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NEXT STEPS IN DEVELOPMENT OF TRANSFER IMPEDANCE CALCULATION OF COUPLERS FOR RECIPROCITY CALIBRATION OF LABORATORY STANDARD MICROPHONES

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ABSTRACT

The most accurate method to establish primary sound pressure standards at medium and low frequencies is pressure sensitivity reciprocity calibration of Laboratory Standard, LS, microphones, with LS microphones and the calibration method standardized in international standards IEC 61094-1 and IEC 61094-2. However, for some years it has been increasingly clear that the calculation of the acoustic transfer impedance of couplers, as described in the standard, needs improvement. Recently, Vincent et. al. suggested a solution to the calculations for low frequencies, reconsidering the background of the full low frequency solution quoted in the standard, and there is consensus that this solution is correct and accurate for cylindrical couplers at low frequencies where uniform pressure in the couplers can be assumed. At higher frequencies this assumption is not fulfilled, and the subject of this presentation is a review of the transfer impedance calculations at medium and high frequencies. The assumptions of the calculations are discussed, numerical calculations of the acoustic field and the microphone diaphragm movement are utilized, and the interaction between the results and calculation of the resulting acoustical transfer impedance are discussed.

1. INTRODUCTION

As of today, the most accurate method to establish primary sound pressure standards at medium and low frequencies is pressure sensitivity reciprocity calibration of Laboratory Standard, LS, microphones. In reciprocity calibration three microphones are consecutively coupled pairwise with a cylindrical volume, a coupler, with one microphone used as a transmitter and the other as a receiver. The electrical transfer impedances of the three coupled microphone pairs are measured. From the measured electrical transfer impedances and the calculated acoustical transfer impedances of the coupler with the microphones, the sensitivities of the microphones can be calculated. LS microphones and the calibration method are standardized in international standards IEC 61094-1 [1] and IEC 61094-2 [2].

For some years it has been increasingly clear that the calculation of the acoustic transfer impedance of couplers, as described in IEC 61094-2, needs improvement. IEC 61094-2 presents two solutions for

inclusion of the losses in the calculation of transfer impedance, the low frequency solution, and the broad band solution, but it is not very clear what frequency ranges are covered by the solutions. It has been demonstrated by the author and others [3, 4] that the two models are not consistent in any frequency range, and hence neither of the two models is correct at all frequencies. In IEC 61094-2 a simple impedance model for the microphones is suggested, and it has been demonstrated by the author [5] that this model is too simple. Finally, a model for taking radial modes into account [6] is referenced in the standard and others have been suggested [7]. To the knowledge of the author, no evidence has been published on how closely any of these models represent the influence of radial modes in the couplers.

The subject of this paper is to present and discuss the present status of the issues mentioned above. Calculations with the models are evaluated by comparisons with numerical calculations of the transfer impedance of couplers in various scenarios. Recently, a solution to the calculation of the transfer impedance at low frequencies was presented by Vincent et. al. [8]. Evidence is presented that this model is probably sufficiently accurate for reciprocity calibrations from zero frequency up to mid-frequencies below 1 kHz. The broad band solution has for long been considered valid for frequencies above around 5 Hz. It is shown that this is only partially valid, and the transfer between the validity ranges of the new low frequency solution and the broad band solution is discussed. The present knowledge on diaphragm excursion pattern, microphone impedance, and radial wave motion in the couplers is also touched upon and a few examples of calculations are discussed. However, the calculations for resolving this are still under development and subject to research. Pressure sensitivity is normally considered relevant up to 10 kHz for LS1 microphones and 20 kHz for LS2 microphones. For the purpose of this paper, the ranges up to around an octave above these limits have been considered.

2. NUMERICAL CALCULATIONS

In this paper numerical calculations are used as reference. The calculations are made with COMSOL multiphysics® version 5.5 [9], COMSOL for short, including COMSOL's implementation of visco-thermal losses in

the Acoustics module and membrane model in the Structural mechanics module. The physical properties of air in the models are calculated with the expressions compiled by Rasmussen [10] that are also presented in IEC 61094-2. The original references for the expressions are listed in the biography of [10]. The implementation of the air properties in COMSOL were made by the author.

