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Free-field reciprocity calibration of measurement microphones at frequencies up to 150 kHz

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Microphones are typically calibrated in a free field at frequencies up to 40 kHz using primary and secondary methods. This upper frequency is sufficiently high as to cover most sound measurement applications related with airborne noise assessment. However, other applications such as measurement of noise emitted by ultrasound cleaning machines, failure detection in aeronautic structures, and the investigation of the perception mechanisms of ultrasound may require that the sensitivity of the microphone is known at frequencies up to 150 kHz. In any of these applications, it is critical to establish a well-defined traceability chain to SI units to support any measurement result. In order to extend the frequency range of absolute free-field calibration, typical reciprocity measurement systems and measurement methods must undergo a series of changes and adaptations which may include using other types of microphones rather than laboratory standard microphones, changing the type of measurement signal, improving the methods for eliminating unwanted reflections from walls, cross-talk, distortion, etc. Herein, a strategy for the changes and adaptations to the existing measurement methodologies, and the determination of the microphone parameters is outlined, the results of its implementation are discussed, and calibrations results are presented and discussed.

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I. INTRODUCTION

Microphones are typically calibrated in a free field at frequencies up to 40 kHz and in couplers up to 30 kHz using primary and secondary methods. This upper frequency is sufficiently high as to cover most sound measurement applications related with airborne noise assessment. However, some recent studies have signaled that involuntary exposure to ultrasound may become an issue of public health.¹ This and other applications such as measurement of exposure to ultrasound in industrial spaces,² failure detection in aeronautic structures, and the investigation of the perception mechanisms of ultrasound³ may require that the sensitivity of the microphone is known at frequencies up to 150 kHz. In any of these applications, it is critical to establish a well-defined traceability chain to SI units to support any measurement result. The sensitivity of a microphone depends significantly on the type of sound field in which it is immersed. Nowadays, practically all microphones are calibrated using pressure-field methods which are based on the assumption of a uniform or quasi-uniform sound pressure acting only on the membrane of the microphone. However, most microphones are used under diffuse-field or free-field conditions.

The reciprocity technique for microphone calibration under pressure-field conditions (in closed couplers) was introduced in the 1940s,^{4,5} and since then has developed to a level of very high accuracy and has been standardized.⁶ The free-field reciprocity technique was also introduced in the 1940s.^{7,8} Reciprocity measurements in a free field are particularly difficult, partly because of the extreme difference in

signal levels (if the transmitter microphone is driven with 10 V at 1 kHz, the response from the receiver microphone will typically be less than 1 μ V), and partly because reflections from the walls anechoic room, which in practice are always less than perfect, have a serious influence. Due to these practical difficulties in the implementation of the technique, it was customary to determine the free-field sensitivity by combining the pressure sensitivity and the free-field correction for a particular type of microphone. This procedure would implicitly have a larger uncertainty and would put a limitation on the frequency range in which a reliable estimate of the free-field sensitivity could be obtained, mainly because of the limitations of the pressure calibration. Furthermore, it would be limited to few types of microphones where both types of calibration were possible. Fortunately, primary calibration in the free field has been progressing steadily, and signal processing procedures designed to remove reflections from walls and some electrical disturbances, such as cross-talk and distortion, have been developed to a stage where it can be applied in practical calibrations without the use of costly anechoic rooms, and overcome the practical difficulties mentioned above.^{9–13}

It can be safely assumed that the reciprocity principle used in free-field calibrations in the audio range is still valid at such high frequencies, and it is tempting to state that the current methodologies can simply be extended to measure higher frequencies as described by Rudnick and Stein.⁸ This is only partly correct: while the physical principles are still valid, the practical realization of the method, instrumentation and validation are taken to untested extremes. For instance, typical sound analyzers may be able to measure at frequencies up to 100 kHz, which falls short of the required upper

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frequency that must be measured. Another issue is that Laboratory Standard (LS) microphones (see Fig. 1) are designed to have a free-field response that is well defined up to a given frequency, typically just above their own resonance frequency, just above the typical audio frequency range.¹⁴ Above that limit, the response decays very rapidly (12 dB per octave), and resonances in the back cavity make the microphone response uneven and sensitive even to small changes in the environmental conditions. This implies that the instrumentation used in the measurements must be modified in order to cover high frequencies, and that new transducers are required. Additionally, LS microphones are the most studied of all microphone types, and their parameters (acoustic centre, environmental coefficients, lumped parameters used in the equivalent circuit of the microphone) are well known. This may not be the case with other types of microphones. An additional issue is that the accuracy of such calibrations must be transferred to other microphones, usually by comparison calibration, or by adding a normalized free-field correction to the pressure sensitivity determined at a single frequency. This poses an additional set of problems when the measurements are to be validated or disseminated. It is the case that often cited airborne noise levels at ultrasound frequencies have had no direct traceability to measurement standards in the past because calibration has not been possible. Traceability has needed to be extrapolated, or a microphone calibration assumed from its lower frequency behavior.

