearity of microphones at very high sound pressure levels, up to about 174 dB that corresponds to 10 kPa.

Keywords: Microphone calibration; pressure reciprocity; free-field reciprocity; coupler comparison calibration; electrostatic actuator; phase response calibration; high-pressure calibration; infrasound calibration; calibration uncertainty

1 Introduction

During the later decades measurement of sound has become increasingly important. More and more people are being disturbed by noise at home, during transportation and at their workplaces. People are getting stressed by noise and some may even, in severe cases, lose their hearing due to the noise. Many manufactures have become aware of the drawbacks related to the noise of their products. If too high, the noise may even harm their own businesses – they may over time lose their ability to compete. Noise, or rather low noise, has become an important competition parameter for many types of products, ranging from consumer products like vacuum cleaners and refrigerators to advanced industrial machinery and to means of transportation like ships, high speed trains and large passenger aircrafts. For these and other reasons, acoustic measurement and acoustic metrology have become very important activities for the modern society.

2 Measurement and calibration ranges

Sound measurements in air are performed over a wide range of frequency that goes from infrasound to ultrasound or, say, from a tenth of a Hertz to about 200 kHz. Sound is also measured over a wide dynamic range that begins below the threshold of human hearing, below 20 μPa or 0 dB, and goes up to more than 20 kPa or 180 dB. These wide ranges and the different types of sound field, which occur, cause a need for many different models of microphone and several different calibration and test methods. This paper describes principles and uncertainties of the basic methods that are standardized by the International Electrotechnical Commission (IEC), Technical Committee No. 29 [1]. Also some supplementary, less commonly applied, methods are briefly described.

3 Measurement and reference microphones

Essentially all commonly used measurement [2] and reference standard [3] microphones are condenser microphones. Condenser microphones are selected, because of their essentially flat frequency responses and their high mechanical stability. Also their simple shape and design is important, as this makes it possible not only to measure, but also to calculate many of their properties, including their interaction with the principal types of sound field.

IEC/TC29 has worked out a standard (IEC61094-4) for the commonly used types of measurement microphone, which are called working standard microphones. Depending on their diameters, 23.77 mm, 12.7 mm and 6.35 mm they are designated WS1, WS2 and WS3 (see Fig. 1). Another standard (IEC61094-1) specifies Laboratory Standard Microphones, named LS1 (23.77 mm) and LS2 (12.7 mm). They are designed to fit into calibration

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Fig. 1. Working standard microphones. IEC61094-4 types WS1 (23.77 mm), WS2 (12.7 mm) and WS3 (6.35 mm) are shown with and without diaphragm protection grids.

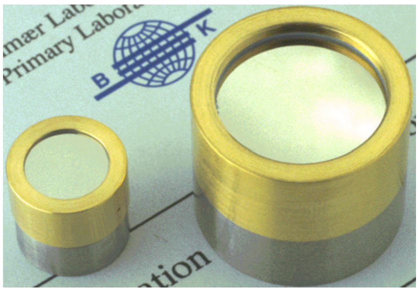

Fig. 2. Laboratory standard microphones. LS2 Ø12.7 mm (left) and LS1 Ø23.77 mm (right) may be calibrated by both the pressure and the free-field reciprocity methods and serve as National Reference Standards.

couplers and are the types of microphone that by national metrology institutes (NMIs) are used as national standards, Reference Microphones (see Fig. 2). The two standards specify mechanical dimensions, sensitivity, frequency response, acoustic impedance, dynamic range, ambient influence and stability.

A condenser microphone is a reciprocal transducer [4]. It can, of course, work as a microphone, by converting an acoustic signal to an electrical signal, but it can also work as a sound source – it can convert an electrical input to an acoustical output. Such reciprocal microphones may be calibrated by the reciprocity calibration principle, which is described in the following.

4 Sound fields and dedicated microphones

Sound is measured at many different places and sound fields can be very different, but there are three basic and principal types. Within cavities, whose dimensions are smaller than say a quarter of the sound's wavelength, the field is called a *pressure-field*. Typically such a field occurs in couplers for calibration of microphones, telephones and hearing aids. The sound field inside an-echoic rooms or out of doors, where sound may propagate freely without disturbance from reflecting objects, is called a *free-field* [5], while the type of field in rooms with hard reflecting walls and/or between many sound sources is called a *diffuse-field* [6].

Any measurement probe influences the quantity it measures – also the condenser microphone. The influence

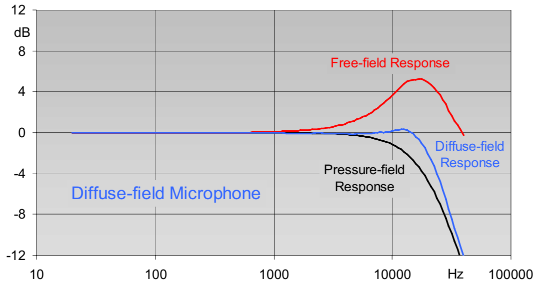

Fig. 3. Free-field, diffuse-field and pressure responses of a microphone (WS2) optimized for use in diffuse sound fields.

depends on the type of sound field. In order not to influence the pressure that occurs in a cavity, the applied microphone should ideally have a very stiff diaphragm (high acoustic impedance). Correspondingly for a free-field, in order not to influence the pressure in the selected measurement point, the diameter of the inserted microphone should be small, ideally less than say 5–7% of the wavelength. In practice, this is rarely achievable; therefore, it is necessary to account for the occurring change of pressure. This should be done both while measuring with the microphone and while calibrating the microphone. A corresponding, but smaller, pressure change occurs, when a microphone is placed in a diffuse sound field.

