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Barrera Figueroa, Salvador; Torras Rosell, Antoni; Rasmussen, Knud; Jacobsen, Finn; Henriquez, Vicente Cutanda

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A practical implementation of microphone free-field comparison calibration according to the standard IEC 61094-8

Salvador Barrera-Figueroa[a)]
Antoni Torras-Rosell[b)]
Knud Rasmussen[c)]
Danish Fundamental Metrology A/S, Matematiktorvet 307, 2800 Kongens Lyngby, Denmark

Finn Jacobsen[d)]
Acoustic Technology, Department of Electrical Engineering, Technical University of Denmark, Ørsteds Plads 352, 2800 Kongens Lyngby, Denmark

Vicente Cutanda-Henríquez[e)]
Peter Møller Juhl[f)]
Institute of Technology and Innovation, University of Southern Denmark, Niels Bohrs Allé 1, 5230 Odense, Denmark

An international standard concerned with the calibration of microphones in a free field by comparison has recently been published. The standard contemplates two main calibration methodologies for determining the sensitivity of a microphone under test when compared against a reference microphone. The two methodologies assume that the two microphones are exposed to the same sound pressure. This can be achieved by measuring the ratio of output voltages either sequentially or simultaneously. The first method requires a stable source to ensure that the sound pressure is approximately the same when the reference and test microphones are measured, whereas the second requires a source with a symmetrical directivity that ensures that the microphones placed at opposite positions are subjected to the same sound pressure. The two methods have been investigated experimentally in an extended frequency range. A third method, consisting of a combination of the sequential and simultaneous methodologies, has also been investigated. Though the application of time selective techniques is not discussed, the experimental results indicate the immunity to unwanted reflections in the sequential and combined approaches while it may be necessary to apply these techniques in the simultaneous approach.

[a] sbf@dfm.dtu.dk
[b] atr@dfm.dtu.dk
[c] kra@dfm.dtu.dk
[d] fja@elektro.dtu.dk
[e] vch@iti.sdu.dk
[f] pmjuhl@iti.sdu.dk

1 INTRODUCTION

The reciprocity technique is the basis for calibrating Laboratory Standard (LS) microphones under different acoustic fields, including a free field. There is an internationally recognized standard that describes the methodology for the realization of the reciprocity technique.[1] As a matter of fact, the uncertainty of the free-field sensitivity determined using the reciprocity technique may be unnecessarily small for everyday measurements in the field. Additionally, LS microphones are only used for calibration purposes, and field measurements are carried out with measurement microphones that may not be suitable for reciprocity calibrations. Besides, free-field reciprocity calibration is highly time-consuming, and therefore expensive. This indicates that this type of calibration may not be used when a larger uncertainty may be sufficient for the application in sight. A solution to this is to use a measurement microphone that has been calibrated in a free field using a comparison technique.

Comparison calibration is based on the direct comparison of a microphone under test (DUT) with a reference microphone (REF). Free-field comparison calibration of measurement microphones is carried out by exposing a calibrated reference microphone and a test microphone to the same sound pressure in a free field. In principle, the ratio of sensitivities is proportional to the measured ratio of output voltages. Thus it is possible to determine the free-field sensitivity of the test microphone from the sensitivity of the reference microphones. The ratio of output voltages can be measured either sequentially or simultaneously. Each of these two methods poses a set of different requirements to the sound source generating the sound pressure. For instance, the sequential method requires the sound field to have good temporal stability. The simultaneous method does not require this; however, it is required that the sound pressure is the same at the positions where the microphones are placed. Another international standard describing the realization of these methodologies has recently been published. The practical implementation of the methodologies described in the standard [2] is described, and the results discussed. A third combined method, not explicitly described in the standard, and the results of its implementation are also described.

2 CALIBRATION METHODOLOGIES

The calibration of microphones by comparison is based on the assumption that a DUT is subjected to the same sound field as a REF. Under such an assumption, the sensitivity of the DUT, M_{DUT}, is the result of multiplying the ratio of the open-circuit output voltages of the DUT, U_{DUT}, and REF, U_{REF}, R_{M}, by the free-field sensitivity of the reference microphone, M_{REF} (in the following, whenever the output voltage is named, it is the open-circuit output voltage that is referred to):

$$M_{\mathrm{DUT}} = M_{\mathrm{REF}} \cdot R_{\mathrm{M}},$$
$$R_{\mathrm{M}} = \frac{U_{\mathrm{DUT}}}{U_{\mathrm{REF}}}. \tag{1}$$