As a high accuracy is required for the purpose of reciprocity calibrations, some effort has been made to verify that the results are reliable within the uncertainty that can be achieved in such calibrations. Space does not allow to cover that here. The calculations shown in the following are made with axi-symmetrical models. The results calculated with the implemented models have been verified to be consistent with results calculated with similar full three-dimensional models. It has also been verified that the models are stable with respect to small changes in mesh, source configurations etc.

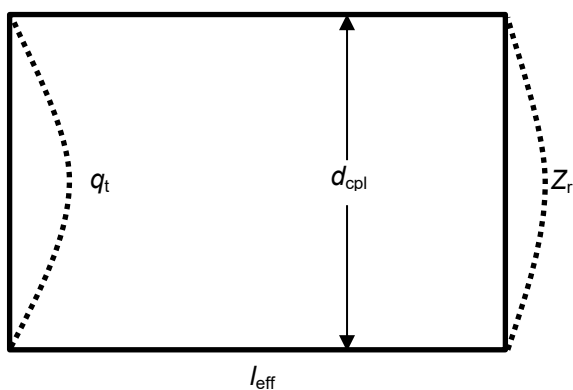


Figure 1. sketch of the model used for the calculations for this paper. The coupler is excited with velocity velocity q_t at the transmitting end and terminated with impedance Z_r at the receiving end. q_t and Z_r are implemented different in three variants, see text.

LS1, $d = 18.6$ mm		LS2, $d = 9.3$ mm	
B&K type	l_{eff}	B&K type	l_{eff}
WA 0834	8.20 mm	WA0837	4.06 mm
WA 0835	9.60 mm	WA0838	4.75 mm
UA 1429	11.40 mm	UA 1430	5.70 mm
WA 0836	13.90 mm	WA0839	7.10 mm

Table 1. Dimensions of couplers used in the calculations for this paper. Note that l_{eff} in the table includes the front cavity depths of the LS microphones.

LS1 (B&K Type 4160)		LS2 (B&K Type 4180)	
f_r	8105 Hz	f_r	22000 Hz
V_{eq}	135 mm ³	V_{eq}	9.8 mm ³
D	1.088	D	1.05
$d_{\text{m,eff}}$	18.00 mm	$d_{\text{m,eff}}$	9.00 mm

Table 2. Microphone parameters used in the calculations for this paper.

Three variants of the coupler model have been used for the numerical calculations. See Fig. 1 for illustration of the model. Eight couplers have been modelled for the purpose of this paper, four for LS1 microphones and four for LS2 microphones. The dimensions of the couplers, including the microphones' front cavities are listed in Tab. 1. For calculations including the microphone impedance parameters of two of BKS DPLA's microphones are used, as listed in Tab. 2. Only a few results of calculations can be shown here. They have been selected by the author for best possible illustration of the differences and the investigated effects.

In the first variant, the model only includes the cylindrical volume with hard walls. The excitation is a surface velocity at one of the end surfaces, and the transfer impedance is calculated from the average sound pressure over the opposite end surface. The calculations were made with parabolic velocity profile at the transmitting end and a uniform weighting of the sound pressure in the receiving end.

In the second model variant, the cylindrical surface and the transmitter are still hard walls, but the receiving end is changed to a surface impedance corresponding to the impedance of the receiver microphone. The calculations were made with parabolic velocity profile at the transmitting end.

In the third variant the transmitter and the receiver are modelled as membranes in the respective end surfaces. The membranes have a slightly smaller radius than the coupler, $d_{\text{m,eff}}$ in Tab. 2. The mechanical properties are adjusted so that the impedance of the membranes best possibly matches the impedance of LS1 or LS2 microphones, utilizing linear elastic material with damping in the COMSOL membrane model. The movements of the membranes are coupled fully to the acoustic field in the coupler. In this variant the excitation is a uniform pressure applied to the transmitter diaphragm. The transfer impedance of the coupler is the ratio of average sound pressure over the surface of the receiving diaphragm to the volume velocity of the transmitting diaphragm. Note that the results must be compared to the results of a transmission line with the microphone termination in one end.

