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Radiation impedance of condenser microphones and their diffuse-field responses[a]

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The relation between the diffuse-field response and the radiation impedance of a microphone has been investigated. Such a relation can be derived from classical theory. The practical measurement of the radiation impedance requires (a) measuring the volume velocity of the membrane of the microphone and (b) measuring the pressure on the membrane of the microphone. The first measurement is carried out by means of laser vibrometry. The second measurement cannot be implemented in practice. However, the pressure on the membrane can be calculated numerically by means of the boundary element method. In this way, a hybrid estimate of the radiation impedance is obtained. The resulting estimate of the diffuse-field response is compared with experimental estimates of the diffuse-field response determined using reciprocity and the random-incidence method. The different estimates are in good agreement at frequencies below the resonance frequency of the microphone. Although the method may not be of great practical utility, it provides a useful validation of the estimates obtained by other means.
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I. INTRODUCTION

Measurement microphones are used in a diversity of acoustic environments: in couplers where uniform acoustic pressure prevails, in open spaces with nearly free-field conditions, and in rooms where nearly diffuse-field conditions occur. Typically, a microphone is calibrated under uniform pressure conditions either using a primary method such as reciprocity or by a secondary method such as comparison calibration or calibration with an electrostatic actuator. The free-field or diffuse-field sensitivity is determined with the aid of a correction that is typical for the type of microphone in question. More rarely a microphone is calibrated under free-field or diffuse-field conditions either using primary or secondary techniques.

Whereas pressure and free-field calibration are more or less well-established techniques at primary and secondary levels,[1] and a good deal of scientific development has been focused on such techniques, diffuse-field calibration on the other hand is a less frequently visited area. Diestel[2] established the fundamentals of diffuse-field reciprocity calibration. Nakajima[3] used the same fundamentals in a realization of the technique in a small reverberation room filled with nitrogen. More recently, Bietz and Vorländer[4] studied the possibility of performing simultaneous free-field and diffuse-field calibration using a time-selective technique. Barrera-Figueroa *et al.*[5] made some observations about the accuracy of the reciprocity estimate in a diffuse field due to the statistical characteristics of the sound field in a reverberant room.

Diffuse-field reciprocity calibration is a primary method that may not be suitable for all types of microphones. Secondary methods for determining the diffuse-field sensitivity have been also developed. The most widespread of these is the random-incidence technique. This is a relative or secondary method that can be applied to microphones and other devices such as sound level meters.[6–8] It is worth noting that the random-incidence response (also in general, free-field, and diffuse-field responses) can be determined relative to the true pressure response[6,7] or to the electrostatic actuator response.[8]

Shaw[9] suggested an alternative formulation based on the concept of radiation resistance. So far, no one has reported the use of this relation for determining the diffuse-field sensitivity of measurement microphones, probably because of the practical difficulties in measuring the velocity of the membrane of the microphone and the pressure on the surface of the membrane. However, it has recently been reported that it is possible to measure the velocity distribution of the microphone membrane with good accuracy and to use these measurements as boundary conditions in numerical calculations for determining microphone parameters, such as pressure response and acoustic centers. Although the underlying assumptions, mainly the need of having a reciprocal microphone with an exposed membrane, might limit the applica-

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tion of such a technique, its study is an interesting way of validating the other well-established techniques.[10,11]

In this paper, a relation between the diffuse-field response and the radiation resistance of a measurement microphone is derived. A hybrid numerical and experimental method is used to determine the radiation impedance from measurements of the velocity of the membrane of a condenser microphone by using it as a boundary condition in a formulation of the boundary element method (BEM). The results of the hybrid method are compared with the results from free-field reciprocity calibration and random-incidence measurements.