It is very important to notice that the pressure changes occurring in free and diffuse sound fields, in practice, depend only on the dimensions of the microphone body. It is, therefore, essentially the same for all microphones units of same model and, therefore, if measured once, the obtained values are valid for and may be used as correction values for any other microphone of the given model. Figure 3 shows frequency responses of a microphone (Ø12.7 mm) that is designed to have a flat response in a diffuse sound field. There, is a fixed ratio between its free-field, diffuse-field and pressure responses (fixed difference in dB). Most microphone manufacturers supply correction data, so, if one of the responses is measured and thus known, the two other ones can be calculated. Essentially all calibrations of working standard microphones make use of this fact.

5 Principle of reciprocity calibration

Microphone calibration by the reciprocity technique was invented in the 1940s [7–9][1]. Since then the method has become refined and standardised and is now the dominating primary calibration technique for determining both pressure-field [10] and free-field [11] responses. The methods that are quite complex and time consuming to work with are mainly applied by national metrology institutes and by leading microphone manufacturers.

Reciprocity calibration is based on the measurement of the transfer function between two coupled microphones that are operated as a source and a sensor respectively.

[1] Reference [8] is abbreviated form of reference [7].

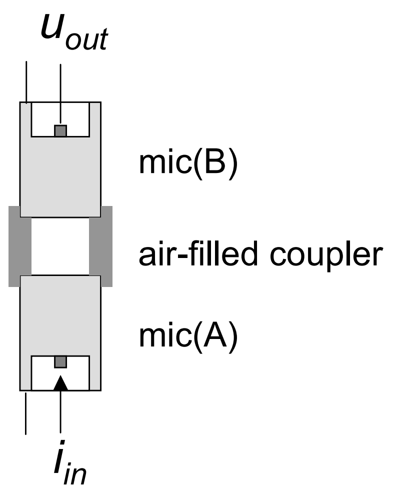

Fig. 4. Microphones coupled by air-filled cavity for pressure response calibration.

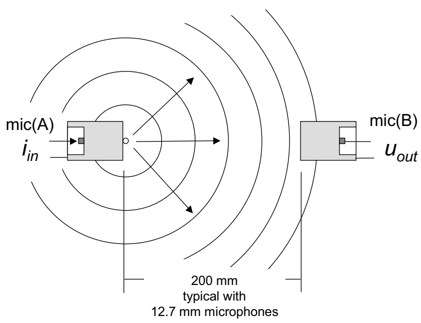

Fig. 5. Microphones coupled by air in the open space for free-field reciprocity calibration.

The microphones are coupled together in an acoustically well-defined way, while the over-all transfer function, the ratio between sensor output voltage and source input current, is measured (see Figs. 4 and 5). From this ratio, called the electrical transfer impedance (Z_e), and from the acoustic coupling represented by the acoustic transfer impedance (Z_a), the product of the microphone sensitivities can be determined:

$$M_1 M_2 = \left(\frac{Z_e}{Z_a}\right)_A ,$$

where M_1 and M_2 are the sensitivities of microphones 1 and 2, Z_e/Z_a is the ratio of electrical and acoustical transfer impedance.

By using three microphones (1, 2, 3) and by making impedance ratio determinations (A, B, C) for the three possible combinations of microphone (1-2, 1-3, 2-3), the sensitivities of all microphones can be calculated by solving the equations below:

$$M_1 M_2 = \left(\frac{Z_e}{Z_a}\right)_A , M_1 M_3 = \left(\frac{Z_e}{Z_a}\right)_B , M_2 M_3 = \left(\frac{Z_e}{Z_a}\right)_C .$$

Free-field or pressure sensitivity can be obtained by proper selection of the microphone coupling method.

The pressure-field responses are thus obtained by coupling the microphones with the air (or gas) contained in a small closed cavity, while the free-field responses are obtained with an open-air coupling in a room with no disturbing reflecting surfaces (an anechoic room) (see Figs. 4 and 5).

6 Primary pressure reciprocity calibration

Today several national metrology institutes around the world perform pressure reciprocity calibration of laboratory standard microphones [12]. Typically the frequency range is from 20 Hz to 10 kHz for LS1 and 20 Hz to 20 kHz for LS2 microphones, but some institutes have experience with calibration to lower and to higher frequencies. Generally, standing waves inside the applied acoustic couplers determine the upper frequency limit of the calibration. Such wave problems may, in practice, be reduced either by filling the coupler cavity with hydrogen, which has a higher speed of sound than air, or by shaping the cavity in a way that leads to a simpler wave pattern and thereby facilitates a better determination of the acoustic transfer impedance. The latter is the case for cylindrical cavities having same diameter as diaphragms of the calibrated microphones. Typically the volume of such couplers is 4–8 cm^3 for LS1 and 0.3–0.7 cm^3 for LS2 microphones. The calculation of transfer impedance for this type of coupler, called a plane-wave coupler, is based on the transmission line theory. IEC 61094-2 describes the method and dedicated software is available for the calculations.