3. THE LOW FREQUENCY SOLUTION

As mentioned in the introduction, Vincent et. al. [8] recently suggested a solution to the calculation of the transfer impedance at low frequencies, reconsidering the background of the full low frequency solution quoted in IEC 61094-2. The solution has been presented in and discussed in the standardization and metrology community, and there is sufficient consensus that it is correct and accurate for cylindrical couplers at low frequencies where uniform pressure in the couplers can be assumed. Although it is not the main subject of this paper, the evidence is briefly touched upon here, as only the evidence by Vincent et. al. has been published so far.

The low frequency solution is consistent with numerical calculations. In the authors calculations, the consistency is better than 0.001 dB and 0.001° up to more than 100 Hz in all the couplers considered. As this author, Vincent et. al. have used COMSOL to verify their calculations of the transfer impedance, but with a widely different implementation of the model. Vincent et al. used an older version of COMSOL multiphysics with an implementation with visco-thermal losses developed at LAUM/LNE [11], also calculating the physical properties of air compiled by Rasmussen [10] that are also presented in IEC 61094 2. The numerical calculations are used for the comparisons throughout this paper, and the consistency is clearly demonstrated in the following.

In [8] Vincent et. al. show experimental evidence for their calculations. The difference in measured electrical transfer impedance of two LS1 microphones coupled in two different couplers is compared to the calculated difference, similarly to the investigations of Jackett [4]. The deviations, evaluated from figure 11 in the paper, seems to be less than 0.05 dB and 0.1°, and zero deviation is by far within the uncertainty of measurement.

Although the difference between the transfer impedance in two different couplers is indeed a good tool to verify the models as those discussed here, it also has limitations. Other effects may counteract in deviations, and rather large deviations may not be visible if they influence the results in the same way [3]. A more rigorous verification of the model is the demonstration of consistency in a complete measurement by comparison with results of an independent method.

At BKSVDPLA, we have been working with extension of the frequency range of reciprocity calibrations for some years in order to provide calibrations for customers down to 0.1 Hz. A hybrid method is used combining reciprocity calibration with electrostatic actuator measurement at the lowest frequencies. Hence, we are able to compare complete reciprocity calibrations with actuator measurements. Note, that the dominant limitation of the method in it's present state is known leakage in the standard couplers, influencing phase results below approximately 5 Hz. It has, however, been chosen to show results without any correction, as they, in the author's opinion, still strongly supports Vincent et. al.'s results, supplementing the numerical calculations. In Fig. 2 the difference between the response of one of BKSVDPLA's reference microphones measured with electrostatic actuator and reciprocity calibration normalized at 250 Hz is shown. The (preliminarily) estimated uncertainty of measurement at 1 Hz is 0.05 dB and 1°, falling to around 0.020 dB and 0.1° at frequencies above 10 Hz.