II. RELATION BETWEEN RADIATION IMPEDANCE AND DIFFUSE-FIELD RESPONSE

The diffuse-field response of a microphone is related to the sound power it emits when it is acting as a source. Diestel[2] defined such a relation between the power, P, and the diffuse-field sensitivity. Diestel considered the sound power radiated to a solid angle element by a reciprocal transducer acting as a source in a free field. He obtained a differential expression of the free-field response of the transducer to a wave coming in the direction of the solid angle element by combining the expressions of the sound power and the reciprocity parameter in a free field. Diestel then determined the squared diffuse-field response by integrating the square of the free-field response to sound waves coming from all directions (random-incidence). From Diestel's expression, one can obtain

$$P = (4\pi)\left(\frac{\rho f}{2}\right)^2\left(\frac{|i|^2/2}{\rho c}\right)M_d^2, \tag{1}$$

where M_d is the diffuse-field sensitivity, ρ is the density of air, f is the frequency, c is the speed of sound, and i is the complex current flowing through the terminals of the microphone.

If the microphone can be assumed to radiate sound like a monopole with a volume velocity q, then the sound power emitted by the microphone is[12]

$$P = \tfrac{1}{2}|q|^2 \ \mathrm{Re}\{Z_{\mathrm{rad}}\}, \tag{2}$$

where the acoustic radiation impedance Z_{rad} is the ratio of the (complex) sound pressure averaged over the surface of the membrane of the microphone, S, to the volume velocity,

$$Z_{\mathrm{rad}} = \left(\frac{p_{\mathrm{av}}}{q}\right). \tag{3}$$

Note, however, that Eq. (2) is only valid if the pressure does not vary too much over the membrane, and this is probably only the case if all parts of the membrane essentially move in phase. Combining Eqs. (1) and (2), one obtains

$$M_d^2 = \frac{|q|^2}{|i|^2}\frac{c}{\pi\rho f^2}\mathrm{Re}\{Z_{\mathrm{rad}}\}. \tag{4}$$

Furthermore, recalling that the pressure sensitivity is defined as $M_p=-q/i$,[1,12] Eq. (4) can be rewritten as

$$\frac{M_d^2}{M_p^2} = \frac{c}{\pi\rho f^2 S}\mathrm{Re}\{Z_{\mathrm{rad}}\}. \tag{5}$$

The expression on the left-hand side of Eq. (5) is the diffuse-field factor. In logarithmic form, it is known as the diffuse-field correction:

$$C_d = 10\ \log_{10}\left(\frac{|M_d|^2}{|M_p|^2}\right). \tag{6}$$

The diffuse-field correction determined using the radiation resistance in combination with the pressure sensitivity can be compared with other methods, such as diffuse-field reciprocity and random-incidence calibration. Equation (5) is very similar to an expression determined by Shaw.[9]

At high frequencies there may be a phase lag between the velocity at the center of the membrane and near the rim corresponding to wave motion in the membrane.[11] Under such conditions, the pressure may vary significantly in amplitude and phase over the membrane, and then the validity of Eq. (2) is no longer obvious.

III. HYBRID NUMERICAL EXPERIMENTAL METHOD

In order to determine the radiation impedance of the microphone, a hybrid numerical and experimental method is introduced. The method is based on the use of the measured velocity of the membrane of the microphone in numerical calculations of the sound field. A more detailed description of the method, the experimental setup, and examples of its application can be found in Ref. 11. The method consists of three steps: (a) the velocity of the membrane of a microphone is measured using a laser vibrometer, (b) this measured velocity is used in a BEM model of a microphone as a boundary condition on the membrane of the microphone, and (c) the calculated sound field is used to determine the pressure distribution on the membrane of the microphone; other parameters such as the directivity index and the acoustic center of the microphone can also be obtained using the calculated sound field.[11]

A. Experimental setup

Some experiments have been carried out. The velocity of the membrane of a microphone was measured using a laser vibrometer Polytech type PDV-100. The microphone membrane was excited using a reciprocity apparatus Brüel & Kjær type 5998. The voltage on the terminals of the reference impedance on the transmitter unit Brüel & Kjær type ZE0796 and the output of the vibrometer were measured using a Brüel & Kjær "PULSE" analyzer. Figure 1 shows a block diagram of the measurement setup.