In this paper, a strategy for extending the frequency range of free-field calibration to frequencies well above the audio frequency range is outlined and discussed. A measurement system has been implemented following the discussed recommendations. Results from the use of this measurement system and a calculation procedure are presented and discussed. Finally, a set of improvements to the current system are described.

II. EXTENDING THE FREQUENCY RANGE

Extending the frequency range of the free-field reciprocity calibration may require some major changes in the

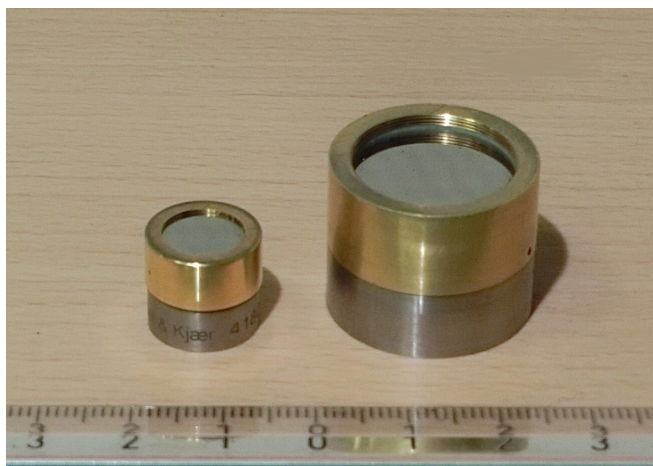


FIG. 1. (Color online) LS microphones. Left: LS microphone type 2 (LS2). Right: LS microphone type 1 (LS1).

existing measurement systems. One can divide these requirements into issues related to the measurement system and issues related with the validity of the reciprocity theory. These two lines will be discussed below.

A. Free-field reciprocity theory

A reciprocity calibration requires that two microphones are acoustically coupled, in this case in a free field. One of the microphones is used as a sound source (transmitter), and the other one as a receiver. The electrical transfer impedance includes the free-field sensitivities of the two microphones. When a third microphone is coupled pairwise with the other two, the sets of electrical transfer impedances contain enough information for determining the individual sensitivities of the microphones. This procedure requires that at least one microphone is reciprocal. In practice, the microphones used are condenser microphones, which are inherently reciprocal, making all transmitter-receiver combinations possible. In the following, it is assumed that the reciprocity principle is also valid at the high frequencies intended to be covered. As outlined above, the determination of the free-field sensitivity is mainly based on the measurement of the electrical transfer impedance between the two microphones, which is the ratio of the open-circuit output voltage at the terminals of the receiver microphone to the input current flowing through the electric terminals of the microphone used as transmitter. The electrical transfer impedance, $Z_{e,12}$ is given by the formula¹⁵

$$Z_{e,12} = \frac{u_1}{i_2} = j \frac{\rho f}{2d_{12}} M_{f,1} M_{f,2} e^{ikd_{12}} e^{\alpha d_{m12}}, \quad (1)$$

where u_1 is the open-circuit voltage on the terminals of a microphone acting as a receiver, i_2 is the current flowing through the terminals of a microphone acting as a source (transmitter), ρ is the density of air, f is the frequency, d_{12} is the distance between acoustic centres of the microphones, $M_{f,1}$ and $M_{f,2}$ are the free-field sensitivities of the microphones, k is the wavenumber ($k = 2\pi/\lambda$), d_{m12} is the distance between the membranes of the microphones, and α is the air attenuation coefficient. The electrical transfer impedance is the basis of the reciprocity technique as it contains information of the free-field sensitivities of the two microphones. If a third microphone is coupled successively with the first two, a set of three equations and three unknowns can be formed. The solution of such a system will be the absolute free-field sensitivities of the three microphones. The sensitivity of microphone 1 in a triad can be calculated using the following formula:

$$M_{f,1}^2 = \frac{2}{\rho f} \frac{d_{12}d_{13}}{d_{23}} \frac{Z_{e,12}Z_{e,13}}{Z_{e,23}} e^{jk(d_{12}+d_{13}-d_{23})} e^{\alpha(d_{m12}+d_{m13}-d_{m23})}. \quad (2)$$

It is apparent from the formula above that the calculation procedure is quite straightforward; however, there are several issues that must be resolved in order to determine the sensitivity with the lowest uncertainty possible: (a) It must be noticed that d_{ij} is the distance between acoustic centres,

and not between microphone membranes. The acoustic centre is well-known for some LS microphones, and it should be determined for any other type of microphone. This can be done by measuring the electrical transfer impedance at several distances in order, and then using linear regression to determine the acoustic centre from deviations of the inverse-distance law.^{16,17} (b) It is also important to notice that correcting the sensitivity to reference environmental conditions requires the environmental coefficients to be known, which is not the case for all microphones. (c) The calculation of the complex propagation coefficient requires that the air attenuation is calculated accurately as a function of frequency. Fortunately, the model based on molecular relaxation and classical absorption theory is still valid in the area of interest.^{18–20} The values of the speed of sound, density, and air attenuation can be calculated using the procedures described in the report by Rasmussen²¹ and International Standards.^{6,15}