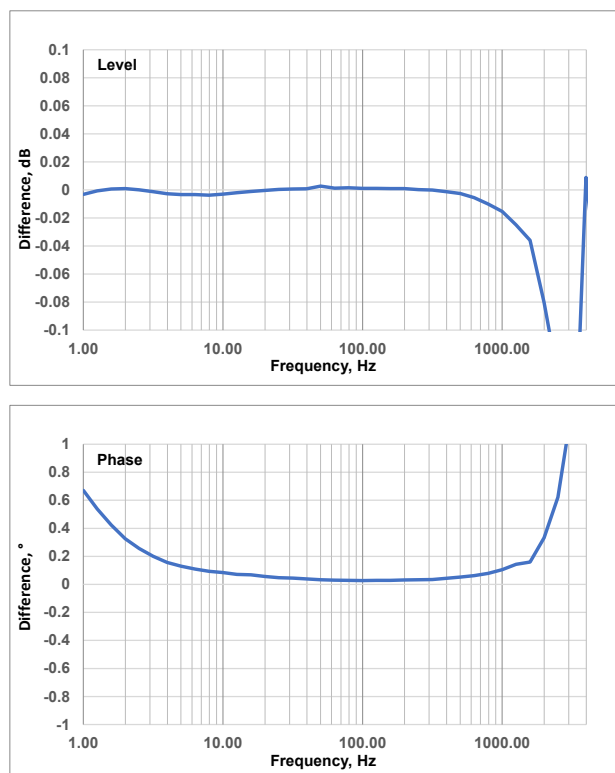


Figure 2. Difference between actuator response and response measured with reciprocity calibration of BKSVDPLA reference microphone.

4. COMPARING SOLUTIONS

In the following, the transfer impedance calculated with the low frequency solution and the broad band solution are compared to numerically calculated transfer impedance admittance for examples of the different variants described above. For the low frequency solution the transfer impedance is calculated as that of a transmission line, eq. (4) in IEC 61094-2, with propagation constant $\gamma = \omega/c$ and the correction term of the low frequency solution (square bracket in [8], eq. (30)) applied as a factor to the cross sectional area, S_0 in $Z_{a,0} = \rho c/S_0$. This way of calculation is used instead of calculation from the transfer admittance of a simple volume, [8], eq. (30), because the wave propagation in the coupler influences the sound pressure at the receiver at frequencies where the low frequency solution is still valid. This is illustrated in the first example below.

4.1 Coupler with rigid walls

In the first example the transfer impedance is calculated for the first model variant, i.e. the coupler alone. In the transmission line equations this corresponds to zero admittance of the microphones. In Fig. 3 the deviations are shown for coupler WA 0836. Also shown in the figure is deviation of the transfer impedance of the coupler considered as a simple volume.

Towards low frequencies the low frequency solution is entirely consistent with the numerical calculations, whereas it deviates towards higher frequencies. This should be expected as only losses due to heat conduction are considered, and the change in speed of sound due to the wall impedances is not taken into account with that solution. The broad band solution deviates towards low frequencies. Most interesting here is that the phase deviates more than 0.1° up to around 30 Hz and the deviation is still 0.02° at 150 Hz. Towards higher frequencies, the broad band solution is consistent with the numerical calculations up to frequencies near the length resonance of the coupler.

It is clearly seen in Fig 3 that if the coupler is considered a simple volume, the calculated transfer impedance deviates significantly from around 200 Hz. This is not elaborated further on here.

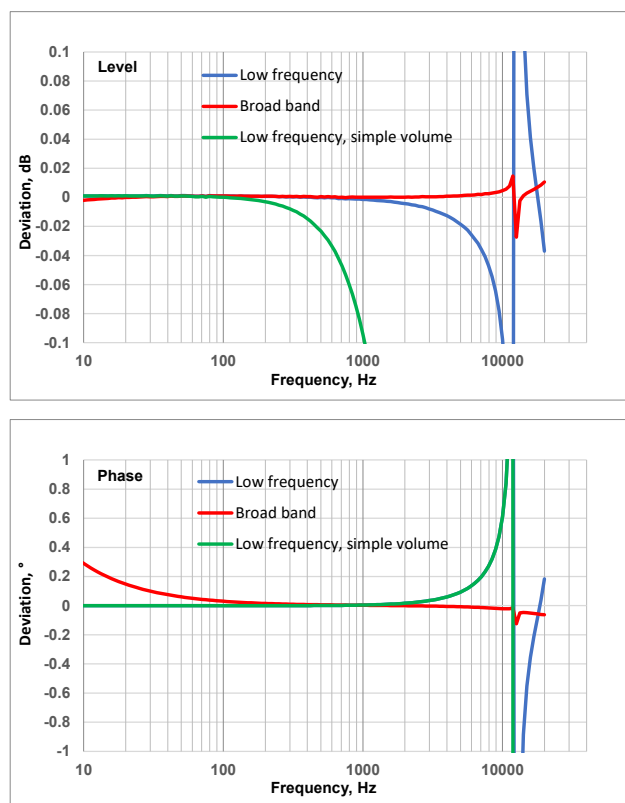


Figure 3. Deviations from numerical calculation for coupler WA 0836 of the transfer impedance of the coupler with hard walls.