The free-field sensitivity of the REF is known beforehand, and the ratio of output voltages can be determined from measurements in a free field. The output voltage is directly proportional to the free-field sensitivity of each microphone. The free-field sensitivity level of the DUT re 1 V/Pa, L_{DUT}, can be obtained in the same way:

$$L_{\mathrm{DUT}} = L_{\mathrm{REF}} + \Delta_{\mathrm{M}},$$
$$\Delta_{\mathrm{M}} = 20*\log_{10}\left(\frac{|U_{\mathrm{DUT}}|}{|U_{\mathrm{REF}}|}\right). \tag{2}$$

Formally, the free-field sensitivity is defined as the ratio of the open-circuit output voltage to the sound pressure that would exist at the position of the acoustic center of the microphone in the absence of the microphone. This indicates that the ratio of open-circuit voltages in Equation (1) depends on the differences of the position of the acoustic center of the DUT and REF. Furthermore, in the practical realization of the free field in an anechoic room, a different position of the acoustic center might also influence how reflections from the walls hit the microphones.

Changes in environmental conditions will affect the sensitivity of different types of microphones in different ways. However, because the sensitivity of the DUT is normally calculated only at measurement conditions, and the sensitivity of the REF will be given at reference conditions, it is thus needed to apply a factor on the sensitivity of the REF. This factor is calculated using:

$$R_{\mathrm{Env}} = 10^{\left(\delta_{\mathrm{p}}(p_{\mathrm{s}}-p_0)+\delta_{\mathrm{t}}(t-t_0)+\delta_{\mathrm{d}}(t-t_0)\right)/20}, \tag{3}$$

where δ_{p} is the static pressure coefficient in dB/kPa, δ_{t} is the temperature coefficient in dB/K, δ_{d} is the diffraction coefficient in dB/K, p_{s} and t are the static pressure and temperature at measurement conditions, and p_0 and t_0 are the reference static pressure and temperature. Typical values for the environmental coefficients of LS microphones can be found in Ref. [3].

Thus, the free-field sensitivity of the DUT (in dB) can be calculated using the following expression:

$$L_{\mathrm{DUT}} = (L_{\mathrm{REF}} + \Delta_{\mathrm{Env}}) + \Delta_{\mathrm{M}},$$
$$\Delta_{\mathrm{Env}} = 20*\log_{10}\left(R_{\mathrm{Env}}\right). \tag{4}$$

An additional refinement may be obtained by comparing the DUT with more than one reference microphone in order to minimize any random variation of the conditions occurred during measurements. This also serves as a check of the reproducibility of the measurements.

2.1 Sequential Calibration

The validity of Eqns. (1) and (2) in the sequential calibration can be examined by defining that the average of the output voltages of the DUT and REF at determined from measurements performed at different periods, τ_{DUT} and τ_{REF}, respectively. Thus, assuming that the DUT and REF are measured at the same position, the output voltages are:

$$U_{\mathrm{REF}} = M_{\mathrm{REF}} \cdot p_{\tau_{\mathrm{REF}}},$$
$$U_{\mathrm{DUT}} = M_{\mathrm{DUT}} \cdot p_{\tau_{\mathrm{DUT}}}, \tag{5}$$

where $p_{\tau_{REF}}$ and $p_{\tau_{DUT}}$ is the sound pressure present at the measurement periods for the REF and DUT, respectively. Thus, the voltage ratio will be

$$R_{\mathrm{M}} = \frac{U_{\mathrm{DUT}}}{U_{\mathrm{REF}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}} \cdot \frac{p_{\tau_{\mathrm{DUT}}}}{p_{\tau_{\mathrm{REF}}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}} \cdot F_{\mathrm{TIME}}, \tag{6}$$

where F_{TIME} is the temporal stability factor related with the sound source. Due to the working principles of most loudspeakers used as sound sources the value of this factor cannot be neglected. Furthermore, the temporal stability factor can be assessed by making repeated measurements of the output voltage of the DUT microphone. The repeatability can then be used as a contributor to the uncertainty of the measurement.

2.2 Simultaneous Calibration

The requirement for temporal stability of the sound source can be left aside if the output voltages of the REF and DUT are measured at the same time. This requires that the sound pressure generated by the source is exactly the same at the positions of the DUT and REF, O_{DUT} and O_{REF}, respectively. This means that the sound source must have a suitable directivity function. That is, the sound pressure should not significantly vary in the measurement region. Efforts have been made for designing a suitable sound source (see Ref. 4); however, small imperfections may always lead to uneven sound fields. For this reason, the output voltages of the REF and DUT can be slightly affected by the imperfections in the sound field:

$$\begin{aligned} U_{\mathrm{REF}} &= M_{\mathrm{REF}} \cdot p_{O_{\mathrm{REF}}}, \\ U_{\mathrm{DUT}} &= M_{\mathrm{DUT}} \cdot p_{O_{\mathrm{DUT}}}, \end{aligned} \tag{7}$$