B. Measurement system

1. Transducers

LS microphones do not have a sufficiently stable or smooth frequency response at very high frequencies, where the higher modes of the membrane and its interaction with the back cavity become significant. It can be assumed from the typical characteristics of LS microphones type LS2aP that this type may not have a smooth and stable frequency response at frequencies above 50 kHz. Working Standard (WS) microphones of type 3 (WS3),²² also known as *quarter-inch* microphones (see Fig. 2), have a well-defined frequency response up to 100 kHz by virtue of their small size which makes them a reasonable choice.^{23,24} It must be taken into account that this type of microphone has a lower sensitivity level, as this would increase cross-talk problems due to large differences in the voltages of the receiving and transmitting measurement channels. Furthermore, environmental coefficients of these microphones are not well known. Using WS3 microphones as sound sources may require using relatively high voltages that, when combined with the low-voltage output of the receiver microphone, will result in electrical cross-talk that cannot be neglected. In addition to the conventional approaches to reducing cross-talk such



FIG. 2. (Color online) WS microphones. Left: GRAS type 40BF microphone. Right: Brüel & Kjær type 4136 microphone (equivalent to type 4939).

as separating the hardware connected to receiver and transmitter channels and the time-selective procedures, it may be necessary to remove the cross-talk using alternative methods, such as measuring the ratio of voltages when a dummy microphone (an inactive microphone with the same capacitance as the WS3 microphone) is mounted on the system instead of the receiver microphone and subtracting this from the actual measured ratio of voltages. If not removing it completely, this operation may reduce the cross-talk significantly.²⁵ Another relevant characteristic of LS and WS microphones of type 1 and 2 is that these types have a well defined ground-shield reference configuration that is used on almost any available preamplifier or transmitter unit. In order to use WS3 microphones with these instruments, it is necessary to use adapters which typically do not have the ground-shield configuration recommended in the standard.²² This may result in differences in the sensitivity determined using different types of adapters and possibly in larger distortion due to the stray capacitance introduced by the unshielded adapter (see Fig. 3).

2. Data acquisition

The first possibility is to use an analyser with an extended frequency range. Commercial instruments with this characteristic may not be readily available to use in acoustic applications. If the analyzer used can measure at the frequencies in question, it may be sufficient to find a suitable signal generator. An alternative is to use a sound card or any other data acquisition device that can sample analogue signals of frequencies up to 200 kHz. An additional characteristic of such a device should be an analogue output able to generate signals with the same frequency bandwidth. This would require that the appropriate measurement software is developed *ad hoc*. Furthermore, it must be ensured that the remaining instrumentation can function in the extended frequency range, and that amplifiers, power supplies, etc., do not exhibit a high frequency roll-off. If that is not the case,



FIG. 3. (Color online) Commercial adapters for WS3 microphones. Notice the absence of shielding around the contact pin in the adapters to the left and in the middle.

modifications should be made in order to fulfil this requirement.

3. Signal types

Most free-field systems use either pure tone signals in the form of stepped sine excitation or analytical signals such as sweep signals. In some cases, systems developed in-house use the sweep signals while the stepped sine excitation is typically found in commercial software. The application of time selective techniques based on inverse Fourier transformation requires that the frequency response (voltage ratio) is measured using linear frequency steps. This makes it possible to use other signal types such as pseudo-random noise but prevents from using logarithmic-stepped signals. Sweep techniques, on the other hand, can be used to determine the time response using either linear or logarithmic sweeps. In any case, pure tone signals may be preferred because these signals maximize the signal-to-noise ratio at the expense of extended measurement time.

III. MEASUREMENT SYSTEM

A measurement system was implemented based on the considerations described above. Figure 4 below presents a

block diagram of the implemented measurement system. A Brüel & Kjær PULSE analyzer capable of measuring up to 200 kHz together with an external signal generator have been selected to provide the signals and the signal analysis. In this configuration, the Steady State Response (SSR) mode of the analyzer cannot be used, and two-channel fast Fourier transform (FFT) is used instead. The external signal generator chosen for this step is a National Instruments DAQ Card that can be programmed to generate random noise up to 200 kHz; alternatively, any other signal generator able to produce a similar signal can be used. The core of the system is the reciprocity apparatus, in this case a Brüel & Kjær type 5998 which is used to measure the electrical transfer impedance and apply the insert voltage technique in the whole frequency range of interest. The reciprocity apparatus only drives the transmitter. The receiver channel is measured with a Brüel & Kjær NEXUS amplifier that has been modified to allow the measurement of the insert voltage. The WS3 microphones used in the system are Brüel & Kjær type 4939. According to the manufacturer microphones type 4939 have a flat frequency response (± 1 dB) at frequencies up to 100 kHz, which is slightly above their resonance frequency 70 kHz. Thus, it may be possible to determine their frequency response at frequencies up to 150 kHz. Mounting

