PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Completing the traceability chain for airborne ultrasound

Salvador BARRERA-FIGUEROA(1)

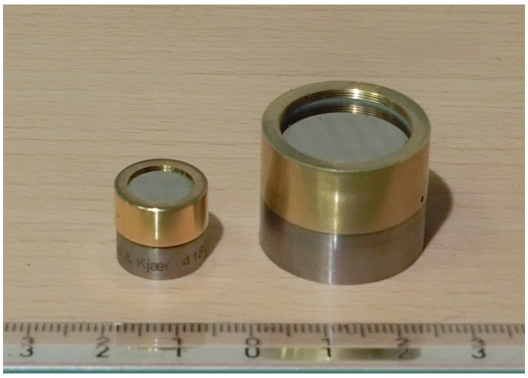
(1)Danish Fundamental Metrology A/S, Denmark, sbf@dfm.dk

Abstract

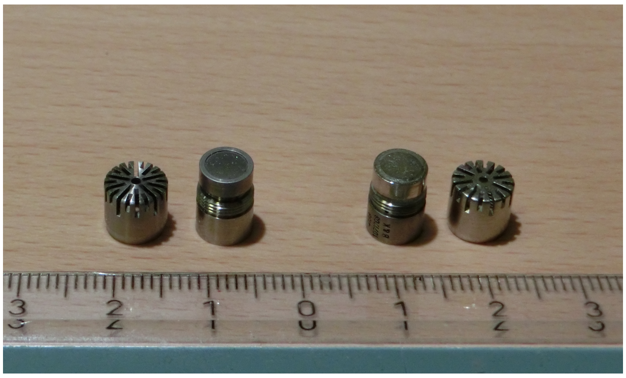
Measurements of sound should be supported by measurement references traceable to the International System of units. Traceability for measurements at frequencies in the audio range are well covered by existing standards, this means that traceability should be extended to cover measurements in the ultrasound region. Recent advances in free-field calibration of microphones have made it possible to determine the absolute sensitivity of working standard microphones up to 150 kHz. Microphones calibrated using this technique can be used as references to calibrating other types of microphones by direct comparison whenever possible. Most microphones used in airborne ultrasound measurements are free-field microphones, hence determining their free-field sensitivity is enough. However, most microphones are calibrated using a single (low) frequency measurement using a sound calibrator, their electrostatic actuator response and a model-based free-field correction. Traceability for the latter two is not always sufficiently documented. Absolute pressure calibration using the reciprocity technique at high frequencies can be challenging because it brings the technique to its limits. Direct comparison is limited to the frequency range in which references calibrated using primary methods are available. This paper presents an account of the current methods for calibration of microphones at ultrasound frequencies, their potential, and prospects.

Keywords: Microphone calibration, Traceability of measurements

1 INTRODUCTION



(a)



(b)

Figure 1. (a) Laboratory Standard microphones. Left: Laboratory Standard microphone type 2 (LS2). Right: Laboratory Standard microphone type 1 (LS1); (b) Working standard microphones. Left: GRAS type 40BF microphone. Right: Brüel & Kjær type 4136 microphone (equivalent to type 4939).

The unit of sound pressure, the pascal (Pa) is realised through the determination of the sensitivity of measurement microphones, particularly the so-called Laboratory Standard (LS) microphones, whose geometrical and acoustic characteristics are defined in the standard IEC 61094-1 (See Figure 1a) [1]. The sensitivity can be determined either in a pressure field (when a uniform sound pressure is applied on the membrane of the microphone) or in a free field in which the microphone is subjected to a plane propagating wave; the basis of the calibration is the described standards IEC 61094-2 and IEC 61094-3, respectively [2, 3].