where $p_{O_{REF}}$ and $p_{O_{DUT}}$ is the sound pressure at the positions the REF and DUT, respectively. Thus, the voltage ratio will be:

$$R_{\mathrm{M}} = \frac{U_{\mathrm{DUT}}}{U_{\mathrm{REF}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}} \cdot \frac{p_{O_{\mathrm{DUT}}}}{p_{O_{\mathrm{REF}}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}} \cdot F_{\mathrm{POSITION}}, \tag{8}$$

where F_{POSITION} is the spatial uniformity factor related with the sound source. Contrary to the case of the temporal stability factor, it may be possible to eliminate this factor by exchanging the position of the microphones. One can safely assume that the directional function will be stable at different measurement instants, so the ratio of output voltages becomes:

$$R'_{\mathrm{M}} = \frac{U_{\mathrm{DUT}}}{U_{\mathrm{REF}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}} \cdot \frac{p_{O_{\mathrm{REF}}}}{p_{O_{\mathrm{DUT}}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}} \cdot \frac{1}{F_{\mathrm{POSITION}}}, \tag{9}$$

By making the product of R_{M} and R'_{M} one obtains the ratio of voltages without the spatial uniformity factor:

$$R''_{\mathrm{M}} = R_{\mathrm{M}} \cdot R'_{\mathrm{M}} = \left(\frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}}\right)^2. \tag{10}$$

This exchanging procedure makes in fact the simultaneous approach immune to the the temporal instability of the source providing that the microphones exchange precisely their respective positions.

2.3 An Alternative, Combined Method

The rationale behind the use of a simultaneous calibration method is to eliminate the effect of any temporal instability of the sound source. It is also apparent that the simultaneous method effectively removes this unwanted temporal instability. However, it may demand a considerable effort to design a suitable source and a calibration rig. A suitable solution is to slightly modify the sequential method by introducing a monitor microphone (MON), and to measure the transfer function between the DUT and MON and the REF and MON. Thus, assuming that the DUT and REF are measured at the same position, the transfer functions between DUT and MON, and REF and MON become

$$\begin{aligned} H_{\mathrm{DUT,MON}} &= \frac{U_{\mathrm{DUT}}}{U_{\mathrm{MON}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{MON}}} \cdot \frac{p(P_{\mathrm{DUT}})}{p(P_{\mathrm{MON}})} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{MON}}} \cdot F_{\mathrm{POSITION},\ \tau_{DUT}}, \\ H_{\mathrm{REF,MON}} &= \frac{U_{\mathrm{REF}}}{U_{\mathrm{MON}}} = \frac{M_{\mathrm{REF}}}{M_{\mathrm{MON}}} \cdot \frac{p(P_{\mathrm{REF}})}{p(P_{\mathrm{MON}})} = \frac{M_{\mathrm{REF}}}{M_{\mathrm{MON}}} \cdot F_{\mathrm{POSITION},\ \tau_{REF}}, \end{aligned} \tag{11}$$

From Eqn. (11), one can obtain

$$R = \frac{H_{\mathrm{DUT,MON}}}{H_{\mathrm{REF,MON}}} = \frac{M_{\mathrm{DUT}}}{M_{\mathrm{REF}}} \cdot \frac{F_{\mathrm{POSITION},\ \tau_{DUT}}}{F_{\mathrm{POSITION},\ \tau_{REF}}}. \tag{12}$$

One can safely assume that the positional factor will be invariant in time because any change in the sound pressure generated by the source will be equally sensed by the MON, REF and DUT, and thus the temporal instability of the sound source is no longer present in the ratio of sensitivities.

3 EXPERIMENTAL SET-UP

The measurement rig used for the calibration is very similar for the three methodologies under scrutiny. The main difference is the source used in the measurements, and the positioning rig. The measurements of the sequential and the combined methods have been carried out in a small anechoic room using the same positioning rig, while the measurements of the simultaneous method have been carried out in a large anechoic room. A scheme of the three measurement set-up is shown in Fig. 1.

In all cases, the REF was an LS2 microphone (Brüel & Kjær type 4180). The DUT types tested were LS2 (Brüel & Kjær type 4180) and several types of WS2 microphones (Brüel & Kjær types 4190, 4191 and 4192). The output voltage of the microphones was measured using a Brüel & Kjær PULSE analyzer. This analyzer is capable of measuring the so-called “Steady-state response (SSR).” The measurements were carried out in the frequency range from 1 kHz and up to 50 kHz. The open-circuit voltage was determined using the insert-voltage technique in all cases.