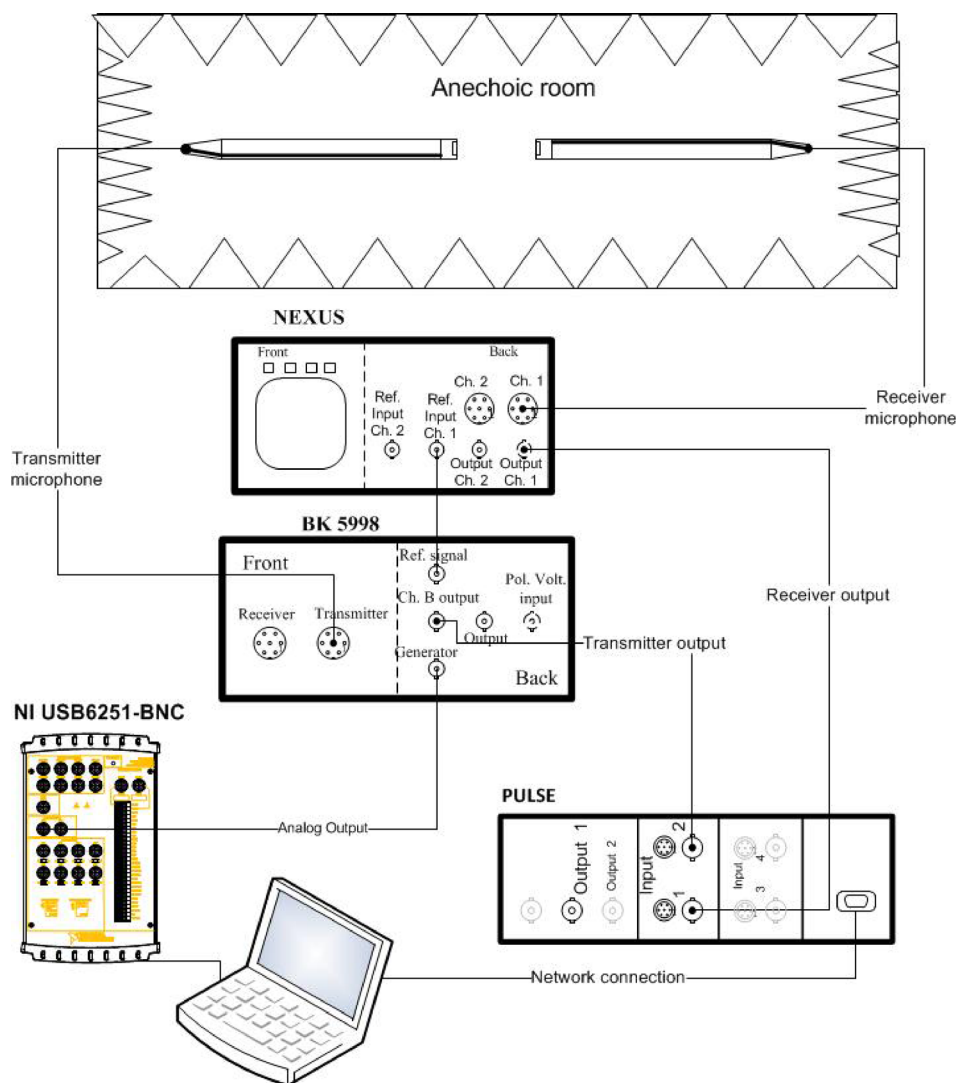


FIG. 4. (Color online) Schematics of the free-field reciprocity system for high frequency calibration.

microphones type 4939 on *half-inch* preamplifiers and transmitter units requires to use *half-inch* to *quarter-inch* adaptors. These adaptors have a tapered transition that goes smoothly from the preamplifier diameter (12.7 mm) to the diameter of the microphones (6.35 mm); at this stage it was assumed that the length of the *quarter-inch* section of the adaptor was sufficiently long as to approximate semi-infinite cylinders in the frequency range of measurement; furthermore, reflections from the tapered section can be separated from the direct impulse response between microphones.