The signal used for exciting the microphone was pseudorandom noise with a bandwidth of 25.6 kHz and 6400 spectral lines. The laser vibrometer can measure up to a frequency of 24 kHz. Only 1 in. and $\frac{1}{2}$ in. Laboratory Standard microphones (LS1 and LS2, respectively) were examined.

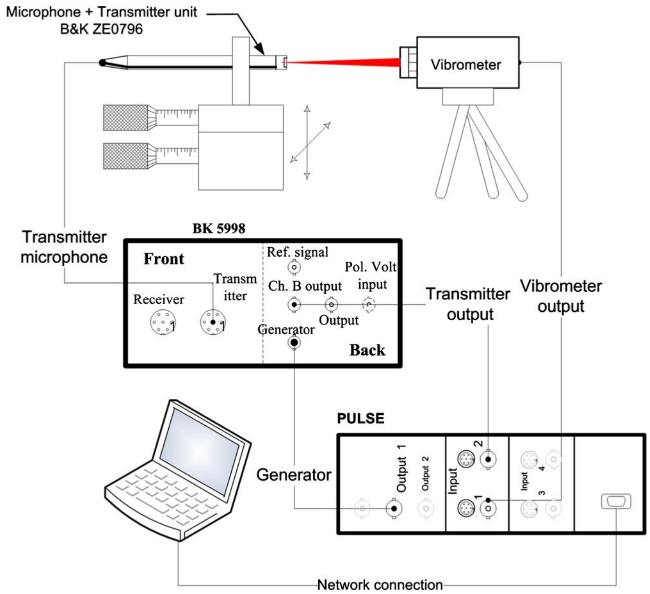

FIG. 1. (Color online) Block diagram of the measurement system.

B. BEM modeling

In the numerical modeling, the semi-infinite rod where the microphone is mounted was approximated by a cylindrical rod with a length of 60 cm with a hemispherical back-end. This will introduce a small disturbance in the simulated results because of reflections from the back of the rod. However, because of the length of the rod, they are expected to have small amplitude. The frequency range used in the calculations was from 1 to 20 kHz for LS1 microphones and from 2 to 21 kHz for LS2 microphones. The sizes of the smallest element in the axisymmetric mesh is 2.5 and 1.5 mm for LS1 and LS2 microphones, respectively. Thus, there were at least six elements per wavelength at the highest frequency.

In order to avoid the nonuniqueness problem, a random CHIEF point has been added in the interior of the geometry as described in Ref. 13, and the calculation has been checked by determining the condition numbers of the BEM matrices and by repeating calculations with small frequency shifts.[14]

In the problem at hand, the microphone acts as a sound source; thus, the radiation problem was solved by assigning the complex velocity measured with the vibrometer to the membrane of the microphone.

IV. DISCUSSION OF RESULTS

A. Movement of the membrane

Figures 2 and 3 show the velocity of the membrane of LS1 and LS2 microphones at different frequencies. It can be seen that in the two cases, the movement of the membrane below the resonance frequency follows the usual assumption, that is, the movement is parabolic. However, at frequencies above the resonance, the interaction between membrane, back-cavity, and air film between membrane and back-plate makes the membrane move in very particular shapes, different from any simple theoretical assumption.