Today hydrogen filled couplers are rarely used. The filling with the hydrogen is very time consuming to work with. The pressure and concentration of the hydrogen that must be precisely known are difficult to determine and to keep constant during the measurements. Therefore, the much more practical plane-wave couplers have taken over, even if they due to their smaller size, have the disadvantage that they require individual corrections for the loading made up by the connected microphones. Table 1 shows the typical calibration uncertainty that today is achieved by an experienced NMI.

Table 1. Typical uncertainty of pressure reciprocity calibration for experienced NMI.

Uncertainty dB ($k = 2$)	20 Hz	32 Hz	63 Hz	4 kHz	10 kHz	20 kHz	25 kHz
LS1	0.06	0.04	0.03	0.03	0.08	–	–
LS2	0.08	0.05	0.04	0.04	0.04	0.08	0.12

Pressure Reciprocity calibration requires no specific acoustic laboratory facilities, but it is practical to work with a small measurement chamber, which can isolate the microphone and coupler set-up from the noise of the ambient (see Fig. 6). The chamber improves the signal to noise ratio, which may shorten the measurement

Fig. 6. Measurement chamber designed for reduction of noise and for pressurisation.

time and improve the measurement repeatability. This may especially be necessary, when making calibrations in the range between 2 Hz and 20 Hz. Other advantages are gained by connecting a pressurisation system to the chamber. This makes it possible to calibrate at various static pressures and, thus, to determine microphone pressure coefficients [13] and to calibrate directly at the standard pressure, 101,325 kPa. For laboratories that are located far above sea level this is especially important when participating in inter-laboratory and key-comparison calibrations.

7 Primary free-field reciprocity calibration

The standard IEC 61094-3, books [14] and articles describe the free-field reciprocity method. But, quite few NMIs are able to perform free-field reciprocity calibration. The theory behind the determination of the acoustic transfer impedance is simpler to deal with than that of the pressure reciprocity calibration, but the practical measurement of the electrical transfer impedance is technically more difficult. This is due to the very weak sound pressure that in the open space is produced by the source microphone and due to the very small receiver output voltages that, therefore, have to be measured. This may lead to serious measurement problems that are related to ambient or inherent noise and to electrical cross-talk in the measurement system. As these problems especially occur at lower frequencies, the lower limit of free-field reciprocity calibrations is typically between 0.8 kHz (LS1) and 2 kHz (LS2). Free-field calibration is made up to about 25 kHz and 50 kHz and for LS1 and LS2 microphones, respectively. It should be added that the mentioned, relatively high, lower limits give no serious problems, as there are only small differences between the pressure and the free-field responses below the limits, and because the missing lower part of the responses can, therefore, be determined by pressure reciprocity calibration.

Another disturbing factor of free-field reciprocity calibration that may highly influence the calibration uncertainty is room reflections. For many years this problem could only be reduced by applying large an-echoic rooms of high quality, which is of course a very costly solution. But even in such rooms the reflections can be too strong for obtaining the uncertainty that today is required. Therefore, some NMIs have worked with newer signal processing methods that can separate the part of the signal that goes directly from the source to the receiver microphone from the delayed parts of the signal that are due to reflected sound arriving via the walls or other reflecting objects of the room.

Among others, former staff members of the Danish Technical University (Lyngby) have developed such a method [15]. The method effectively suppresses the reflections and implies even that much smaller and acoustically "bad" rooms are applicable for obtaining some of the very best results. Small rooms or chambers of few cubic meters are in fact also advantageous in other respects. They may be placed within a normal laboratory room (see Fig. 7). This eases the work and gives shorter cables that help to reduce possible problems related to cross-talk. The company Brüel & Kjaer has developed a turn-key system [16] applying the DTU method and has also built such systems for customers. The calibration uncertainty that can be obtained with this system is shown in Table 2.

Table 2. Typical uncertainty of free-field reciprocity calibration for experienced NMI.

Uncertainty dB ($k = 2$)	1 kHz	2 kHz	4 kHz	8 kHz	10 kHz	20 kHz	25 kHz
LS1	0.10	0.08	0.07	0.07	0 08	0.10	–
LS2	–	0.10	0.08	0.07	0.07	0.09	0.12

8 Free-field corrections for LS microphones

Even if new methods and measurement systems are now available, the facilities, the equipment and the experience that are needed for performing free-field reciprocity calibration may for some laboratories be too costly to establish and maintain. Therefore, IEC has issued a standard IEC61094-7 with values for the difference between free-field and pressure responses of Laboratory Standard Microphones, LS1 and LS2. It is thus possible to obtain individually valid free-field frequency responses of these microphones by making pressure reciprocity calibrations and by adding the corrections stated in the standard [17]. The free-field responses are valid for perpendicular sound incidence (0°) on the diaphragms. The uncertainty of responses obtained this way is higher than that, which may be achieved by making direct free-field reciprocity calibration (see Tab. 3).

The above method is valid, because the difference between the free-field and the pressure responses depends dominantly on the dimensions of the microphones, which are the same within the model, and only to a small degree

Fig. 7. Small an-echoic chamber designed for free-field reciprocity calibration by the Danish Primary Laboratory of Acoustics (DPLA). Total volume: 6 m^3, inner volume: 1.7 m^3 density of glass wool: 90 kg/m^3 (not critical). The microphones being calibrated are mounted on displaceable rods to allow selection of the distance between the microphones. Prof. Knud Rasmussen in front of the room.