4.2 Coupler with impedance termination

In the second example the coupler is terminated with the microphone impedance at the receiving end. The deviations, shown in Fig. 4 are very similar to those in the first example, except at the coupler resonance. As the acoustic impedance of the microphone is much higher than the impedance of the air in the coupler except near the resonance, this should also be expected. The example is mostly included so as to illustrate that the sound field

in the coupler does not change noticeably due to the microphone impedance.

As observed for coupler WA 0836 in the two first examples, the phase of the transfer impedance calculated with the broad band solution deviates from the numerically calculated phase up to frequencies above 100 Hz. At the same time the transfer impedance calculated with the low frequency solution deviates at frequencies not much higher. As a transition from the low frequency solution to the broad band solution is necessary in order to cover the full frequency range of pressure sensitivity reciprocity calibrations, it is investigated for the eight couplers at which frequency ranges the transition shall occur. As it turns out, it is barely possible to find such a range.

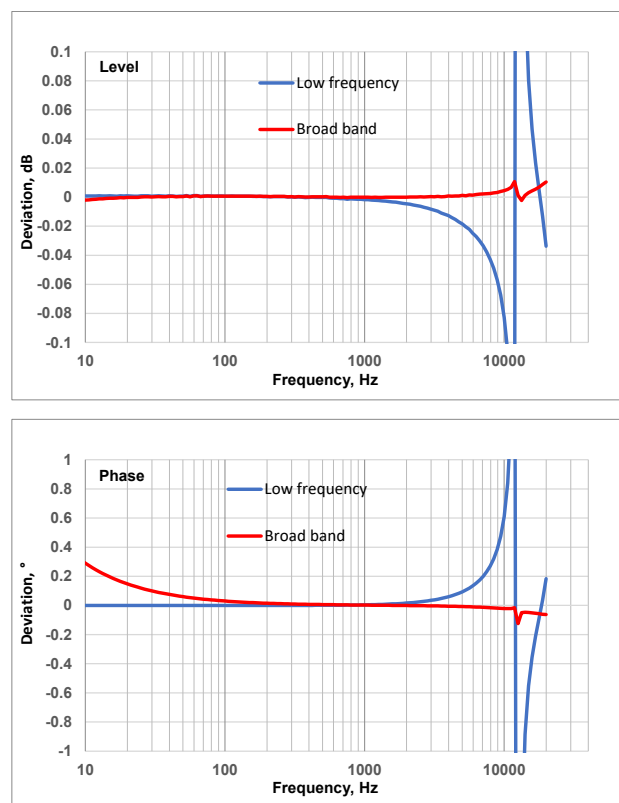


Figure 4. Deviations from numerical calculation for coupler WA 0836 of the transfer impedance of the coupler terminated with a uniform impedance distribution.

In Fig. 5 the differences between the transfer impedance calculated with the low frequency solution and the broad band solution for the eight couplers considered are shown. An unambiguous transition requires that there exists a frequency range, and not only a single frequency, in which the level and phase differences are zero, or negligible at the least. Concerning the transfer impedance level, it seems that the transition could be made at frequencies around 500 Hz for all the couplers, but there is not a similar range

for the phase, and clearly not the same range. Note also, that the order is not related to the length of the couplers. Evidently, the differences shall be evaluated in relation to the achievable or targeted uncertainty of measurement. With current state of the art measurements, it is reasonable to assume that an uncertainty of measurement of 0.015 dB and 0.1° should be achievable in the mid-frequency range, but this requires the calculation accuracy to be significantly better, say, a fifth, i.e. 0.003 dB and 0.02°. In Table 2 the upper frequency limits of the low frequency solution and the lower frequency limits of the broad band solution for fulfilment of these criteria are listed for each of the eight couplers considered here.