It can also be observed that there is a phase lag at the center of the membrane with respect to the outer portions of the membrane and that the delay increases with the frequency. Thus, the membrane does not move uniformly back and forth in the whole frequency range, and this might have an effect on the determination of the radiation resistance of the microphone. However, it is only at very high frequencies for LS1 microphones (compared with their resonance fre-

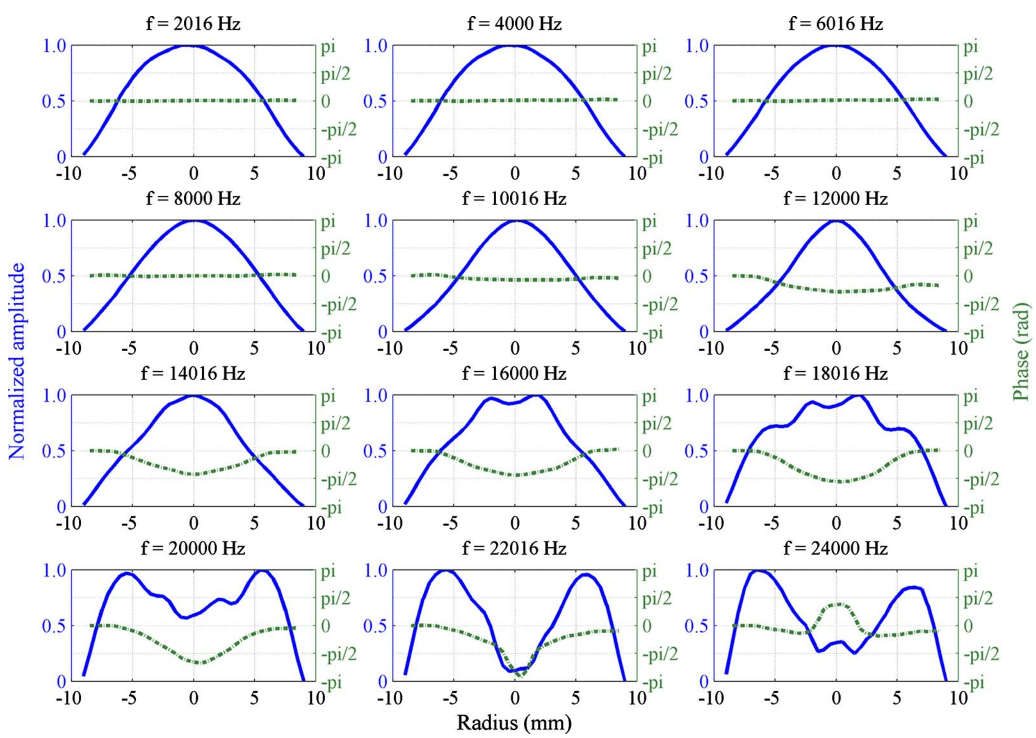

FIG. 2. (Color online) Normalized amplitude and phase of the velocity of the membrane of an LS1 microphone at several frequencies. Solid line: normalized amplitude; dash-dotted line: phase.