Table 3. Typical uncertainty of a free-field response obtained by adding corrections to a pressure reciprocity calibration made by an experienced NMI. The numbers include correction uncertainties stated by IEC61094-7.

Uncertainty dB ($k = 2$)	1 kHz	2 kHz	4 kHz	8 kHz	10 kHz	20 kHz
LS1	0.09	0.12	0.14	0.18	0.28	0.20

on the acoustic impedance of the diaphragm that varies a little from unit to unit.

9 Determination of diffuse-field responses

Diffuse-field responses may in principle be measured by the reciprocity calibration method like pressure and free-field responses. Some researchers have made reciprocity calibration experiments during the time [18], but the method needs further analysis to be practically applied for metrology. One difficulty is to design a room, within which diffuse sound fields of required quality can be generated. Therefore, other methods are applied.

The diffuse-field response or correction may be calculated of a number of free-field responses that are measured for different angles of sound incidence and that together make a good representation of all possible angles. The standard IEC61183 [19] describes the calculation and gives details about choice of the measurement angles and the associated weighting factors for the calculation (see Fig. 8).

The diffuse-field response of a larger microphone might also be measured by comparing its response with a several

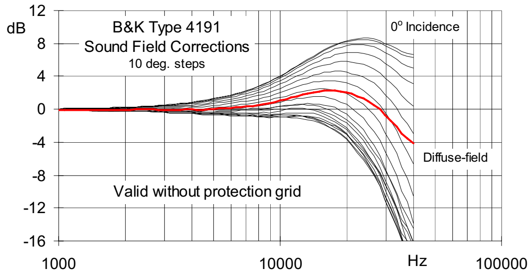

Fig. 8. Free-field corrections of WS2 microphone measured in steps of 10° sound incidence and the diffuse-field correction calculated in accordance with IEC61183.

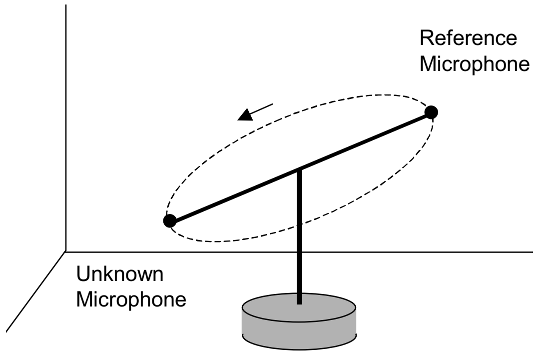

Fig. 9. Diffuse-field calibration by comparing a large unknown microphone with a reference microphone that is several times smaller. By moving the microphones in the room the possible effects of dominant standing waves at specific frequencies is minimized.

times smaller pressure-field calibrated reference microphone. If the reference microphone is sufficiently small, the difference between its pressure and diffuse-field responses may be so small that it can be neglected. The measurement may be made with a practically obtainable, yet not fully perfect, diffuse sound field by interchanging the microphones between fixed positions or better, by mounting them on moving arms that slowly pass them through the same circular orbit within the sound field of the reverberant room [20] (see Fig. 9).

10 Coupler comparison calibration

The sensitivity and frequency response calibration of a measurement microphone may either be performed by making comparison measurements with a reference microphone at a series of frequencies, or by using a combined technique that implies a comparison at one frequency only and a relative frequency response measurement. This response can be measured by excitation with an Electrostatic Actuator (see description below). In the latter case, the sensitivity is generally measured at a frequency that is so low that the pressure-, free- and diffuse-field sensitivities of the microphone are essentially equal. The frequency 250 Hz is most commonly used, as this

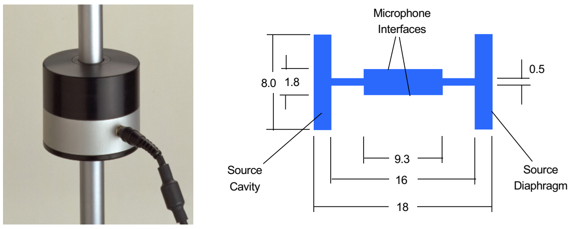

Fig. 10. Typical comparison coupler with built-in sound source for calibration of WS2 microphones. It is shown beside the cross-sectional view of its air-filled cavity.

is also the operation frequency of some common type of acoustic calibrator (pistonphone).

Comparison calibration of pressure sensitivity is covered by IEC61094-5 [21]. The standard describes different ways of mounting the two microphones. In all cases, they are lined up along their axes of symmetry with their diaphragms or protection grids facing each other in a distance of typically 2–3 mm. One might either use couplers with built-in sound sources or microphone holding jigs with separate, nearby mounted sound sources. A typical coupler and its cross-sectional view are shown in Figure 10. Such mountings are useable over wide frequency ranges, as the pressure exciting the two microphones is essentially the same. The comparison uncertainty for $f < 1000$ Hz is typically <0.03 dB ($k = 2$), while it is about 0.20 dB for good couplers and equally large microphones up to 16 kHz. The resulting uncertainty of the method is obtained by combining these uncertainties with those of the reference microphone calibration. Typically this becomes <0.12 dB ($k = 2$) for WS1 and WS2 microphones if $f < 1000$ Hz.

