Numerical design and testing of a sound source for secondary calibration of microphones using the Boundary Element Method

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Introduction

In Acoustic Metrology, the primary standards are reciprocity calibration systems where a special kind of microphones (Laboratory Standard, LS) is used. Pressure reciprocity calibration requires the use of three of such LS microphones, which are reciprocal, in pairs inside a coupler. In this way their sensitivities are determined in an absolute manner.[1,2]

Secondary calibration of microphones is the metrological link between the highest acoustic measurement standards and the practical use of acoustic measurement devices. Here the measurement reference is transferred from the primary system to general measurement microphones, the Working Standard (WS) microphones.

Pressure calibration method is the most widely used method for secondary calibration of WS microphones. The procedure is described in the standard IEC 62094, part 5. The method implies fitting the reference and measured microphones in a cavity, where they are exposed to a uniform pressure sound field. [3]

However, most real-life measurement conditions are closer to free field, where sound waves impinge on the microphone from a frontal direction, creating a scattered sound wave that increases the output of the microphone at high frequencies. A particular type of measurement microphone, the so-called free-field microphone, is designed to compensate for this increase.

The method for secondary calibration under free field conditions involves the comparison with a calibrated reference microphone in a free field. This technique allows calibration of microphones in a situation that is more similar to the actual way they are used. Besides, many microphones have a variety of sizes, protections grids, etc that make very difficult to fit them in couplers.[2]

A typical setup for secondary calibration of microphones in free field involves: i) an anechoic chamber with fittings to hold the devices at fixed positions; ii) a sound source that covers the desired frequency range and showing sufficient stability; iii) a calibrated microphone, traceable to the primary system; iv) the microphone under test; v) equipment to feed the source and collect the output of the microphone, such as oscillator, amplifier, microphone preamplifier and amplifier and frequency analyzer. The microphones are consecutively exposed to the sound generated by the source, and their outputs are compared. This leads, using the data from the calibrated microphone, to an estimation of the sensitivity of the unknown microphone.

There is a growing interest among acoustic metrologists to study and improve different aspects of secondary calibration. The European Association of National Metrology Institutes (Previously EUROMET, now EURAMET) conducted a comparison among several European laboratories in order to better understand the practical application of this technique and develop a common procedure.[4] In this exercise, all measurements were done by consecutively measuring both microphones. Among other issues, it was proposed that the sound source should be optimized.

Later, a new project was started by EURAMET, proposing lines of research to improve secondary calibration of microphones in free field, and much weight is put on the specification and design of suitable sound sources.[5]

A possible development of the free-field secondary calibration of microphones is to perform the calibration exposing the two microphones to the sound field simultaneously. This would have clear advantages: simpler and faster procedure, less influence of source stability, varying ambient conditions, etc. However, this method requires ensuring that both microphone positions are equivalent and that the influence of positioning errors does not have a strong impact on the overall uncertainty. In the usual substitution method, the position is always on the symmetry axis of the source, thus minimizing the effect, mainly at high frequencies, of increased source directivity.

In this paper a new design of the sound source for simultaneous calibration is proposed, simulated and measured. The new source would allow measuring both reference and measured microphones simultaneously. The microphones should be placed at symmetrical 10-20 degrees of-axis positions, apart enough to avoid mutual influence, but close enough to achieve almost identical excitation. The new source provides a more uniform sound field at those positions, that is, its spatial variation is tolerable up to frequencies as high as 50 kHz, thus reducing the contribution to overall uncertainty of the measurement.

Numerical simulations using BEM

This design has been found very adequate for a study using the Boundary Element Method (BEM), which is particularly well suited for exterior problems. A large number of sound source shapes and their variations were thoroughly tested with no need of actually building them. The implementation of the BEM employed (OpenBEM) has been developed by some of the authors and it is routinely used in research and development by the authors and other researchers.[6]

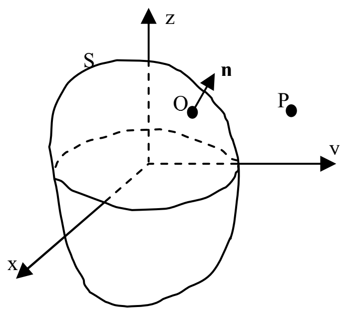

Figure 1: Generic integration domain and boundary surface in acoustic BEM.