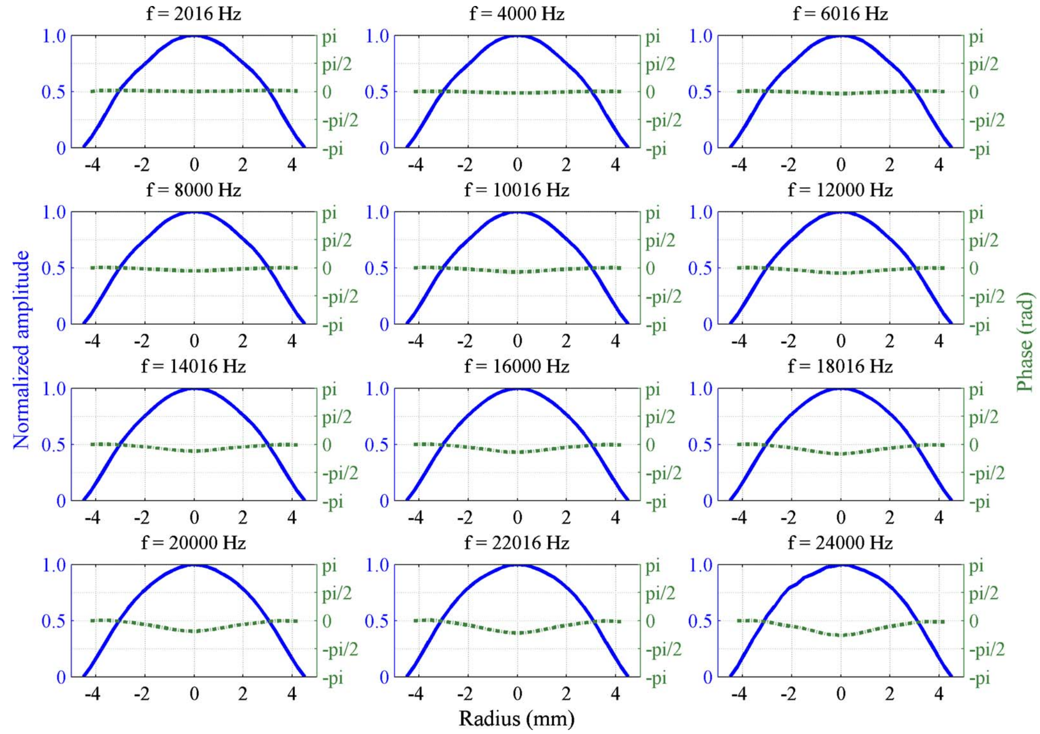

FIG. 3. (Color online) Normalized amplitude and phase of the velocity of the membrane of an LS2 microphone at several frequencies. Solid line: normalized amplitude; dash-dotted line: phase.

quency) that the phase lag becomes significantly large, introducing a clear wave movement on the membrane of the microphone. In the case of LS2 microphones, the wave motion is also present, but it can be regarded as negligible. This is because the upper frequency limit of the measurements is not sufficiently high compared with the resonance frequency of the microphone.

B. Radiation impedance and diffuse-field response of a microphone

Figures 4 and 5 show the diffuse-field correction of LS1 and LS2 microphones, respectively, determined using different methods: diffuse-field reciprocity, random incidence, and radiation impedance. In the last mentioned case, the correction was calculated using the radiation impedance determined using the measured velocity of the membrane of the microphone in the axisymmetric BEM formulation. The figures also show the difference between the individual estimates and an average of the three estimates.

Results of the diffuse-field sensitivity determined using reciprocity are only presented from 2 kHz for LS1 and LS2 microphones. The diffuse-field results at frequencies below 2 kHz for LS1 and below 3 kHz for LS2 microphones cannot be trusted. The estimate presents large deviations due to the time-selective procedure applied for separating the free-field and diffuse responses, and more specifically because of the roll-off frequencies of the passband filter used in the time-selective procedure. Details can be found in Ref. 5. Similarly, results of the random-incidence correction are only presented from 1 kHz for LS1 microphones and from 2 kHz for LS2 microphones. In this case, the values of the random-incidence correction are not reliable because of the application of the time-selective procedure described in Ref. 7. For the sake of clarity, the graph showing the difference between estimates for LS1 microphones shows only values above 2 kHz and 3 kHz for LS2 microphones.

It can be seen that the diffuse-field correction of LS1 microphones determined using the radiation resistance at low

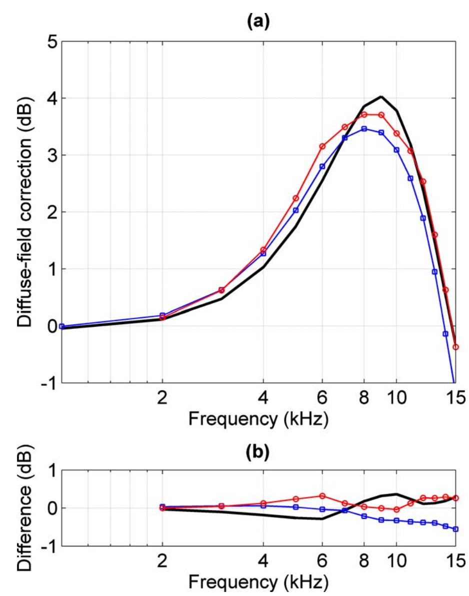

FIG. 4. (Color online) Diffuse-field correction for LS1 microphones: (a) modulus of the correction determined using different techniques and (b) difference between the individual estimates and the average of the three different techniques. In both graphs, the thick solid line is the diffuse-field correction determined from the radiation resistance, the line with circular markers is the diffuse-field correction determined using reciprocity from Ref. 5, and the line with square markers is the random-incidence correction from Ref. 7.