Free-field and diffuse-field frequency responses may be obtained by adding corrections to measured responses, but it should be noticed that the sound field corrections that should be applied depend on the type of the coupler or jig – and also that the corrections differ from corresponding free- and diffuse-field corrections valid for other measurement methods.

11 Electrostatic actuator calibration

The reciprocity calibration methods described above are absolutely necessary for primary calibration of reference standard microphones, but these methods are quite slow, and generally too slow for calibration of working standard microphones that are calibrated in large numbers. In order to measure their frequency responses, it would be natural to look for a sound source that within narrow tolerances could supply a constant sound pressure over a wide frequency range. Unfortunately, such sources do not exist, but the electrostatic actuator is a very good substitute. It can generate a constant electrostatic pressure (a uniformly distributed force) on the flat metallic (electrically conducting) diaphragms that are used with all WS microphones.

The actuator is a plane and very stiff metallic plate with holes or with slits that make it acoustically transparent (see Fig. 11). During the operation, it is placed close to (0.5 mm) and in parallel with the microphone diaphragm. It generally stands on its small glass legs on top of the supported part of the microphone diaphragm. Typically 800 V DC and 30 V AC are applied between the actuator and the diaphragm (see Fig. 12). These voltages will with a typical actuator generate an equivalent sound pressure of about 1 Pa (94 dB). The pressure may be calculated by the equation below:

Fig. 11. Electrostatic actuator used for frequency response calibration of WS1 microphones. Actuators are standardised by IEC and are widely used for calibration of working standard microphones. They can excite the microphone diaphragms with constant electrostatic pressure over very wide frequency ranges.

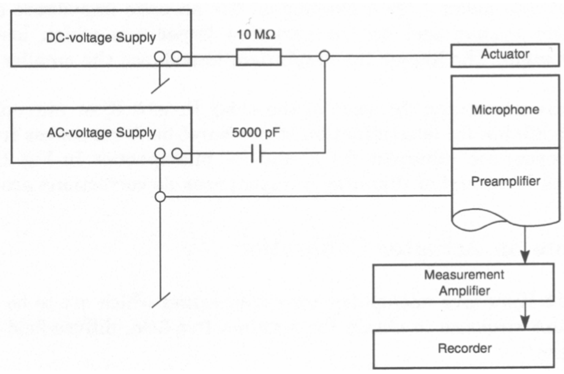

Fig. 12. Principle of electrostatic actuator voltage supply.

$$p(t) = -\frac{\varepsilon a}{2d^2}\left(U_0 + u\sin(\omega t)\right)^2 \qquad (1)$$

where

$p(t)$ equivalent instantaneous pressure (Pa),
ε dielectric constant of the surrounding air (8.85×10^{-12} F/m),
a ratio between the areas of the perforated actuator and the diaphragm,
d distance (m) between actuator and microphone diaphragm,
U_0 DC voltage (V) applied between actuator and diaphragm,
u peak value of sinusoidal AC voltage (V) applied between actuator and diaphragm,
ω angular frequency (rad/s),
t time.

Table 4. Typical uncertainties of actuator response (A) and of free-field response (B) obtained by adding corrections. The reference frequency is 250 Hz.

Uncertainty dB ($k = 2$)	0.02 kHz	0.1–5 kHz	10 kHz	20 kHz	40 kHz
WS2–A	0.12	0.10	0.15	0.20	0.30
WS2–B	0.14	0.14	0.20	0.35	0.60

In principle, the actuator method is a primary method, but the method is not used for absolute sensitivity calibration, as the uncertainty of some parameters (a, d) and, therefore, of the resulting pressure is generally too large.

The pressure that the actuator produces on the microphone diaphragm is frequency independent, if the supplied AC and DC voltages are kept constant during the calibration. One should, therefore, expect to measure the pressure response of the microphone, but the measured response deviates from this. The deviation is due to a small additional pressure that is generated, because the diaphragm moves, when this is excited by the actuator. The magnitude of this pressure is smaller for less sensitive microphones, having stiffer diaphragms, than for more sensitive microphones. However, there are essentially fixed ratios (differences in dB) between the actuator response and each of the three principal responses, the pressure, the free-field and the diffuse-field responses. Therefore, if these ratios are known, all three responses may simply be determined by applying corrections to the easily measured actuator response. The corrections, which depend on the microphone model, are available from the leading microphone manufacturers. The actuator method is widely used by calibration service centres. Typical uncertainties of the actuator calibration itself and of a free-field response are shown in Table 4 for a Working Standard Microphone (WS2). The method is generally used between 20 Hz and 100 kHz, but it can be used at both higher and lower frequencies. But by low-frequency calibration, say $f < 20$ Hz, attention should be paid to the facts that any measurement microphone has a static pressure equalization vent that influences its low-frequency response and that the effect of this cannot, in all cases, be measured with an actuator. Therefore, when low-frequency calibration is required, it may be necessary to apply specific calibration methods.

The actuator method is relatively cheap to establish, as no specific acoustic laboratory facilities are required. The method is described in detail in the standard IEC61094-6 [22] and in reference [23].