IV. EXPERIMENTAL RESULTS

The reciprocity procedure has been applied using three Brüel & Kjær type 4939 microphones. The electrical transfer impedance was measured in the frequency range from 32 Hz to 200 kHz using random noise and 2-Channel FFT. A time-selective procedure similar to the one described in Ref. 10 has been applied. The intermediate results are presented below. The electrical transfer impedance between the three pairs of microphones was measured at four different distances between microphones, namely, 80, 100, 120, and 140 mm. In all cases, the microphones were measured *without* their protection grid. Figure 5 shows the measured electrical transfer impedance between two WS3 microphones; the electrical transfer impedance between two LS2 microphones is shown as well for comparison purposes. As it is expected, the amplitude of the transfer impedance is much lower for the WS3 microphones, though in the case of the LS2 microphones, it shows higher resonances of the membrane and back cavity just above 50 kHz while the WS3 impedance reaches its maximum smoothly and then rolls off. The trade-off is that the lower sensitivity of the WS3 results in lower output voltages that are more sensitive to cross-talk that noticeably shows as a ripple in the whole frequency response with an amplitude that changes inversely to the amplitude of the transfer impedance.

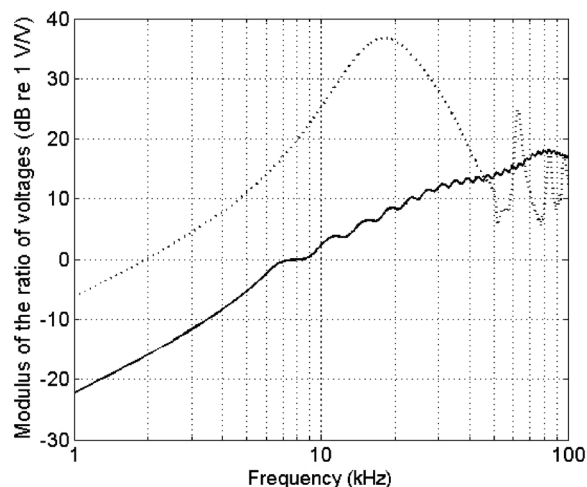


FIG. 5. Electrical transfer impedance between two WS3 microphones Brüel & Kjær type 4939 measured with the high frequency system (continuous line). The same quantity for a pair of LS2 microphones is shown as reference (dotted line).

A. Impulse response

The impulse response corresponding to the electrical transfer impedance between two B&K type 4939 microphones at 80 mm separation between microphones is shown in Fig. 6. It can be noticed that electrical cross-talk, occurring at the beginning of the impulse response, is the most relevant perturbation when compared with the acoustical interference between microphones, occurring at 0.7 ms and reflections from the walls and the measurement rig that will occur later. The time-selective window will effectively remove these perturbations, resulting in a reflection and cross-talk free electrical transfer impedance that can be used for determining the free-field sensitivity of the microphones. On the other hand, the diameter transition from 6.35 to 12.7 mm in the adaptor will occur at about 0.15 ms immediately after the direct impulse response. It is clear from the figure that this cannot be removed from the measurement. This implies that the sensitivity obtained from these measurements can only be related to the adaptor-microphone combination. In order to obtain the true microphone sensitivity, an adaptor with a longer 6.35 mm section should be used; that is at least twice as long as any existing commercial adaptors.

B. Acoustic centres

The free-field sensitivity is calculated using the distance between acoustic centre of the microphones, and not the physical distance between membranes. It is then necessary to use an estimate of the acoustic centre for each microphone. The value taken by this quantity as a function of frequency is well known for LS microphones,¹⁷ but for other types of microphones this is unknown, hence the acoustic centre must be determined for the WS3 microphones from deviations from the inverse-distance law. Calibration procedures may include the measurement of the electrical transfer impedance between the paired microphones to at least four

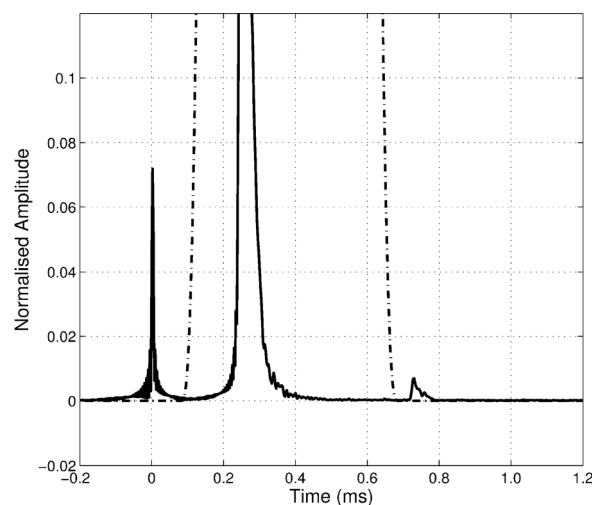


FIG. 6. Fragment of the normalised impulse response from an electrical transfer impedance between two WS3 microphones located at a distance of 80 mm from each other. The solid line represents the impulse response, and the dash-dotted line represents the time window applied to remove reflections and cross-talk.

distances. This usually serves as an assessment of the quality of the measurement, but it can also be used for determining the acoustic centre of the microphones. Figure 7 shows the acoustic centres of three microphones Brüel & Kjær type 4939 and an estimate of the acoustic centre determined from simulations based on the Boundary Element Method (BEM). The agreement between the experimental and the numerical estimates is quite good between 10 and 80 kHz. Above that, the estimates diverge. This divergence may be explained considering that the numerical estimate was determined assuming a parabolic movement of the membrane. While it may be true that the movement of the membrane will approximately be parabolic up to the resonance frequency, the actual movement will differ from a parabolic shape at higher frequencies. In any case, the experimental acoustic centre has been used to determine the free-field sensitivity of the WS3 microphones.

