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INFRA SOUND CALIBRATION OF MEASUREMENT MICROPHONES

Erling Frederiksen*

Danish Primary Laboratory of Acoustics (DPLA) and Brüel & Kjaer
Skodsborgvej 307, 2850 Naerum, Denmark
erlingfred@bksv.com

Abstract
This paper describes methods and equipment for frequency response calibration of measurement microphones over the range from 0.1 Hz to 250 Hz. New calibration principles are described together with the design of a new reference microphone and a dedicated low-frequency calibration unit. Expected calibration uncertainties are also stated. The motivation for the work behind the paper is the, presently, very high international interest in low-frequency microphone calibration that, among other activities, has initiated a BIPM key comparison project on calibration of one-inch Laboratory Standard Microphones down to 2 Hz.

INTRODUCTION

Within the last decade, the interest in low-frequency microphone calibration has increased all over the world. This interest was expressed to the Bureau International des Poids et Measures (BIPM) who, therefore, initiated a key comparison calibration project with the title 'Comparison of laboratory standard microphone calibrations at low frequencies'. One-inch microphones (IEC61094-1 LS1) are to be calibrated from 2 Hz and 250 Hz. The project is running with participation from national metrology institutes. As most participants apply the reciprocity technique, the project is also very interesting for the International Electrotechnical Commission (IEC), who is presently revising the pressure calibration standard (IEC61094-2) to extend the frequency range down to 2 Hz. This paper describes a part of the work performed by the Danish Primary Laboratory of Acoustics (DPLA). The intention with the work behind the paper is partly to examine other methods that might verify the reciprocity results and partly to develop a system for low-frequency calibration of all types of measurement microphone. This system should preferably work down to 0.1 Hz.

OPERATION MODES AND LOW-FREQUENCY RESPONSES

Most measurement microphones are pressure-sensing condenser microphones. Their diaphragms respond to the difference between the pressure on their front and rear sides. The latter is the pressure in an air-filled cavity behind the diaphragm. As static pressure variations over time may be very large, they could overload and destroy the functioning of the microphone. Therefore, the static pressure must be equalized with the ambient pressure. The cavity must have a vent that equalizes static pressure, but prevents equalization of sound pressure at the lowest frequencies of interest.

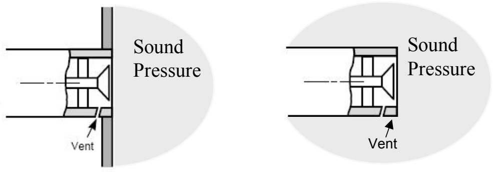

Fig. 1 Ways of exposing microphones to sound fields. Diaphragm only (left) relates to pressure response. Both diaphragm and vent (right) relates to the free- and diffuse-field responses

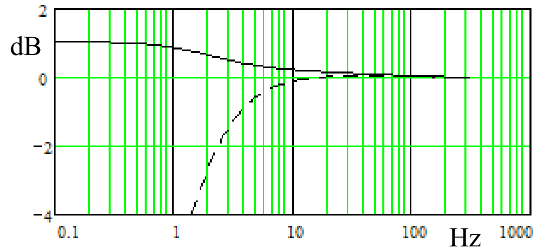

Fig. 2 Pressure Response (solid curve) and Free- and Diffuse-field Response (dashed curve) of the microphone B&K Type 4190

The frequency response depends on the way in which the microphone is exposed to the sound pressure. If only its diaphragm is exposed, the response is essentially flat to DC, while it rolls off at low frequencies, if both diaphragm and vent are exposed. The frequency of the '-3 dB-point' is called the lower limiting frequency. For most microphones this is between 1 Hz and 3 Hz, but lower for dedicated low-frequency microphones; see Fig.1 and Fig. 2. The flat response is the microphone pressure response, which is defined for exposure of the diaphragm only. When applied for measurements in free or diffuse sound fields, the microphone is fully surrounded by the sound. Therefore, the vent is also exposed and, therefore, the free- and diffuse-field responses roll off.