12 Infrasound calibration

Presently relatively few NMIs deal with infrasound calibration, but low-frequency measurements and calibration are fields of growing interest. Windmill parks, power stations, aircrafts and road traffic are some sources that may create disturbing infrasound noise. This will have to be measured with dedicated low-frequency microphones

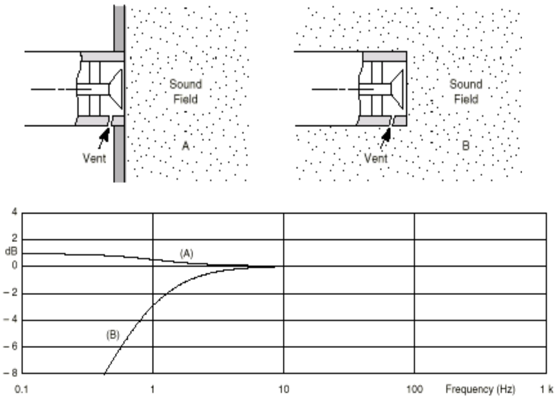

Fig. 13. Different sound exposure of microphones and related responses. Diaphragm only (left) gives upper response (A). Diaphragm and vent (right) gives lower response (B).

that are calibrated by specific methods accounting for the influence of the microphone vents that equalize changes of static pressure.

It is important to be aware of that the microphone low-frequency response depends very much on, if the vent – during measurements and calibration – is exposed to the sound pressure or not (see Fig. 13).

Different methods have been and are still used, but no method has yet been standardized. One simple method that is, however, not very precise, is to calculate the cut-off frequency (the –3 dB point) from the decaying response to a step-change of the ambient pressure. A more advanced method is to make the calibration with a device that is called a laser pistonphone. Such devises are designed and described by several NMIs. Other calibration devices that are used have an electro-dynamic sound source of low acoustic impedance that generates the calibration pressure inside a very small cavity. By the low source and the high load impedance an essentially flat frequency response may be obtained.

Furthermore, some five years ago Brüel & Kjaer presented a new infrasound calibration method [24] and have now developed a system that is based on this. It measures frequency responses from 250 Hz down to 0.1 Hz with an uncertainty less than 0.1 dB. The system calibrates its own reference microphones by a method that is called the *Related Microphones Method*. It can also calibrate working standard microphone and expose them to the sound in both of the above mentioned ways (see Figs. 13 and 14).

13 High- and low-level testing

As previously mentioned sound measurements are made in a range from say 0 dB (20 μPa) to 180 dB (20 000 Pa). There is thus a ratio of 1:1.000.000.000 between the weakest and the strongest measured sound. However, most calibration and test methods work within a narrow range – say between 0.2 Pa and 30 Pa. This is, of course, fine if the microphones are linear over their dynamic application range. With respect to this, it is common to rely on the

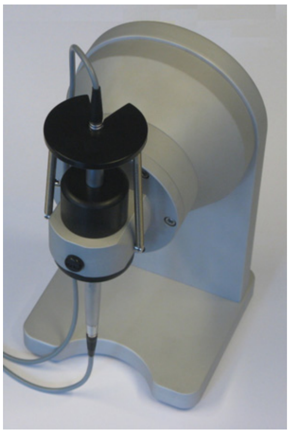

Fig. 14. Infrasound calibration Unit with built-in sound source. The unit and its associated measurement system work from 250 Hz down to 0.1 Hz and can calibrate its own reference microphones as well as working standard microphones. They may be exposed only on the diaphragm or on both diaphragm and static pressure equalization vent.

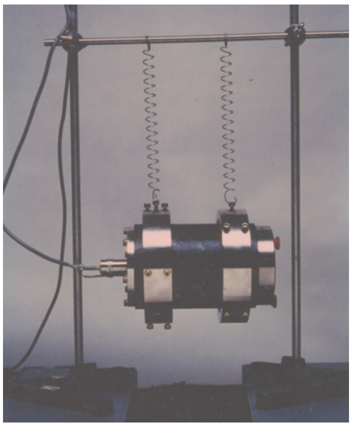

Fig. 15. Sealed and vibration isolated measurement chamber for determining the inherent noise of condenser microphones and their preamplifiers. The volume of the chamber is about 2000 cm^3. The shown chamber has been applied for testing low-noise microphones with an inherent A-weighted noise level below 0 dB.

specs stated by the microphone manufacturer, but there are cases, where testing of dynamic range is prescribed. An example is the standard for pattern evaluation of sound level meters that requires testing of both the inherent noise and the distortion at the upper end of the dynamic range. High pressure microphone testing may also be necessary in connection with very costly, high-tech projects, like launching of rockets and testing of jet engines and air-crafts.

Low-level or inherent noise tests are performed by enclosing the microphone and its preamplifier in a sealed cavity with very stiff sound-isolating walls. Depending on the levels to be measured, it may be necessary to make a set-up with soft springs that can insulate the chamber from vibrations created by applied instruments or maybe occurring in the test facility (see Fig. 15).

Fig. 16. The B&K high-pressure system for testing of dynamic linearity and distortion of measurement microphones and sound level meters. The system is optimized for low distortion of the generated sound and for low vibration excitation of the microphones.