The BEM for acoustic radiation and scattering problems in air is based on the Helmholtz Integral Equation that relates the pressure *p(Q)* and normal velocity *v(Q)* on the surface of a body of any shape (see figure 1) with the pressure at any point *p(P)* and the pressure of an incoming wave $p^I(P)$. The harmonic time dependence $e^{i\omega t}$ is omitted, giving:

$$C(P)p(P) = \int_S \left(\frac{\partial G}{\partial n} p(Q) + ikz_0 v(Q)G \right) dS + 4\pi p^I(P) \qquad (1)$$

where *S* is the surface of the body, *Q* a point on that surface and *P* any exterior or interior point. The normal vector ***n*** is directed into the computational domain. The factor *C(P)* is the geometrical constant and represents the exterior solid angle at *P*. *G* is the Green's function for 3-D free space. In BEM, the surface S is discretized into elements, resulting into a matrix equation. Then the pressure on the nodes can be expressed as a function of the normal velocity and/or the incident pressure, for radiation and scattering problems respectively, by solving the system of equations. The sound pressure on any point of the domain can then be obtained from the surface values of pressure and normal velocity by integrating (1) again. This is called the *direct collocation* method.

In this investigation an axisymmetrical formulation of the BEM is used. The objects to simulate must have axial symmetry, and only their generator needs to be meshed. This reduces the computation time and storage, and simplifies the process.[7]

Source design

Free-field secondary calibration of microphones is performed at the Danish Primary Laboratory of Acoustics (DPLA), a part of the Danish Fundamental Metrology Institute. The procedure normally uses a source as shown in figure 2, a Vifa tweeter covered with a tennis ball shell on the back. The calibration is carried out using the substitution technique, that is, the two microphones are measured one at a time and placed on the symmetry axis of the source, as in figure 3a. The source should be modified in order to allow a simultaneous measurement by comparison, as in figure 3b.

However, at high frequencies, any source tends to have a more complicated radiation pattern, far from omnidirectionality. A simultaneous comparison technique would be more sensitive to such directionality variations, being the microphones off-axis. Moreover, the calibration system should be designed to work up to around 50 kHz, a frequency range pressure methods cannot reach, but many measurement microphones are designed to cover.

Figure 2: Source for free-field calibration used at DPLA.

The diaphragm of the tweeter is basically a coil attached to two concentric suspensions. The central plug does not move and is fixed to the body. The movement of the diaphragm was simulated by making the vertical velocity larger the closer to the coil, and projecting it on the vector normal to the diaphragm surface, as shown in figure 4.

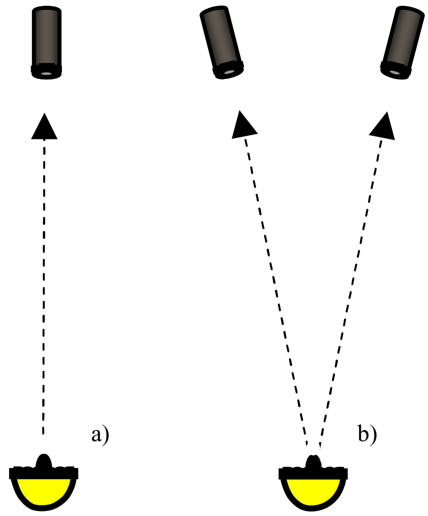

Figure 3: Sketch of the source and microphones under calibration. Methods: a) substitution; b) comparison.

Many different additions, such as reflectors and scatterers of different shapes and sizes have been simulated in combination with the source. The sound field at the positions of the microphones has been examined, in particular the spatial gradient of the sound pressure. Keeping this gradient under about 0,5 dB/cm is required in order to have a low enough uncertainty contribution.