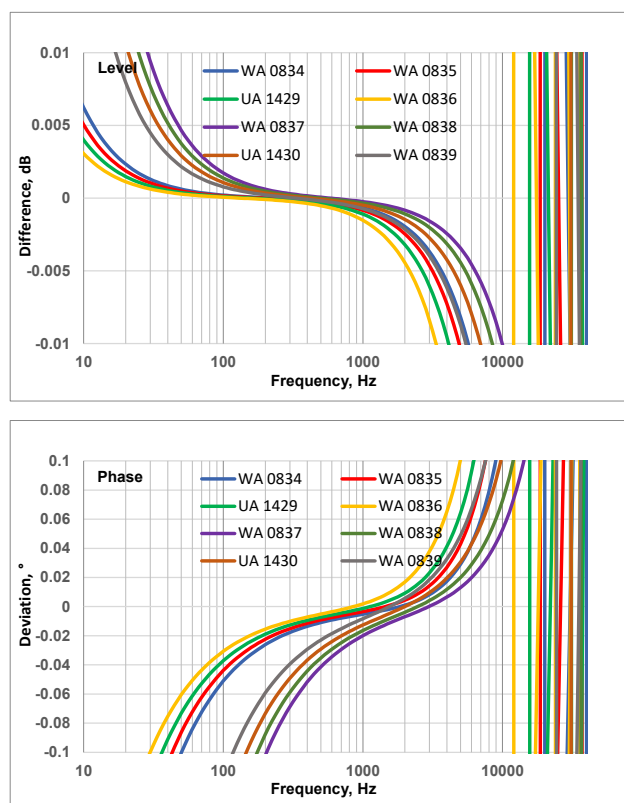


Figure 5. Differences between the low frequency solution and the broad band solution calculated for the eight couplers considered. Notice the ordinate scales.

B&K type		f_u , LF	f_l , BB
WA 0834	LS1, 8.20 mm	2750 Hz	260 Hz
WA 0835	LS1, 9.60 mm	3750 Hz	224 Hz
UA 1429	LS1, 11.40 mm	2000 Hz	188 Hz
WA 0836	LS1, 13.90 mm	1550 Hz	155 Hz
WA0837	LS2, 4.06 mm	4730 Hz	1000 Hz
WA0838	LS2, 4.75 mm	4217 Hz	875 Hz
UA 1430	LS2, 5.70 mm	3200 Hz	740 Hz
WA0839	LS2, 7.10 mm	2500 Hz	590 Hz

Table 3. Frequency limits for the low frequency and broad band solutions for the eight couplers considered, for a maximum deviation of 0.003 dB and 0.02°

4.3 Coupler with diaphragms

In the third calculation example the transmitter and receiver are modelled as diaphragms with the third variant of the numerical model. As the influence of radial waves in the coupler are expected to be most dominant in short couplers [6, 7] and at high frequencies, this example is calculated for WA 0834 and only the broad band solution is considered.

The deviations of the broad band solution from the numerical model is shown in Fig. 6. The transfer impedance is clearly influenced by the more complicated vibration pattern of the diaphragms, and a deviation from the transfer impedance calculated with the broad band solution is seen, in this case up to around 0.04 dB around 11 kHz. Although this is significant, the influence on the sensitivity result of a calibration is 0.02 dB. Smaller, but in same order of magnitude, as the uncertainty of measurements that can be achieved at these frequencies.