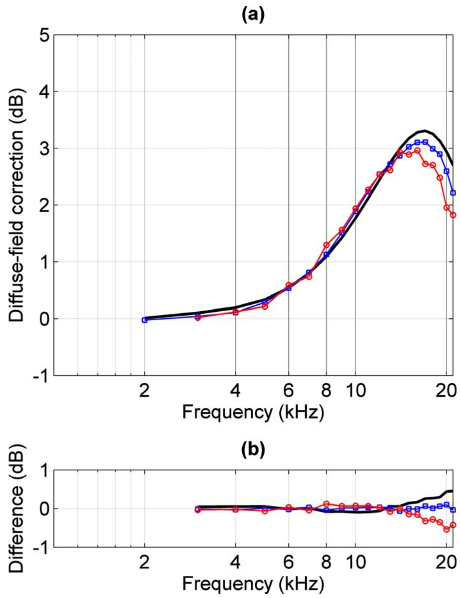

FIG. 5. (Color online) Diffuse-field correction for LS2 microphones: (a) modulus of the correction determined using different techniques and (b) difference between the individual estimates and the average of the three different techniques. In both graphs, the thick solid line is the diffuse-field correction determined from the radiation resistance, the line with circular markers is the diffuse-field correction determined using reciprocity from Ref. 5, and the line with square markers is the random-incidence correction from Ref. 7.

and midfrequencies (up to 7 kHz) is in reasonable agreement with the estimates obtained using the reciprocity and random-incidence techniques; the average difference between estimates is within 0.2 dB. Around the resonance frequency of the microphone (between 7 and 10 kHz), this agreement degrades. Above 10 kHz the agreement seems to improve again. The diffuse-field correction for LS1 microphones shown in Fig. 4 is not reliable above 15 kHz because the pressure sensitivity determined by reciprocity has reached its limits of applicability.

The behavior of the diffuse-field correction of LS2 microphones is very similar to the LS1 correction. At midfrequencies and up to 15 kHz, the agreement between the different estimates is good; the average difference between estimates is better than 0.1 dB. Above 15 kHz the agreement degrades, and the average difference takes values up to 0.5 dB.

The agreement between estimates at midfrequencies is much better for LS2 microphones than for LS1 microphones. A possible explanation for this behavior is that the assumption made in deriving Eq. (2), that either the velocity of the membrane or the sound pressure on the membrane do not vary too much over the surface of the membrane, is satisfied to a larger extent for LS2 than for LS1 microphones, because the surface of the membrane is larger and more compliant in the latter case. This gives rise to larger phase differences between the center of the membrane and the portions closer to the rim. There is no apparent reason why the diffuse-field response determined from the radiation impedance differs from the reciprocity and random-incidence estimates.

V. CONCLUSIONS

A relation between the radiation impedance and the diffuse-field response of a transducer has been derived. The validity of this relation is limited to sources with real-valued surface velocities.

The diffuse-field correction has been determined from the derived relation making use of a hybrid experimental-numerical method. The velocity of the membrane of LS1 and LS2 microphones has been measured with a laser vibrometer. This measured velocity was used in a BEM formulation for determining the radiation impedance. The results of the hybrid method are in good agreement with other realizations of the diffuse-field correction, namely, diffuse-field reciprocity and random-incidence measurements. Thus, this method can be used as a validation of the traditional methods.

Furthermore the hybrid method can also provide more reliable values of the diffuse-field correction at low frequencies where the traditional methods fail.

ACKNOWLEDGMENT

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