The lumped parameter model (see Fig. 3) shows the elements that determine the low-frequency response and sensitivity of a microphone. As in a real field, pressure

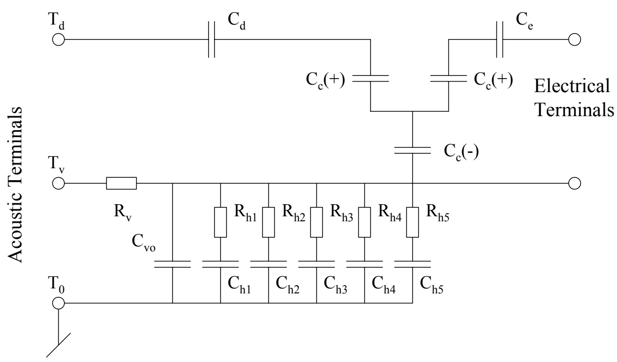

Fig. 3 Low-frequency model of a typical condenser microphone. Specific low-frequency elements (marked $R_{h\#}$ and $C_{h\#}$) account for the heat conduction effects related to the walls of the internal microphone cavity. The testing of the expression (Eq. 3) for frequency response estimation is made with this model

can be applied in to ways. The pressure response is simulated by applying the input signal between the diaphragm terminal (T_d) and the ground terminal (T_0), while the terminal of the equalization vent (T_v) is connected to ground (T_0). The equal free- and diffuse-field responses are simulated by applying the signal to both diaphragm and vent (T_d and T_v). The impedance of the internal microphone cavity is simulated by the (adiabatic) compliance of the internal volume (C_{vo}) and by the 'R' and 'C' elements marked h1, h2, … , h5. They represent the effect of heat conduction – exchange of heat between the compressed/decompressed air and the solid cavity surfaces.

The model leads to the following equations for calculation of the pressure- (Eq. 1) and the free- and diffuse-field (Eq. 2) sensitivity as a function of frequency:

$$M_p(f) = \frac{Z_c}{Z_d + \dfrac{Z_{cav} \cdot R_v}{Z_{cav} + R_v}} \quad \text{Eq. (1)}$$

$$M_{fd}(f) = \frac{Z_c}{Z_d + \dfrac{Z_{cav} \cdot R_v}{Z_{cav} + R_v}} - \frac{\dfrac{Z_{cav} \cdot Z_d}{Z_{cav} + Z_d}}{\dfrac{Z_{cav} \cdot Z_d}{Z_{cav} + Z_d} + R_v} \cdot \frac{C_d}{C_c} \quad \text{Eq. (2)}$$

where

$M_p(f)$	Microphone pressure sensitivity (V/Pa)
$M_{fd}(f)$	Microphone free-/diffuse-field Sensitivity (V/Pa)
C_c	Electro-mechanical coupling compliance of microphone* (m^3/V)
C_d	Microphone diaphragm compliance (m^3/Pa)
R_v	Microphone vent resistance ($Pa{\cdot}s/m^3$)
Z_c	Impedance of coupling compliance, $(j \cdot 2\pi f C_c)^{-1}$ - ($Pa{\cdot}s/m^3$)
Z_d	Impedance of diaphragm compliance, $(j \cdot 2\pi f C_d)^{-1}$ - ($Pa{\cdot}s/m^3$)
Z_{cav}	Impedance of rear cavity - see equivalent circuit C_{vo} - Compliance of rear cavity volume (V/Pa) $C_{h\#}$ - Additional compliance due to heat conduction (V/Pa) $R_{h\#}$ - Element of loss due to heat conduction ($Pa{\cdot}s/m^3$)

* '+' and '-' signs of C_c indicate positive and negative element values, whose absolute values are equal

In this project and for this paper, the model has been applied for creating frequency response graphs and, more important, for testing the equation (Eq. 3) that was worked out for determining the frequency response of the reference microphone, i.e. reference for the comparison calibration system described in the following.

FREQUENCY RESPONSE CALIBRATION

The primary pressure reciprocity calibration method (IEC61094-2) yields to the pressure response of the calibrated microphones (IEC61094-1 LS1 and LS2). Therefore, further steps have to be taken to determine free- or diffuse-field responses of these and other microphones. In fact, due to the low ratio between the microphone dimensions and the wavelength of the sound, there is no difference between the free-and the diffuse field response of a microphone at the low frequencies that are dealt with in this paper (f < 250 Hz). For the same reason neither a free nor a diffuse sound field is necessary for low-frequency calibration - only the proper sound expose of diaphragms and vents is important. It is thus possible to perform calibrations of free- and diffuse-field responses by using the pressure field of a comparison coupler. The unknown microphones should in this case be fully inserted in its cavity, while the reference microphone, which is generally pressure response calibrated, should be placed in the coupler wall with its vent opening outside the cavity; see Fig. 4.