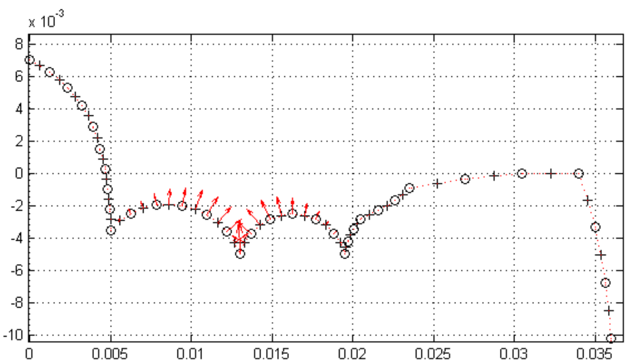

Figure 4: Detail of the source generator mesh. The arrows show the normal velocity amplitudes. The axes (ρ,z) are in meters.

The most advantageous devices have been long central plugs or *noses* attached to the static centre of the tweeter. Two of the source configurations with noses are shown in figure 5.

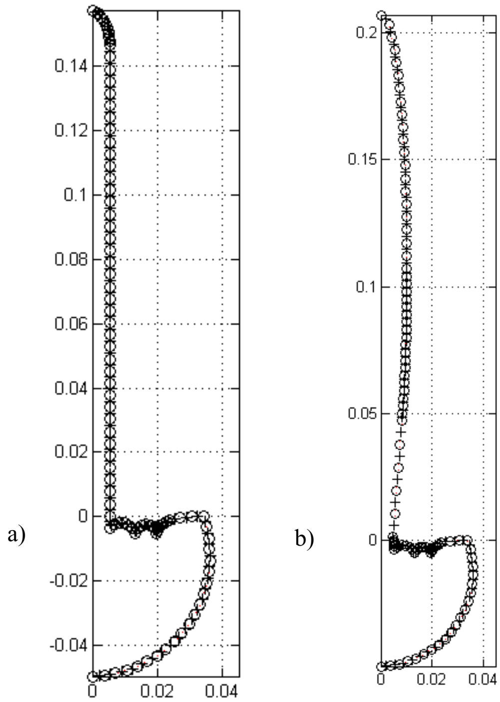

Figure 5: Generators of two of the source configurations. Nose: a) cylindrical; b) ellipsoidal. The axes (ρ,z) are in meters.

Measurements

The source configurations in figure 5 have been constructed and tested. Figure 6 shows pictures of the actual devices.

a) b) c)

Figure 6: Photographs of the sources with a) cylindrical nose, b) ellipsoidal nose, and c) ellipsoidal nose and rounded back

The cylindrical nose model in figures 5a and 6a was measured and tested first and preliminary results are shown elsewhere.[8] The ellipsoidal version in figures 5b and 6b was drawn using CAD software and produced in acrylic plastic with a 3D printer. It was made hollow to reduce the weight and attach it to the tweeter central plug.

In parallel, another version of the source with ellipsoidal nose and apple-shaped mounting for the tweeter was produced at DPLA. However, this last setup showed poor results, possibly due to the direct mounting of the nose through the tweeter body, inflecting some writhing onto the diaphragm. For this reason, only measurements made with the sources in figures 6a, 6b and 2 will be shown.

The directional responses of the sources were measured in an anechoic chamber. The source was mounted on a rotating table and was rotated over an axis crossing as close as possible to the acoustic centre. The positions of the acoustic centre in relation to the chosen rotation axis and over the frequency range of interest were computed using the BEM models and measured independently at DPLA, giving similar results. The influence of misalignment was calculated and considered negligible.

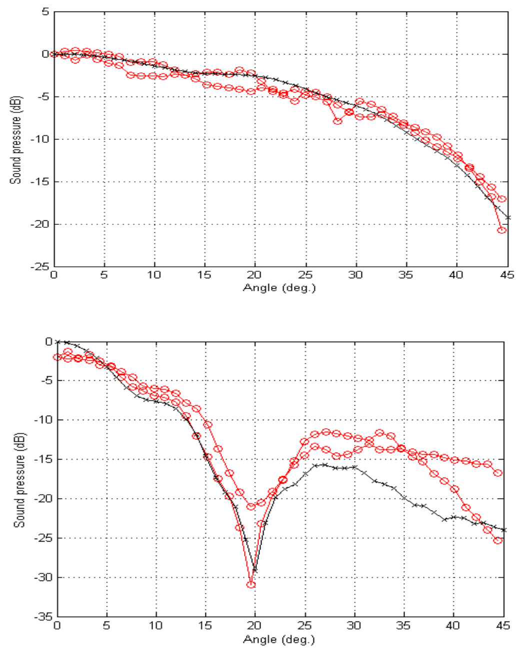

Figure 7: Comparison between measurements (o) and simulations (x). The sound pressure level at 1 m distance at several angles from the axes is plotted. Source with ellipsoidal plug, a) 16 kHz, b) 40 kHz.