Four different sound sources were used in the simultaneous measurements: (a) a specially designed source that consists of a loudspeaker mounted on a quasi-elliptical body. The loudspeaker is a modified ring tweeter with an extended “nose” along the axis of symmetry of the source (see Ref. [4]), (b) the same source with a loudspeaker without the “nose”, (c) a loudspeaker mounted on a quasi-spherical body, and (d) same source as in (c) with a long “nose” attached to the center of the loudspeaker. For the sequential measurements only source (c) was used. The combined measurement requires a loudspeaker very similar to (c) however with a built-in monitor WS3 microphone (Brüel & Kjær type 4136).

No time selective technique was applied to remove reflections from the walls of the anechoic room or the acoustic interference between microphones. All measurements were performed at environmental conditions close to reference values: a static pressure of 101.325 ± 2 kPa, a temperature of 23 ± 2 ºC, and a relative humidity of 50 ± 20%.

4 RESULTS AND DISCUSSION

4.1 Sequential and Combined Methods: Time Stability

The influence of the time instability of the source in the sequential and combined methods can be tested by measuring the output open-circuit voltage of the DUT and REF microphones, the one immediately after the other. Figure 2 shows the estimate of the free-field sensitivity level for an LS2 (Brüel & Kjær type 4180) on the left, and a WS2 (Brüel & Kjær type 4191) microphone on the right. The estimate is determined from the average of three immediate measurements using the sequential and the combined methods. Figure 2 shows the standard deviation from these three measurements as well.

It can be seen that the estimates of the two methods coincide quite well in the whole frequency range. Furthermore, the time stability is only marginally different for the two methods. This may lead to conclude that the combined method does not provide any fundamental advantage over the sequential method. However, it should be noticed that in both approaches the measurements of the output voltages of the DUT and REF were made the one immediately after the other, without leaving any idle time between them. Thus, any possible differences due to changes in the behavior of the loudspeaker are minimized, and hence not reflected in the estimated sensitivity. In principle, the combined method should present a greater immunity to instabilities of the sound source because it is not measuring the sound pressure at a single position, but a transfer function calculated from the sound pressure at two positions in the sound field, depending mostly on the environmental conditions of the measurement space. This seems not to be the case with the current set-up, and the matter should be investigated further.

4.2 Simultaneous Method: Influence of the Source

The selection of an adequate source is one of the most important tasks when the simultaneous method is to be applied. However, the procedure described in Sect. 2.2 indicates that the effect of the imperfection of the source may be minimized. Figure 3 shows the free-field sensitivity of two microphone types, an LS2 (Brüel & Kjær type 4180) on the left, and a WS2 (Brüel & Kjær type 4191) on the right. The sensitivity was determined from measurements with the four different sources described in Section 3. The difference from the common average of these sensitivities is also shown. The results for the LS2 microphone are within 0.1 dB in the whole frequency range. This indicates that the imperfection of the sources may not have a significant effect in the studied frequency range. Furthermore, a similar behavior can be observed for the WS2 microphone (Brüel & Kjær type 4191). The differences for the WS2 microphone are well within 0.1 dB up to 30 kHz, and within 0.2 dB in the remaining of the frequency range.

The results from the LS2 microphone may help to set a reference for the expected variability for estimating the severity of the results from other microphones, such as the WS2. Differences in the geometry of the REF and the DUT microphones make it difficult to place the microphones in the correct place with respect to the source, and positioning errors may occur, resulting in an increased variability of the measurement. In fact the validity of Eqn. (10) requires that the DUT and REF microphones exchange the same positions in the sound field.

From the above results, it can be said that the exchanging procedure seems to reduce the influence of these errors. Furthermore, it seems to work equally well with all four sources, with marginal differences at frequencies above 30 kHz.

4.3 Comparing with reciprocity calibration

In order to determine how good is the estimate of the free-field sensitivity level determined with the three realizations of the comparison technique with respect to the actual sensitivity of the microphones, it is necessary to compare these estimates with an absolute realization. The free-field reciprocity sensitivity can typically be determined for LS2 microphones, and it is not widely available for WS2 microphones yet. This will limit this comparison exercise to LS2 microphones.

Figure 4 shows the results of the three comparison methodologies and the reciprocity technique for an LS2 microphone; Figure 5 also shows the difference between each estimate and the reciprocity estimate. It can be seen that the difference between reciprocity and comparison is very consistent over the whole frequency range, below 0.1 dB up to 30 kHz, and below 0.2 dB up to 50 kHz. This confirms that the three comparison approaches are valid, and consistent with reciprocity.