From a metrological point of view, Airborne Ultrasound has remained for a long time a gray subject. On the one hand, the matter presents enticing technical and scientific challenges encountered when extending the frequency range of primary and secondary calibration methods to higher frequencies, that is, the establishment of absolute measurement references, and the dissemination of their accuracy via an uninterrupted traceability chain towards devices used in actual measurements. On the other hand, it has been set aside because the institutions dedicated to establish these references, the National Metrology Institutes (NMIs), tend sometimes to act reactively rather than preemptively concerning the needs for new measurement standards, and it can always be argued that applications and manufacturers producing instrumentation used in these applications will always move faster than the Metrological community producing an number of transducers, signal conditioners, adapters that pose challenges to the unique definition of measurement references. Figure 2 shows an illustration of the hierarchical traceability chain from absolute (primary) calibration to user measurement devices.

Figure 2. Illustration of the metrological traceability for Acoustical measurements.

This can be exemplified by examinating the capabilities declared by NMIs in the subject of Sound in Air, there are only few entries covering frequencies above 20 kHz and none above 40 kHz [4]. Figure 3 shows a graphical representation of the status quo concerning the cover of frequency ranges and uncertainties for acoustic measurement references.

Cooperation between NMI’s and users of ultrasound measurements can help to extend the range covered by primary calibrations. An example of such cooperation has been the EARS projects [5, 6] which were partially devoted to investigate the effects of ultrasound in humans both in terms of perception and on the effects of exposure to ultrasound in industrial settings and in public spaces. The interest on the effects of ultrasound emitted by readily available domestic appliances, industrial machines, and communication systems has also been materialised in the publication of an special issue in the Journal of the Acoustical Society of America devoted to Airborne Ultrasound [7].

This paper presents a brief description of recent efforts to extend the frequency range of primary (absolute) calibration of measurement microphones at ultrasound frequencies, up to 100 kHz to 150 kHz. Most of these efforts have been devoted to the determination of the free-field sensitivity but the need of disseminating the accuracy of primary calibrations makes necessary to validate the measurement tools used for transferring this accuracy to measurement microphones.

2 FREE-FIELD CALIBRATION

The development of measurement references in ultrasound has been focused on the determination of the free-field sensitivity of measurement microphones at frequencies above 100 kHz [8, 9]. These studies have in common the introduction of a new reference microphone. The free-field response of Laboratory Standard micro-

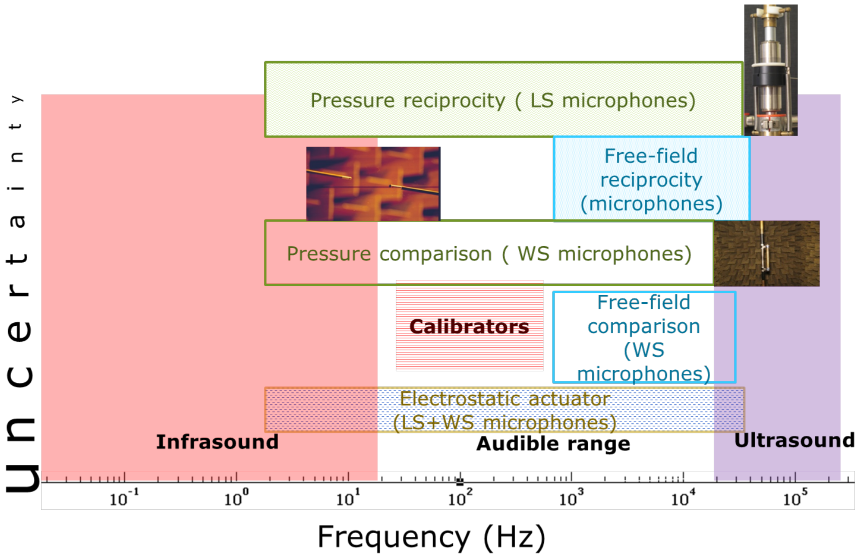


Figure 3. Illustration of the uncertainty and frequency range covered by Primary calibrations in the BIPM-KCDB for Acoustical measurements.