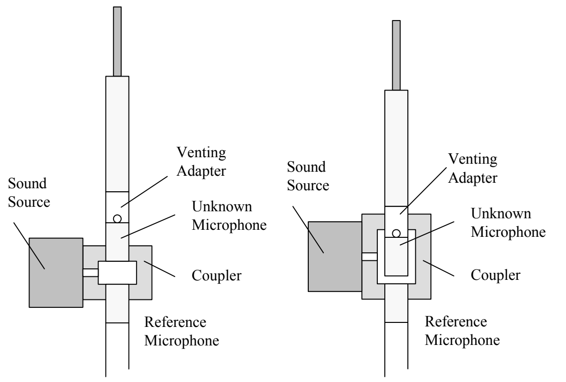

Fig. 4 Mountings for calibration of Pressure (l) and Free-/Diffuse-field Responses (r)

In the low-frequency range (f < 20 Hz), the well-established reciprocity calibration method has some practical and theoretical weaknesses, such as less elaborated theory on coupler and microphone impedance, and problems with leakage of couplers. For these reasons and because of the lack of a method for the 0.1 Hz to 2 Hz range, other methods were invented and considered for this project; see below.

These methods are not absolute methods, but relative methods, They can be used for determining frequency response relative to the sensitivity level at a selected reference frequency. Absolute sensitivities can be obtained by combining one of the methods with an absolute calibration at the reference frequency. The selected reference frequency should be a frequency at which the absolute sensitivity can be determined with low uncertainty.

DESIGN OF LOW-FREQUENCY REFERENCE MICROPHONE

In principle, any type of stable condenser measurement microphone that can be precisely pressure calibrated could be applied as the reference standard of a low-frequency comparison calibration system. However, a specific half-inch microphone was made for the project. Compared to similar measurement microphones this has a higher diaphragm tension and larger internal cavity. This leads to a lower fraction of air-stiffness and, therefore, to an essentially flat pressure frequency response. This varies by less than 0.2 dB over the range between 0.1 Hz and 250 Hz; see Fig. 6. The stiff diaphragm also reduces the effect of static pressure variations on the microphone sensitivity. This is important as minor, but disturbing, pressure changes may easily arise inside the low-frequency couplers and inside the microphone cavities. The changes may occur due to the electrical heating of source and preamplifiers and the relatively long pressure equalization time constants of the couplers.

Furthermore, this low-sensitivity (–43.5 dB re 1 V/Pa) half-inch microphone is designed with same housing and geometry of its internal cavity as that of the much more sensitive (–26 dB re 1 V/Pa) standard type of microphone B&K Type 4190.

This means that large batches of Type 4190 microphones are available for selecting a unit that matches the dedicated reference microphone on venting resistance and that it, therefore, becomes easy to form a pair of microphone that is well suited for use with the Related Microphones Method described below.

Fig. 5 The frequency response of the half-inch Reference Microphone (right) is essentially flat due to its highly tensioned diaphragm and its large internal cavity

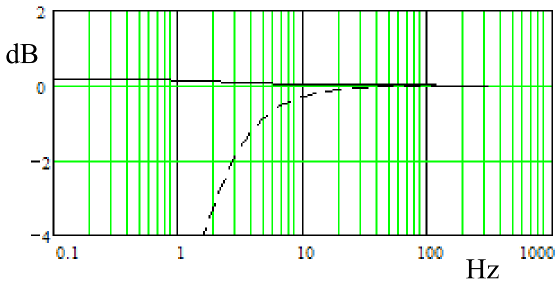

Fig. 6. The pressure response of the low-frequency reference microphone is flat within < 0.2 dB between 0.1 Hz and 250 Hz

CALIBRATION OF REFERENCE MICROPHONE

Electrostatic Actuator Method

Electrostatic actuators are, in principle, ideal tools for low-frequency pressure response calibration as their simulated sound pressure is frequency-independent, if the driving AC-voltage is kept constant. However, as neither the driving instruments nor the applied analyzer have fully flat frequency responses, the measured responses must be corrected for the response of the measurement system itself. This is not easily done, because the actuator voltage is far too high to be led to the microphone input terminals. It is not easy to obtain a frequency-independent attenuation of about 70 dB (about 3000 times) with a circuit that can withstand 100 V AC and 800 V DC and that does not load the amplifier output significantly.

This led to the idea of measuring the system response without making any changes of the normal actuator measurement setup, but by placing the microphone in vacuum, where its low-frequency response is essentially flat and thus without influence on the system response. The pressure should just be about 5 kPa (or lower) to ensure that the response of the above reference microphone is flat within 0.01 dB.