4.4 Comparison Between the Three Approaches

A final exercise is to compare the results of the three comparison approaches from other types of microphones. The free-field sensitivities of two types of WS2 microphones have been determined using the three comparison approaches. Figure 5 shows the results for these WS2 microphones (a microphone Brüel & Kjær type 4190, and a microphone Brüel & Kjær type 4191). It can be seen that the differences between the three approaches remain within 0.1 dB up to 20 kHz; however, the results indicate that the microphone type 4190 is more sensitive to the reflections that find place in the measurement rig of the simultaneous method. It is interesting to notice that the sequential and combined methods are nearly immune to these unwanted reflections. This immunity can be confirmed in the results for all the other types of microphones. Microphone type 4191 shows no strong sensitivity to these unwanted reflections; however, it shows a relatively large difference between 10 kHz and 20 kHz. This difference may be caused by differences in the environmental coefficients of the type 4191 microphone, and the REF type 4180 microphone. The microphone type 4191 has a larger sensitivity to temperature and static pressure than the microphone type 4180 in the frequency range in which the largest difference is observed (see Ref. 3). In order to minimize the differences it may be necessary to apply typical environmental corrections to those microphones from manufacturer or other published data.

5 CONCLUSIONS

Three different approaches for determining the free-field sensitivity of measurement microphones have been investigated: the methods are based on a) sequential and b) simultaneous as indicated in Ref. [2], and a combined method. The three approaches give consistent estimates of the free-field sensitivity.

Switching the position of the microphones in the simultaneous method, minimizes the effect of the imperfections of the source, making it unnecessary to use large efforts on designing a special source unless a frequencies higher than 50 kHz are of interest.

The sequential and the combined approaches are consistent, and the repeatability from a number of immediate repetitions is only marginally different. However, in a different measurement set-up the time stability of the output voltages measured using the combined approach may be better than that of the sequential method alone.

Whereas the sequential and combined approaches appear to be immune to unwanted reflections from the measurement rig, the simultaneous can be sensitive to these. In this case it may be of interest to apply a time selective technique to remove these unwanted reflections in order to obtain a reflection-free, free-field sensitivity.

6 REFERENCES

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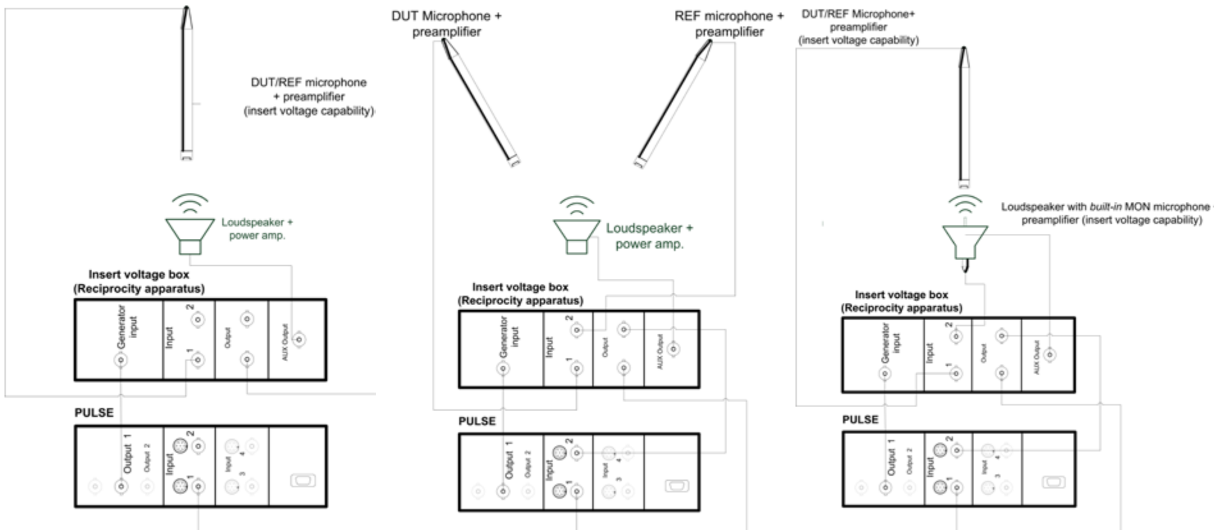

Figure 1. Measurement set-up for sequential (left), simultaneous (center), and combined (right) comparison calibration in a free field.