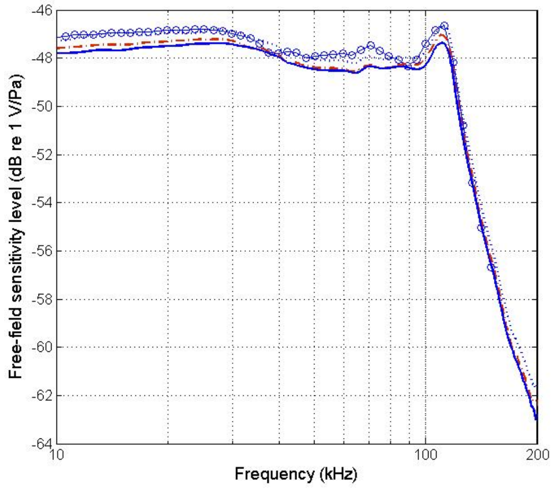
phones loses metrological estability above 40 kHz, this makes it necessary to use microphones that cover a larger frequency range. These microphones are colloquially known as *quarter-inch* microphones, and their electroacoustic characteristics are described in the International Standard IEC 61094-4 under the Working Standard Microphone type 3 (WS3) category [10]. Figure 1b shows an example of these microphones.

Besides the microphones, there is a number of adaptations to measurement systems, signals and data processing. One of the most relevant is the use of microphone adapters. Laboratory and Working Standard microphones of type 1 and 2 have a well defined ground-shield reference configuration that is used on almost any available preamplifier or transmitter unit in the market. 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 [10]. (see Fig. 4a).

The introduction of different adapters will result in differences in the free-field sensitivity, and, possibly, in larger distortion due to the stray capacitance introduced by the un-shielded adapter. This is shown in Figure 4b. This figure shows the experimental estimate of the free-field sensitivity of a WS3 microphone when used with different adapters, and the manufacturer data for the same microphone.

It can clearly be seen that there is a bias in the most of the frequency range for two of the adapters, while one seems to follow the manufacturer data more closely. This bias is most likely to be caused by the absence of a guard all the way around the contact pin in the adapter (B&K type UA0035). Results with he adapter GRAS type RA0019, which geometry is very similar to the B&K UA0035 are also shown. According to the manufacturer, the guard should be longer than in the B&K UA0035 however, not coming all the way out around the contact pin. The sensitivity obtained with this adapter has a smaller bias, however it is still significant. A third adapter (B&K type WA0031) 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. The free-field sensitivity level obtained with this adapter does not show a significant a bias. 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. Regardless, agreement between this data and the reciprocity estimate is quite good, and clearly indicates that the best way to proceed is to have an adapter with the proper geometry and shield configuration.

(a)



(b)

Figure 4. (a) Some commercial adaptors for WS3 microphones. Notice the absence of shielding around the contact pin in the adaptors to the left and in the middle. (b) 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 circle markers is the free-field sensitivity provided by the manufacturer.

An alternative to the use of adapters is be to use a *quarter-inch* preamplifier with insert-voltage capabilities on the receiver side, and similarly, to use a *quarter-inch* transmitter unit. However, there are no transmitter units of this size. A *quarter-inch* transmitter unit could be built *ad hoc* but no attempts have been carried out in this direction. Rather, long adapters with the recommended guard configuration have been developed [9].

A fact is that there exists a wide variety of geometry and configurations of the electric guard for *quarter-inch* preamplifiers and adaptors, and that any calibration should be made compatible and consistent with the configuration used in the actual measurments or calibrations. 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 absolute free-field sensitivity of a WS3 microphone can be made under the assumption that microphone and adapter are a single unit, and that they are to be used together for measurement or calibration purposes.

3 PRESSURE CALIBRATION

From the body of applications for Airborne Ultrasound, it can be said that the vast majority involves measurement in free field or *quasi* free field in open spaces rather than in small, closed cavities. This would make the pressure calibration at high frequencies rather unnecessary, or at most, a matter of academical interest. However, the number of microphones calibrated in a free field is rather small. Manufacturers of measurement microphones will recommend the use of a combination of a normalised electrostatic actuator response determined as prescribed by the standard IEC 61094-6[11], a low-frequency estimate of the pressure sensitivity (usually determined with a pistonphone or a sound calibrator), and a *free-field correction* (the latter being the difference between the free-field response and the pressure response or the actuator response); this is apparently a reasonable, practical solution. However, there are some issues that must be considered when this solution is implemented.