C. Free-field sensitivity

The free-field sensitivities of the set of microphones was determined using Eq. (2) using the experimental acoustic centres determined from the electrical transfer impedance measured at four different distances (80, 100, 120, and 140 mm). Reflections, cross-talk, and the acoustic interference between the microphones were removed using a time selective technique. Figure 8 shows the experimental estimate of the free-field sensitivity of the set of WS3 microphones and the manufacturer data for the same microphone. It can clearly be seen that there is a bias in most of the frequency range. This bias is most likely to be caused by the absence of a guard all the way around the contact pin to the adaptor (B&K type UA0035). The absence of the guarding ring all the way up to the contact introduces an additional capacitance that may be about 1 pF. Considering that the capacitance of the microphone capsule is about 6 pF, this can result in sensitivity differences of up to 0.7 dB at low frequencies; this is similar to the difference observed in the

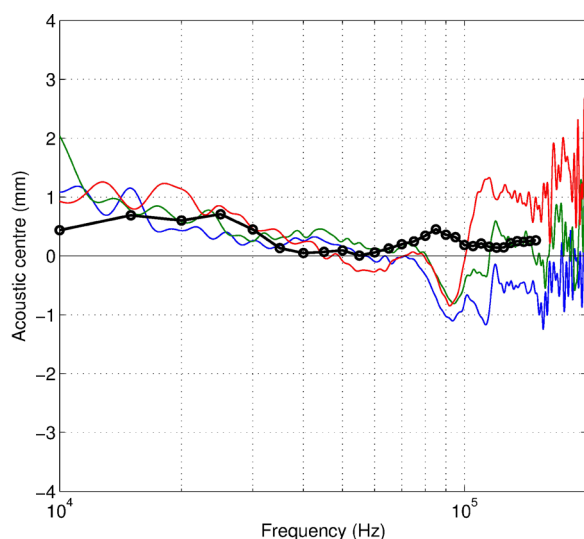


FIG. 7. (Color online) Acoustic centre of three microphones Brüel & Kjær type 4939 (coloured lines) and a numerical estimate of the acoustic centre determined using BEM (black line with circular markers).

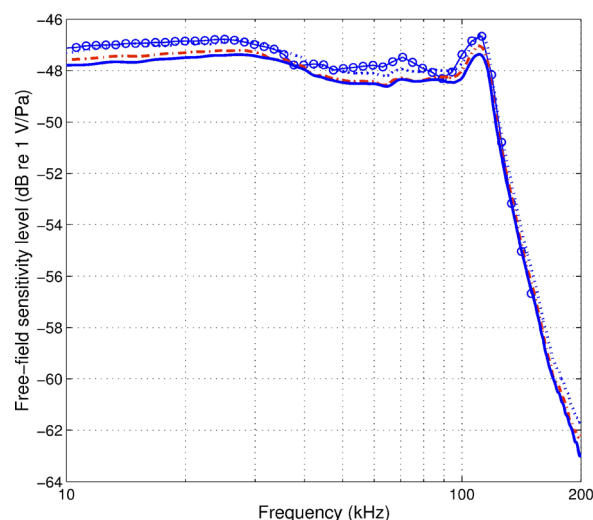


FIG. 8. (Color online) Free-field sensitivity level of a WS3 microphone Brüel & Kjær type 4939 obtained using different adapters: (a) the continuous blue line is the sensitivity obtained using an adapter Brüel & Kjær UA0035, (b) the red dash-dotted line is the sensitivity obtained using an adapter GRAS type RA0019, (c) the black dotted line is the sensitivity obtained using an adapter Brüel & Kjær WA0031, and (d) the line with dot markers is the free-field sensitivity provided by the manufacturer.