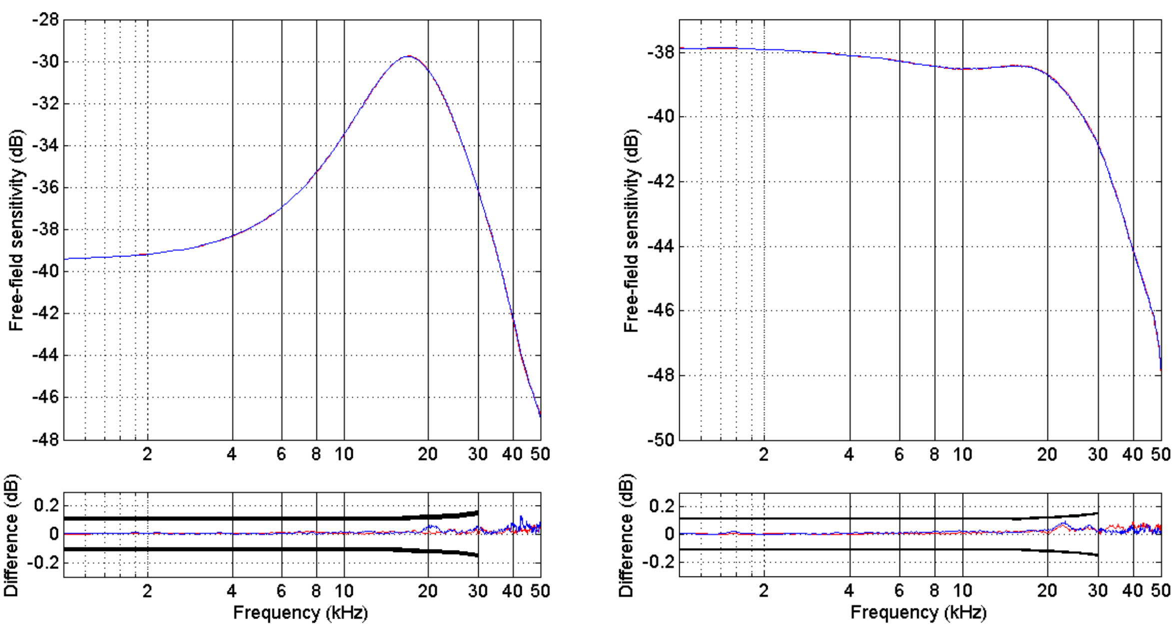

Figure 2 Comparison of the free-field sensitivity determined using the sequential and combined methods. On the left results from an LS2 microphone (Brüel & Kjær type 4180), on the right results from a WS2 microphone (Brüel & Kjær type 4191). The upper chart shows the free-field sensitivity level in dB re 1 V/Pa. The lower graph shows the standard deviation of the sensitivities determined from the two approaches. The thick, black lines represent the uncertainty bounds for sequential calibration as a reference.

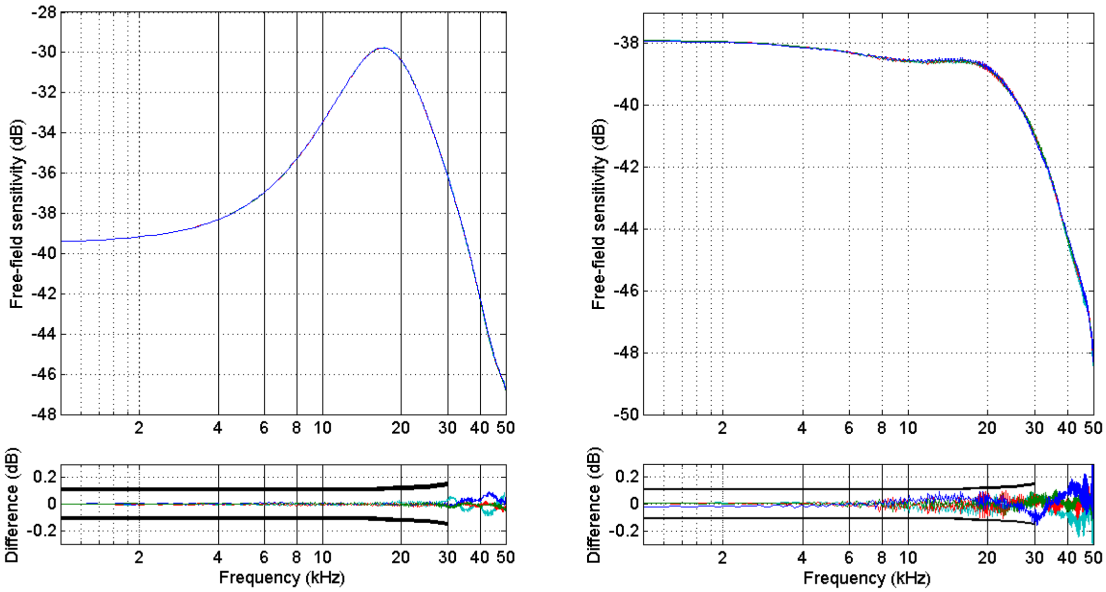

Figure 3. Comparison of the free-field sensitivity determined using the simultaneous method and four different sources. On the left results from an LS2 microphone (Brüel & Kjær type 4180), on the right results from a WS2 microphone (Brüel & Kjær type 4191). The upper chart shows the free-field sensitivity level in dB re 1 V/Pa. The lower graph shows the difference from the common average of the sensitivity determined using the four sources; the thick, black lines represent the uncertainty bounds for sequential calibration as a reference.