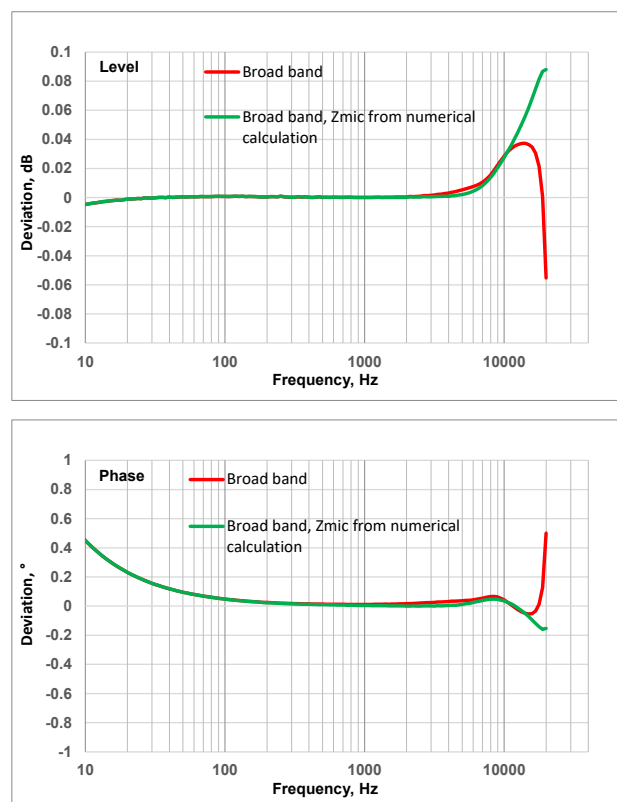


Figure 6. Deviations from numerical calculation for coupler WA 0834 of the transfer impedance of the coupler terminated with diaphragms and calculated with the broad band solution using lumped parameter microphone impedance and impedance from numerical calculations.

Another effect takes place, however, as the effective impedance of the diaphragm, i.e. the ratio of the average pressure over the diaphragm to the volume velocity of the diaphragm, depends on the pressure distribution over the diaphragm. In Fig. 7 the effective impedance of the diaphragm – as modelled for the calculations presented here – relative to the lumped parameter model is shown for the model variants and for the diaphragm model when excited with a uniform sound pressure. Note that the impedance of the diaphragm with a uniform pressure also departs from the lumped parameter model at and above the resonance frequency, as it is not a simple single degree of freedom system. It influences the calculation of the transfer impedance with the broad band solution to take the effective impedance into account, actually making the deviation from the numerically calculated transfer impedance larger at the highest frequencies included here. This is also shown in Fig 6.

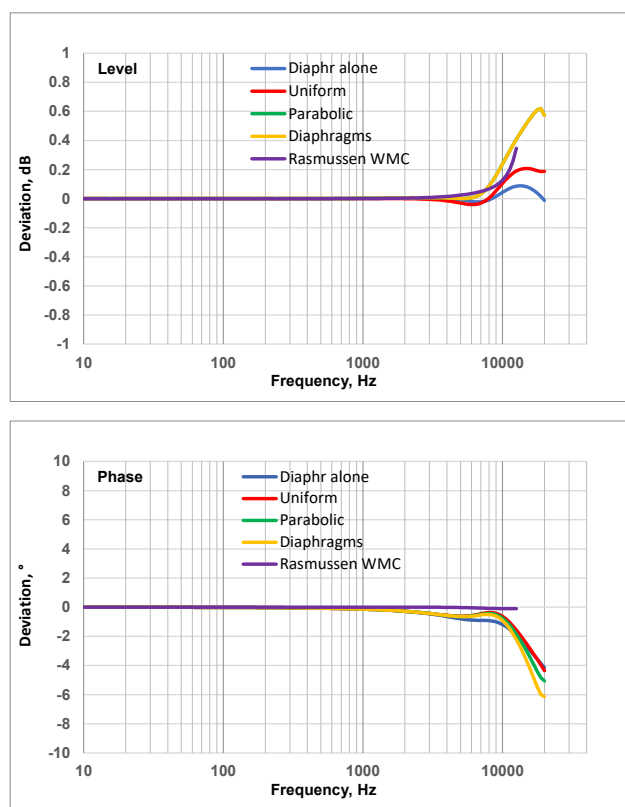


Figure 7. Deviations of the effective diaphragm impedance for the diaphragm alone and in coupler WA 0834 from the impedance calculated with the lumped parameter model suggested in IEC 61094. Also shown is the radial wave motion correction as suggested by Rasmussen.