This method was evaluated and was expected to give very precise calibration results, with uncertainties less than 0.05 dB. This expectation is still valid, but the experiments failed, because the vacuum equipment that was available did not have a static pressure stability that was high enough for performing repeatable measurements down to low frequencies. With the B&K PULSE Analyzer and the SSR (Steady State Response) software it takes about 30 minutes to measure frequency response in 1/3-octave steps from 250 Hz down to 0.1 Hz (St. dev. 0.01 dB).

Calibration laboratories with suitable vacuum systems are encouraged to test the method and report their results.

RELATED MICROPHONES METHOD

This method of low-frequency response calibration requires two microphones of related designs. The dimensions of the internal cavities and the resistance of their static pressure equalization vents should be equal. Ideally, the microphones should differ on the tension of their diaphragms. If these requirements are fulfilled, the frequency response of the less sensitive microphone can be determined by measuring 1) ratios of frequency response, 2) average sensitivity and 3) capacitance of the two microphones and by performing a calculation in accordance with the equation below:

$$\left(\frac{M_2(f)}{M_2(f_{ref})}\right)_{estim} \cong \left(\frac{M_1(f)}{M_1(f_{ref})} \cdot \frac{M_2(f_{ref})}{M_2(f)} - 1\right) \cdot \left(\frac{M_{a,1}}{M_{a,2}} \cdot \frac{C_{ac,2}}{C_{ac,1}} - 1\right)^{-1} + 1 \qquad \text{(Eq. 3)}$$

where

$\left(\frac{M_2(f)}{M_2(f_{ref})}\right)_{estim}$	Estimated normalised frequency response of the less sensitive microphone (2)
$\frac{M_1(f)}{M_1(f_{ref})} \cdot \frac{M_2(f_{ref})}{M_2(f)}$	Measured ratio of normalised frequency responses of the related microphones (1) and (2)
f_{ref}	Normalization frequency (250 Hz)
$\frac{M_{a,1}}{M_{a,2}}$	Measured ratio between average sensitivities of microphones (1) and (2)
$\frac{C_{ac,2}}{C_{ac,1}}$	Measured ratio between active capacitance of microphones (2) and (1). Passive microphone housing capacitance (typically between 1 pF and 3 pF) should be subtracted from measured values

The above equation is not exact. It is empirically determined, but it has been tested with the general low-frequency microphone model shown in Fig. 3 and has been found to be quite precise. The testing was made with two specific models of microphone, one of them corresponding to the specially designed low-frequency reference microphone and the other to a selected microphone B&K Type 4190, which meets the requirements of relation mentioned above. Fig. 7 shows the frequency responses calculated for the two microphones that have different diaphragm tension, but same impedance of their rear cavities. The figure also shows the calculated ratio, i.e., the difference in dB between the frequency responses, which, in practice, is easily measured for a real pair of microphone. Fig. 8 shows partly the estimated response of the less sensitive reference microphone obtained by using the above equation and partly the directly calculated response. Also the error of the estimation, i.e., the difference between the estimated and directly calculated responses, is shown. The error is less than 0.01 dB over the entire frequency range from 0.1 Hz to 250 Hz with models of microphone that meet the mentioned requirements and have sensitivity of –26 dB and –43 dB re. 1V/Pa respectively. This was found also to be the case for microphones with a rear cavity that differs much more from the applied model than the assumed uncertainty of this. In practice, it may be difficult to find a microphone that closely matches the reference microphone on the vent resistance, but a test has shown that the total error of the estimation equation is less than 0.01 dB if the vent resistances of the microphones differ by less than 10 percent.

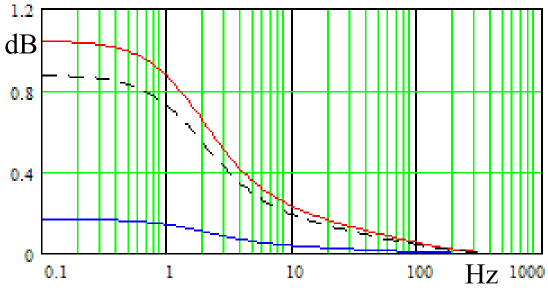

Fig. 7. Calculated frequency responses of models of the reference microphone (lower solid curve) and of the related, more sensitive, microphone (upper solid curve). The dashed curve is the calculated difference