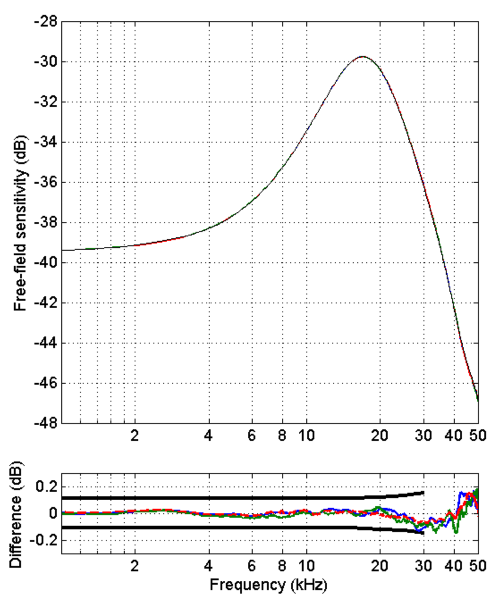

Figure 4. Comparison of the free-field sensitivity of an LS2 microphone (Brüel & Kjær type 4180) determined using the reciprocity technique and the simultaneous, sequential substitution and combined methods. The upper chart shows the modulus of the free-field sensitivity level in dB re 1 V/Pa. The lower graph shows the difference between the sensitivity determined using the comparison methodologies and the reciprocity estimate; the thick, black lines represent the uncertainty bounds for sequential calibration.

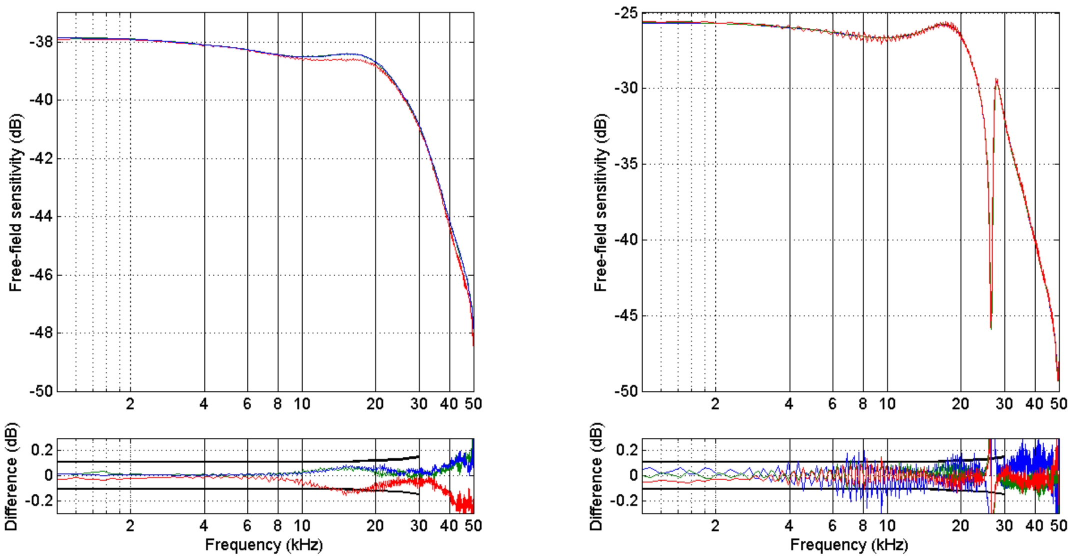

Figure 5. Comparison of the free-field sensitivity determined using the sequential and the simultaneous methods. The results correspond to a WS2 microphone Brüel & Kjær type 4191 (left) and to a WS2 microphone Brüel &Kjær type 4190 (right). The upper chart shows the modulus of the free-field sensitivity in dB re 1 V/Pa. The lower graph shows the difference between the sensitivity determined from measurements with the different sound sources and the reciprocity estimate, and the uncertainty bounds for sequential calibration.