The sound pressure was measured at 1 m from the rotation axis at frequencies from 10 to 40 kHz. Pure tones at central 1/3 octaves were used. This is the most critical frequency region, where directional effects are of greatest importance. However, the simulations were made at a wider frequency range. Higher frequencies could not be readily measured with the available equipment at SDU. This measurement procedure can be greatly improved by making static measurements at angle increments, by averaging measurements over longer time intervals and by using other kinds of excitations and analysis. The purpose of the measurements was the verification of the simulations, rather than thorough testing of the setups, and therefore the measurement procedure was made as simple as possible.

Results

Verification with measurements

The measurements and simulations are compared for some selected frequencies in figure 7. It can be seen that the simulation follows the measured data. Therefore, the quality of the measurement is sufficient to generally confirm the goodness of the models.

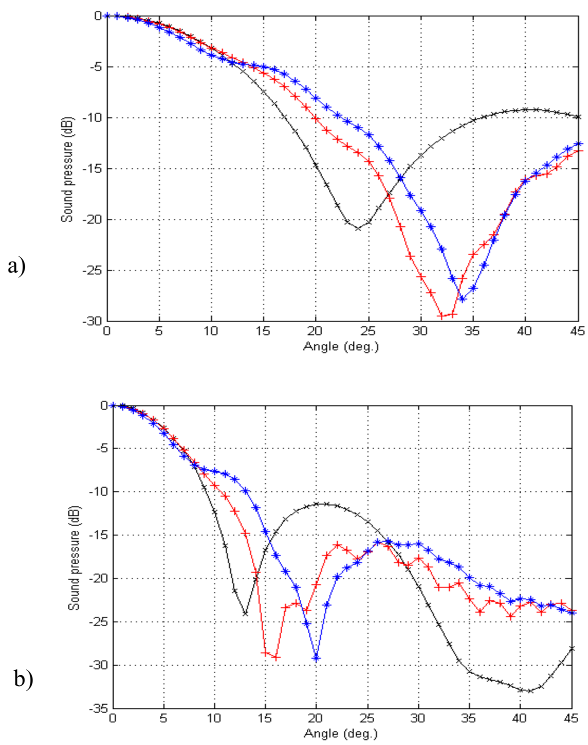

Figure 8: Comparison between simulations of sources with no nose (x), cylindrical nose (+), and ellipsoidal nose (*). The sound pressure level at 1 m distance at several angles from the axes is plotted. a) 25 kHz, b) 40 kHz.

Simulated radiation patterns

Figure 8 presents a comparison of the radiation patterns for three source configurations: no nose, cylindrical nose and ellipsoidal nose. The benefit of the ellipsoidal nose can be clearly observed if we assume the microphones to be compared are situated around 10 degrees off axis. At this point the ellipsoidal source presents, at all the frequencies studied, less spatial variation. It can be shown that this variation is within the requirements for secondary calibration of microphones.

Conclusions

Several configurations of a source for simultaneous secondary calibration of microphones have been simulated and measured experimentally. It is shown that a nose plug mounted in a calibration source can reduce positional uncertainty in. In particular, an ellipsoidal nose plug of certain dimensions produces the best results.

Measurements provide verification of the numerical model of the calibration source and support the conclusions.

Future work

Measurements on the source with the apple-shaped body, and the ellipsoidal nose using incremental angular steps should be available soon.

The next step is to use the designed sources in a calibration exercise and to compare the results with a sequential comparison calibration.

Further simulations may include 3D BEM models of the source and microphones and the effect of the scattering and interaction of the microphones.

Acknowledgement

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