The dependence on the pressure distribution on the effective diaphragm impedance has another, much larger influence on the calibration results, as it translates directly into a dependence of the sensitivity of the

microphone on the pressure distribution. To the first approximation the dependence is the same as for the effective impedance. In more detail the variation and dependencies of the sensitivity as well as of the acoustic impedance of the microphone depend on details in the microphone construction. Also shown in Fig. 7 is the wave motion correction as suggested by Rasmussen [6]. It is included in this figure mostly to show that there does not seem to be a close relation, but also because it may be more related to the deflection pattern of the diaphragms than to the sound field in the coupler.

The issues related to radial wave modes in the couplers and the interaction with the diaphragm deflection is presently subject to further research by the author and colleagues in Denmark.

5. DISCUSSION

Reciprocity calibration based on IEC 61094-2 constitutes the present primary sound level standard. Therefore, the reliability of these calibrations in terms of the uncertainty of measurement is of utmost importance in all contexts where sound level is measured. The methods of the standard should therefore continuously be subject to critical review and improvements shall be looked for.

Above, the methods as suggested in IEC 61094-2 have been subject to analysis with the help of comparison with numerical calculations. Also, the new, revised low frequency solution suggested by Vincent et.al. has been considered.

A fundamental question with the method used here is of course to what degree the numerical calculations are accurate. It is the experience of the author from a variety of modelling tasks that it is possible to obtain sufficient accuracy for the present purpose. The COMSOL software does indeed solve the equations considered valid for this analysis. It requires, however, careful and critical development of the models, and evidently shall the metrology society seek to underpin the analysis with experimental evidence wherever possible.

In the opinion of this author, there is reasonable evidence that the low frequency solution now available is accurate within any uncertainty relevant for reciprocity calibrations. If the solution is applied to the cross-sectional area of the calibration couplers, it is usable up to the mid-frequency range of the calibrations.

With the low frequency calculations in place, the next question is of course whether a seamless transition to a solution at higher frequencies can be found. For many years, the broad band solution described in IEC 61094-2 has broadly been considered valid for all except the very lowest frequencies. However, the discussion of the low frequency solution has also revealed that the assumptions for the broad band solution needed consideration. As demonstrated here, the broad band solution is rather a high frequency solution. Unfortunately, there is not room for detailed discussion of this here, but the influence of the individual surface elements seems to interact

significantly up to mid frequencies, and that is probably part of the explanation. As demonstrated here, there is only just a frequency range where both solutions can be considered reasonably accurate so that a transition can be made. In the opinion of the author, the best compromise for calibrations will be to make a gradual transition between the two solutions between the frequencies listed in Tab. 3.

At the highest frequencies of application of pressure sensitivity reciprocity calibrations, the sound field in the coupler and the deflection pattern of the diaphragms get complicated. This is presently subject to research, and only a relatively simple calculation with a damped diaphragm was presented above. This example did, however, show that these patterns have a relatively small influence on the transfer impedance of the coupler, but on the other hand does it seem that sensitivity of the microphone depend strongly on the pressure distribution over the diaphragm. A better understanding of this is indeed needed.

6. CONCLUSIONS

In this paper the current methods for calculation of the transfer impedance of couplers for pressure sensitivity reciprocity calibrations have been reviewed. Of course, all is still open for consideration and discussion, but interesting results have been found. In short, the conclusions are

- The revised low frequency solution presented by Vincent et.al. can be considered valid. There is both independent calculations and experimental evidence supporting this.
- Applied in the transmission line calculation for calibration couplers, the low frequency solution is valid up to mid frequencies.
- The broad band solution for calculation of the transfer impedance of the couplers seems only to be valid at mid and high frequencies.
- There is not a frequency range where the results of the low frequency solution and the broad band solution coincide fully. However, a transition frequency range can be identified.
- Different transmitter velocity distributions and different configurations at the receiver does influence the transfer impedance of the couplers. However, it does not seem to be a large influence.
- The sound pressure distribution over the microphone diaphragm seems to influence the microphone sensitivity significantly.

7. ACKNOWLEDGEMENTS

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