measurement. In order to test this, the free-field sensitivity was determined from measurements using another commercial adaptor, now from the manufacturer GRAS. The adaptor is the type RA0019, which has geometry very similar to the B&K UA0035. However, according to the manufacturer, the guard should be longer than in the B&K UA0035, but not coming all the way out around the contact pin. This additional cover may reduce the stray additional capacitance. Figure 8 shows the resulting free-field sensitivity level determined using the adaptor RA0019 as well. There, it can be seen that the bias has been further reduced, but is still present. A third adaptor was used to further confirm this dependence, the adaptor B&K type WA0031. This adaptor does actually have a guard ring around the contact pin. However, the *quarter-inch* section has been severed, and only the transition from *half-inch* to *quarter-inch* remains. In any case, this adaptor would not add any capacitance, and there should be no bias between estimates. Figure 8 shows the free-field sensitivity levels determined from measurements made using the B&K WA0031 adaptor. The free-field sensitivity level obtained with this adaptor does not have a bias; the difference between the reciprocity and the manufacturer data is below 0.1 dB up to 50 kHz. At higher frequencies, some differences appear. These differences may be caused by the geometrical configuration of the adaptor, though it is necessary to take the manufacturer data only as an indication due to the lack of information about the measurement procedures used to determine the frequency response. The agreement between this data and the reciprocity estimate is quite good, and clearly indicates that the best way to proceed is to have an adaptor with the proper geometry and shield configuration. Another alternative may be to use a *quarter-inch* pre-amplifier with insert-voltage capabilities on the receiver side. However, there are no transmitter units of this size. A *quarter-inch* transmitter unit could be built, but this goes

beyond the scope of this paper. A fact is that there exists a wide variety of geometry and configurations of the electric guard for *quarter-inch* preamplifiers and adaptors. It is clear that a standardization effort is needed to ensure interchangeability of devices and the dissemination of the accuracy of calibration. All in all, at this stage, it seems clear that the determination of the free-field sensitivity of a WS3 microphone can be made under the assumption that the microphone and the adaptor are a single unit, and that they are to be used together for measurement or calibration purposes. Finally, Fig. 9 shows the average free-field sensitivity level determined from four measurements and its standard deviation. The measurements were made using an adaptor B&K UA0035. It can be seen that the standard deviation, or repeatability, is better than 0.05 dB for the frequency range from 10 to 150 kHz. This repeatability is quite good considering the poor signal-to-noise ratios, and the changes in environmental conditions that may occur during a measurement.

D. Influence of environmental conditions on the free-field sensitivity

Results presented in Sec. IV C come from measurements performed under similar environmental conditions, and without correcting to reference environmental conditions (a static pressure of 101.325 kPa, a temperature of 23 °C, and a Relative Humidity of 50%). While temperature and humidity can be controlled in the laboratory, static pressure may change from day to day. The upper chart in Fig. 10 shows the free-field sensitivity measured at different days in which the static pressure was different by 1–2 kPa without any correction. It can be seen that differences are quite large and with a frequency dependence. The difference peaks around 70 kHz. This behaviour points to the need of determining the

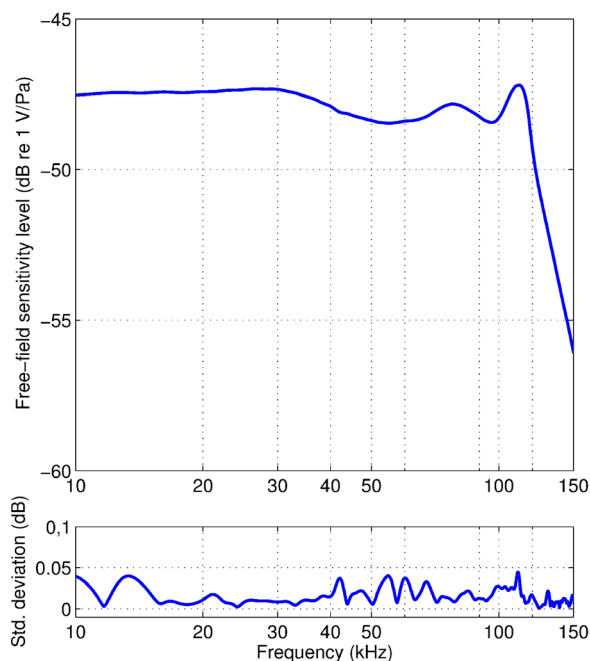


FIG. 9. (Color online) Average free-field sensitivity level (upper curve), and the standard deviation (lower curve) determined from four calibrations of a WS3 microphone Brüel & Kjær type 4939.