There are different methods that can be used for high-pressure calibration or testing. Traditionally such tests have been performed with a pistonphone. This is a motor-driven mechanical device that consists of a closed cavity with a piston that can compress and decompress the enclosed air. The generated pressure is a function of the static pressure, the cavity volume and of the pistons volume displacement. The sound pressure is also influenced by the so-called heat-conduction effect that occurs between the air and the walls of the cavity. The described pistonphone is generally a simple and a rather cheap device. It usually suffers from lack of flexibility with respect to selection of sound pressure and from its distortion that may often be higher than that of the microphones that are to be tested.

A dedicated and elaborated system for measurement of dynamic linearity [25], but also a more complex system, has been developed by Brüel & Kjaer. The sound is produced by a loudspeaker. Via some acoustically coupled tubes the sound is lead to a position, where the diaphragms of the microphone being tested and of a high-pressure reference microphone are placed. On its way through the tube system the pressure of the sound is drastically magnified and "cleaned" for distortion components. The system can, by the selected type of reference microphone and by the optimized sound system, measure dynamic RMS-linearity within 0.3% and distortion within 0.5% all the way from 1 Pa up to 10 kPa RMS or 14 kPa peak (0.14 bar). The linearity of the system is ensured by two high-pressure reference microphones of different operation principles that over the dynamic range must trace each other within narrow tolerances (see Fig. 16).

14 Phase frequency response calibration

Measurement of sound intensity and mapping of sound fields have created a need for making absolute and relative phase response measurements. This is necessary for applying the intensity measurement principle that is standardized and described in IEC61043 [26]. Sound

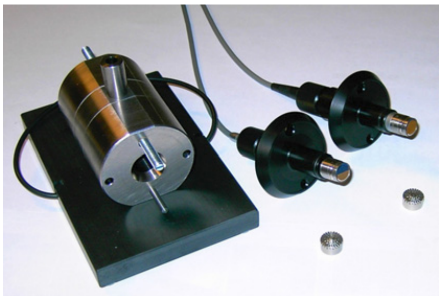

Fig. 17. Wide band coupler for phase comparison calibration of ⌀12.7 mm microphones. used for matching of microphones to sound intensity measurements. the coupler fully encloses the microphones in its cavity and works from 20 Hz to 16 kHz.

Table 5. Uncertainty of phase comparison calibration of an intensity microphone pair obtained with the B&K phase calibration system and its dedicated couplers.

Uncertainty of phase comparison calibrations - deg	20–500 Hz	1 kHz	2 kHz	5 kHz	10 kHz
	0.01	0.02	0.04	0.10	0.20

pressure and air-particle velocity must be measured and multiplied to obtain the intensity, but because of the lack of suited particle velocity transducers both quantities are determined by two pressure-sensing microphones that, in order to ensure valid results, must have essentially identical phase frequency responses [27]. The requirements are so strong that it is not possible to produce the microphones with the required uniformity – matching pairs must be selected from large microphone batches. The selection is made with specifically designed couplers that expose the two microphones to the same magnitude and phase of the pressure. Figure 17 shows such couplers that are designed for use with the phase response comparison system developed by B&K.

Sound mapping is made with small and large microphone arrays. Some systems may consist of hundredths of microphones. The microphones of such arrays must also fulfill certain requirements to the uniformity of their phase frequency responses, but fortunately a significantly larger spread can be accepted. Maintenance and extension of such arrays requires reference microphones with absolutely calibrated phase frequency responses. Modern reciprocity calibration systems that determine the complex microphone sensitivity meet the required tolerances and can cover this need (see Tab. 5).

15 Calibration of sound level meters

Specification and calibration of sound level meters (SLM) are standardized by IEC and covered by the following three standards [28–30]:

- IEC61672-1 Specifications.
- IEC61672-2 Pattern evaluation tests.
- IEC61672-3 Periodical tests.

Fig. 18. Main unit of the B&K SLM calibration system that depending on the type of SLM works fully automated, semi-automated or manually.

The pattern evaluation standard prescribes a very thorough checking of a number of general points, environmental tests, electrostatic and radio frequency tests, electrical performance tests and, of course, some acoustical tests of:

- Directional responses.
- Frequency response (ref. direction).
- "Free-field correction values".
- "Adjustment value(s)".
- Self-generated noise.

The long series of tests requires a large collection of specific instruments and several costly test facilities, including a good and large an-echoic room. These tests are, therefore, only performed in relatively few laboratories. In lack of local testing and results, it is very common to accept test results and approvals of sound level meters originating from other countries.

The verification of that a specific SLM meets the requirements of IEC61672-1 requires that its model has passed the tests of IEC61672-2 and that the instrument itself has passed the periodical tests of IEC61672-3. Periodical tests are performed in many countries. Often these tests are made by calibration service centers, but in smaller countries or countries that are just starting up acoustic activities the tests are often performed by the NMI. It was a goal for the IEC working group to define effective and relatively simple periodical tests that are not too costly to perform and that will, therefore, become more widely used. The testing of IEC61672-3 is, thus, limited to a general inspection, to seven electrical performance tests and to the following three acoustic tests:

- Indication at reference frequency.
- Inherent noise.
- Frequency response. (measured by using actuator, multi-frequency calibrator or sound field).

SLM calibration systems that – without specific acoustic facilities – can perform these ten tests are available from different manufacturers (see Fig. 18).