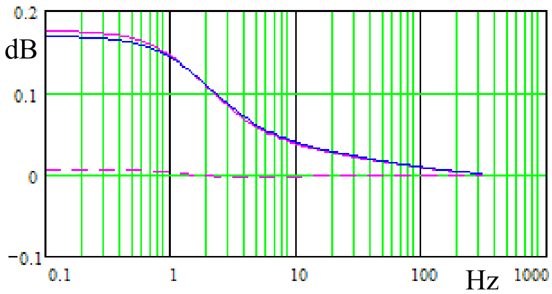

Fig. 8. Frequency responses of the reference microphone model. The directly calculated response (blue curve) together with the response estimated from the difference between the microphone responses in accordance with Eq. 3. The error of the estimation is also shown. Its max. value is about 0.01 dB

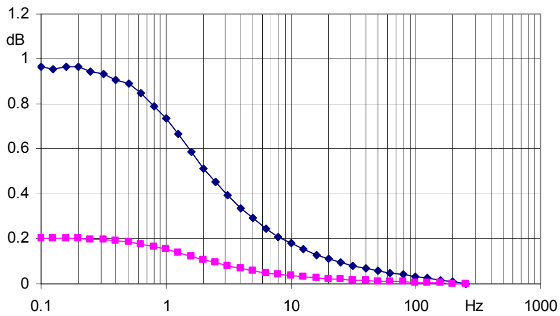

Fig. 9. Measured and normalized ratio of frequency responses (upper curve) used for estimation of the frequency response of the less sensitive microphone (lower curve)

The measured and normalized ratio between the responses of the two microphones is shown in Fig. 9 together with the response of the less sensitive microphone that is determined by the estimation equation (Eq. 3). The response varies slightly more than expected, but it is assumed to be within the tentatively estimated uncertainty that is stated in Table 1.

After the calibration, this microphone served as the reference microphone for calibration of different types of microphone by using of the comparison calibration unit described in the following.

0.1 Hz	0.316 Hz	1 Hz	3.16 Hz	10 Hz	250 Hz
< 0.05 dB	< 0.05 dB	< 0.04 dB	< 0.03 dB	< 0.02 dB	Ref.

Table 1. Tentatively estimated calibration uncertainty of reference microphone (k=2)

LOW-FREQUENCY COMPARISON CALIBRATION COUPLER

One part of this project was design and calibration of a reference microphone that should be used with a comparison calibration unit for calibration of different types and sizes of microphone. Another part was the design of this unit that will briefly be described in the following. The unit operates over the range from 0.1 Hz to 250 Hz. Its built-in sound source is an ordinary loudspeaker with an airtight diaphragm. This works into a speaker cavity that, via sound channels, is connected to the cavity, where microphones are inserted in accordance with the sound exposure principles illustrated in Fig. 4. The design ensures that the sound pressure at the two microphones is the same – also at the highest frequency 250 Hz. The reference microphone is mounted at the lower side of the coupler, while the unknown microphone is inserted from above; see Fig. 10. Different adapters were designed for proper sound exposure of the calibrated microphones. Sometimes the microphone preamplifier influences the path along which the equalization takes place. In such cases the adaptor should enclose both microphone and preamplifier. The volume of the adapter cavity that loads the coupler is not critical. A cavity behind the loudspeaker diaphragm prevents sound emission to the ambient. The cavities in front of and behind the speaker are vented. The values of the vent resistances are selected as a compromise between flatness of frequency response and efficiency of the vents to equalize the minor, but disturbing, static pressure variations that may occur. They may originate from the ambient and/or be generated by the electrical power supplied to microphone preamplifiers and loudspeaker. The frequency response of the unit is generally flat, but it increases by about 3 dB at 250 Hz. The testing and the measurements were made at levels of 94 dB to 114 dB.

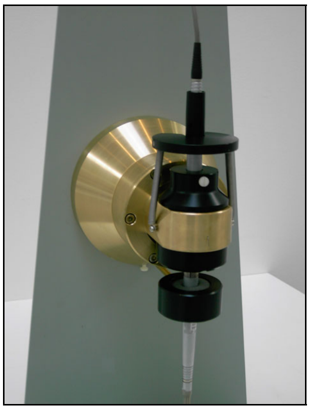

Fig. 10. Low-frequency Calibration Unit. It has a diameter of 145 mm

SUMMARY

The activities behind this paper have resulted in a new low-frequency method for frequency response calibration, in a new reference microphone and in a practically applicable low-frequency calibration unit. As the frequency range, 0.1 Hz to 250 Hz, of the reference microphone and the calibration unit overlaps the audio range, the absolute sensitivity at low frequencies may be obtained by calibrating the reference microphone at an audio frequency, say at 250 Hz, where low uncertainty is easily obtained. Promising results have been obtained, but the activities will continue with further measurements that are expected to support the work of BIPM and IEC. The method called the vacuum method is an alternative and promising method.