APPENDIX A -- UNCERTAINTY CONTRIBUTIONS

Equation (4) can be used as the basis of a mathematical model for estimating the uncertainty of the free-field sensitivity. A suitable model that contains the contributions from the reference microphone, $L_{\mathrm{M,Ref}}$, the ratio of output voltages, C_{M}, the acoustic distance, C_{d}, environmental corrections, C_{Env}, and repeatability, $C_{\mathrm{Rep,}}$ (expressed in dB) is given by:

$$L_{\mathrm{M,DUT}} = L_{\mathrm{M,Ref}} + C_{\mathrm{M}} + C_{\mathrm{d}} + C_{\mathrm{Env}} + C_{\mathrm{Rep}}. \qquad \text{(A.1)}$$

A.1 Sensitivity of the Reference Microphone ($L_{\mathrm{M,Ref}}$)

This value comes directly from a calibration certificate of the REF. Typically, the REF will be calibrated using free-field reciprocity. However, it may be possible to use published data for the difference between pressure response (obtained either from measurements using an electrostatic actuator or a comparison coupler) together with the appropriate pressure response.

A.2 Ratio of Voltages (C_{M})

The uncertainty of the voltage ratio is estimated from the measurement parameters of the B&K PULSE analyzer which is used in the Steady State Response (SSR) mode. Although the accuracy requirements are set to be the same for all frequencies, 0.01 dB, at low and high frequencies the uncertainty increases slightly because the maximum measurement time is reached without getting to the desired accuracy level.

Additionally, the effect of the polarization voltage must be added. This value will come either from a calibration certification of the polarization voltage or from the specifications of the internal polarization voltage of the measurement amplifier used in the calibration.

A.3 Acoustic Distance (C_{d})

The effect of differences in the acoustic center of the DUT and REF depends very strongly on the distance between acoustic centers. If the difference between the acoustic centers of the REF and DUT is known, a correction factor can be applied to Eqn. (3). Assuming that the acoustic center is in front of the microphones, the correction factor is:

$$R_{\mathrm{d}} = \frac{d_{\mathrm{DUT}}}{d_{\mathrm{REF}}} = \frac{d - \Delta_{\mathrm{DUT}}}{d - \Delta_{\mathrm{REF}}}, \qquad \text{(A.2)}$$

where d_{DUT} and d_{REF} are the acoustic distances between the sound source and the DUT, and between the sound source and the REF respectively. Δ_{DUT} is the sum of the acoustic center of the DUT microphone and the sound source; and Δ_{REF} is the sum of the acoustic center of the sound source and the REF microphone. The quantity d is the physical distance between the surface of the source and the membrane of the DUT and REF microphones. One can rearrange Eqn. (A.2), and expand it in a Taylor series. Disregarding high-order terms, one obtains:

$$R_d \approx 1 + \frac{1}{d}\left(\Delta_{\mathrm{REF}} - \Delta_{\mathrm{DUT}}\right). \qquad \text{(A.3)}$$

Thus, the correction factor becomes small if the distance between the acoustic centers of the sound source and the microphones is large. This is also the case when the difference in acoustic centers of the DUT and REF is small. Typically the acoustic center of the DUT microphone is unknown, so the influence of R_d is normally minimized using long separations between source and microphones.

When the acoustic centers are known, this effect can be calculated and used as a correction in Eqn. (A.2). However, this is not normally the case for WS microphones. In such a situation it seems reasonable to assume that a maximum difference can occur. The acoustic center is a quantity that is strongly related to the geometry of the microphone. The acoustic centers of LS1 and LS2 microphones have been measured, and some values of WS1 microphones have been reported in the literature (see Ref. A.1). These results can be used to estimate the maximum difference in the values of the acoustic center that can occur in the frequency range of interest.

A.4 Environmental Corrections (C_{Env})

The uncertainty of the environmental corrections is about 10% for LS1 and LS2 microphones. At high frequencies the difference between the static pressure- and temperature coefficients for LS/WS microphones may take values up to 0.05 dB/kPa, and 0.04 dB/K (see Ref. 3). It can be recommended that calibrations may not take place if the room temperature and/or static pressure exceed the limits 23 ± 1°C, and 101.325 ± 3 kPa, respectively.

A.5 Repeatability (C_{Rep})

The repeatability considered here is the standard deviation of all measurements of the ratio of the open-circuit voltage on the terminals of the DUT to the open-circuit voltage on the terminals of the monitor microphone. This may vary from measurement to measurement, and should be taken from each case in particular.

A.6 Other Contributions

Eventually, the application of a time selective technique for removing the reflections and acoustic interference should also be included as a contributor to the total uncertainty of the measurement.

When the output voltage of the microphones is not measured by the open-circuit technique a contribution accounting for the unknown difference of the capacitance of the microphone capsules must also be included.

A.7 References

A.1 K. Rasmussen, *Acoustic centres of condenser microphones*, The Acoustics Laboratory, Technical University of Denmark, Report 5, (1971).