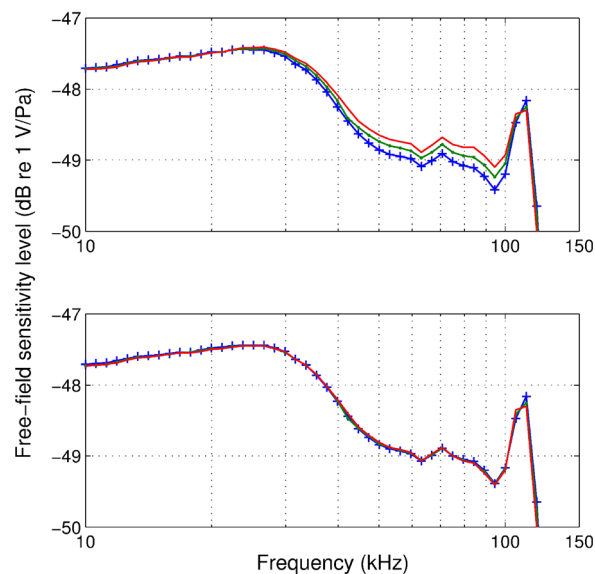


FIG. 10. (Color online) Free-field sensitivity of a WS3 microphone Brüel & Kjær type 4939 determined from measurements at different static pressures. Upper chart: uncorrected sensitivities. Lower chart: sensitivities corrected at the reference static pressure 101.325 kPa. Continuous red line $p_s = 101.16$ kPa, green line with dot markers $p_s = 99.1$ kPa, and blue line with cross markers $p_s = 98.9$ kPa.

environmental coefficients of the free-field sensitivity. A partial solution is to apply the environmental coefficients of the pressure sensitivity (see Ref. 26) to correct the sensitivity to the reference static pressure. The lower chart shows the sensitivity after the correction to reference static pressure, $p_s = 101.325$ kPa. The improvement in the agreement among the measurements is clear. This emphasizes the need of determining the environmental coefficients of the free-field sensitivity for this type of microphones.

V. CONCLUSION

A measurement system capable of measuring the electrical transfer impedance of WS3 microphones up to 200 kHz has been set up. This system has been used to perform measurements needed for determining the free-field reciprocity sensitivity of WS3 microphones. This is achieved using a calculation procedure that includes the removal of unwanted reflections and cross-talk. Results are reliable and reproducible up to 150 kHz. The differences observed among the sensitivities determined from measurements using different preamplifier adapters lead to the observation that the microphone and adaptor must be considered as a unit and the recommendation that the sensitivity be specified for that unit. In any case, the reproducibility for such a combination is better than 0.1 dB in the whole frequency range. Potential improvements include (a) using an analyser with a generator capable to generate signals up to 200 kHz so sinusoidal signals can be used in order to improve the signal-to-noise ratio, (b) constructing a set of adaptors that have the proper geometry and electric shield configuration. It could also be possible to build a set of preamplifier and transmitter unit that equally satisfy the insert-voltage method and the geometry and electric guard configurations, and (c) determining the environmental coefficients of the *free-field* sensitivity. However, the

results presented indicate the viability of primary free-field calibrations in the ultrasound frequency range, capable of providing a basis for traceability to support, for the first time, general measurements of airborne sound pressure level in this frequency range.

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APPENDIX: CONTRIBUTING FACTORS TO THE UNCERTAINTY OF THE FREE-FIELD SENSITIVITY

The main sources of uncertainty of the free-field sensitivity are listed below. Each realisation of the measurement system will have different values of each contributing factor.

Polarizing voltage. This value is typically found from a calibration of the output voltage of the source of polarization voltage. Due to the small deviations from the nominal polarization voltage (200 V), the uncertainty contribution is assumed to be constant in the whole frequency range.

Reference impedance. The reference impedance is measured in the frequency range from 1 to 150 kHz. The reference impedance may have diverse configurations and depending on the calibration method, its contribution may have a frequency dependence.

Voltage ratio. The uncertainty of the voltage ratio is estimated from the measurement parameters of the signal analyser and the signal used in the measurements. It is expected that this contribution has a given frequency dependence; typically at low and high frequencies, the uncertainty increases slightly.

Distance between acoustic centres. The uncertainty of this parameter is the combination of the uncertainties of the reference used to set up the distance between front rims of the microphones, the uncertainty of the cavity depth, if any, and the uncertainty of the acoustic centre of the microphones.

Environmental conditions. The environmental conditions are the input variables for the density of air and the air attenuation. Furthermore, the free-field sensitivity has a certain dependence of the environmental conditions. The environmental coefficients are well-known for pressure sensitivity. These can be used in combination with the expected changes in diffraction and radiation impedance due to changes in the environmental parameters. The uncertainty is small because the measurements are always made at environmental conditions close to the reference values, that is when the room temperature and/or static pressure do not exceed the limits $23^{\circ}\text{C} \pm 2^{\circ}\text{C}$, and $101.325\text{ kPa} \pm 2\text{ kPa}$, respectively.

Uncertainty of the technique used for removing reflections: The Fourier-transform based technique for removing the effect of reflections from walls and acoustic interference

between the microphones introduces systematic variations at the extremes of the frequency interval. This is due to the use of a short time-selective window. This can be assessed using results from numerical simulations.

Plane-to-spherical wave correction. The diffraction of a microphone differs whether a plane or a spherical wave impinges on the microphone. During a calibration in a free field, the microphones are close to each other, giving place to this phenomenon. The difference between plane and spherical diffraction can be calculated numerically though it is most significant at low frequencies.

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