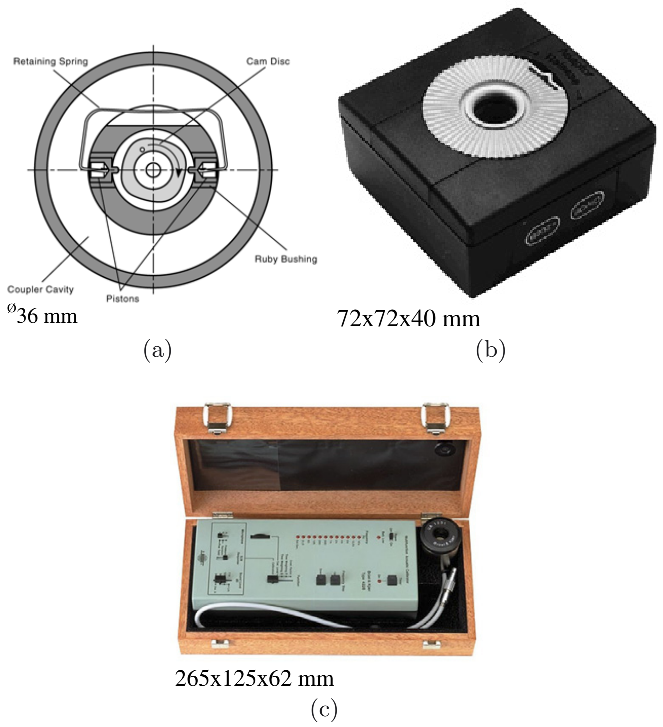

Fig. 19. (a) Operation principle of pistonphone. (b) Typical feed-back calibrator 94 dB, 1000 Hz. (c) Multi-frequency calibrator 94 dB–114 dB, 31.5 Hz–16 kHz.

16 Calibration of sound level calibrators

Sound level calibrators are sound sources that produce known sound pressure levels and are, thus, well-suited for calibration or verification of sound level meters and other sound measurement systems. They are now considered to be necessary accessory parts to all measurement systems and are used for system checking before and after performing all important measurements. Nowadays there are basically two types. One type is a mechanical device with a cavity and with, usually two, small pistons that are driven by a miniature electric motor (see Fig. 19a). They operate at relatively low frequencies, typically 250 Hz, and are generally very stable sound sources, which make them well-suited for reference standards for comparison calibration of other types of calibrator. They are called pistonphones.

Today the most common calibrator type is the "feedback calibrator". It contains some, not especially critical, sound source, but a very stable microphone that measures the generated pressure and that via a feed-back circuit adjusts this to the proper level. This principle has lead to some relatively small and highly stable calibrators whose sound pressure is essentially independent of the ambient pressure. They typically work at the SLM reference frequency 1000 Hz (see Fig. 19b). The feed-back principle is also used for multi-frequency calibrators that may cover nearly the full frequency range of common sound level meters (see Fig. 19c). The standard IEC60942 [31] specifies sound level calibrators of different classes and describes their way of calibration. The calibrator calibration and its uncertainty is based on reciprocity calibration of Laboratory Standard Microphones, LS1 or LS2.

17 Field calibration by sound level calibrators

Single-frequency sound level calibrators are widely used in the field to ensure proper operation of sound measurement systems, but often they are not used the optimal way. Connecting the calibrator to the microphone, starting this and adjusting the system to display the level specified for the calibrator implies a risk for not discovering or for hiding a calibrator or a system error. Much higher confidence to proper functioning of the system may be obtained by setting this up in accordance with the stated sensitivity of the microphone and then check with the calibrator that the displayed level is within acceptable limits. With modern and well-maintained equipment the displayed value should not differ by more than few tenths of a decibel from the expected reading. After having observed the reading one might either leave the system setting or re-adjust it, depending on the degree of confidence one have in the two calibration methods. If the deviation is too high, one should find the reason and not take the risk to hide a possible defect by correcting the microphone sensitivity parameter of the system.

18 Summary

Several different calibration methods and systems have been briefly described. Some of them are very commonly used by NMIs that operate acoustical departments, while others are only available in case of specific needs in the country. Pressure reciprocity calibration is the basic method that delivers reference standards for sensitivity calibration of all types of measurement microphone and for level calibration of sound calibrators. The method may even be used for obtaining free-field responses of reference standards LS1 and LS2, as the necessary free-field corrections are specified by IEC61094-7. In some cases it may, thus, be avoided to establish a free-field calibration system that is generally more costly and space requiring.

In lack of local calibration service centers some NMIs find it necessary to establish secondary calibration of working standard microphones. The standardized, easily operated and widely used methods for this are coupler comparison calibration for sensitivity at 250 Hz and electrostatic actuator for frequency response calibration combined with adding of corrections supplied by the microphone manufacturers or others.

SLM calibration is important in many countries. Many NMIs do not perform pattern evaluations themselves. They rely on those performed and reported by other internationally leading acoustic laboratories and establish periodic testing only. This is far less costly and it does not require specific acoustic measurement facilities.

More specific types of calibration and testing like infrasound calibration, phase comparison calibration and dynamic linearity testing are today performed by relatively few NMIs. If needs should occur for such applications, they may often be combined with common calibration systems that nowadays are usually based on modern multi-function analyzers.

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