The first one is that the actuator response does not necessarily represent the pressure response of the microphone, but rather the mechanical response, and that around the resonance frequency of the microphone, the actuator response is affected by the load of the radiation impedance on the acoustic impedance of the microphone.

The second consideration is that the provided free-field correction may not be accompanied with sufficient information about its uncertainty at each frequency. Furthermore, the correction is locked to a particular combination of actuator type and microphone type. This means that the user or the calibration laboratory must ensure that the current actuator response is carried out with the same type of microphone and actuator that were used for determining the original correction.

Considering that the current body of work has solved partially the lacking of traceability for free-field calibration, some efforts should be put onto solving the lack of traceability for the electrostatic actuator response, or to at least validate it. A straightforward solution to this problem, is to determine the pressure sensitivity in an absolute manner, that is, by means of the reciprocity method.

The absolute calibration of microphones using the reciprocity method is described in the standard IEC 61094-2 [2]. A study on pressure calibration of WS3 microphones described an implementation of the pressure reciprocity technique for the calibration of such microphones [12]. The study included a comparison with other realisations, including electrostatic actuator measurements, and an optical (Laser Doppler Vibrometry) method described earlier as well [13, 14]. Figure 5 presents the results of the application of the three methods onto microphones WS3 GRAS type 40BP.

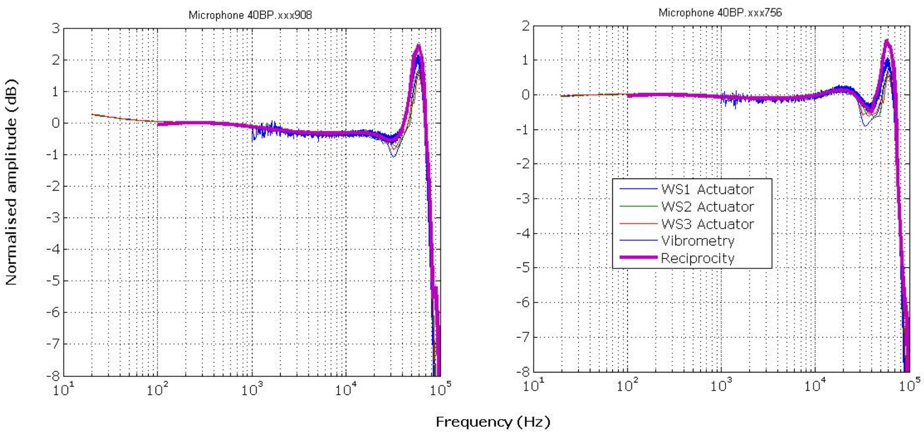


Figure 5. Pressure respons of a WS3 microphone GRAS type 40BP obtained using methods: a) the continuous magenta line is the estimate obtained using an reciprocity, b) the continuous blue line is the estimate obtained using measurements of the membrane velocity using LDV, c) remaining lines are the estimate of the response using different types of electrostatic actuators

4 SECONDARY CALIBRATION

One can safely assume that not all microphones will be calibrated using primary methods. Once Sound Pressure references have been established by primary means, its accuracy must be transferred to secondary standards and to measurement devices used in field studies and test laboratories. This is done by means of comparison calibration methods. There are standards for free-field comparison calibration [15] and for pressure comparison calibration [16]; there is also the electrostatic actuator method [11]. These methods could also be used for calibrating other microphones or measurement devices using these standards. There are, however, some challenges in their implementation.

A challenge, which applies both to pressure and free-field calibration, is the large variety of measurements microphones that are available in the market. The variety of adapter/preamplifier configurations multiplies at this level. Furthermore, the way connectivity to measurement devices is realised adds to this variety. Manufacturers' offer include fixed microphone-preamplifier sets, using the traditional interface or feature the IEPE standard (Integrated Electronics Piezo Electric) such as the ICP ®, CCLD ®, and Deltatron ®. These variations put some additional requirements on the side of calibration laboratories that must be able to calibrate such configurations, and from the user that must clearly specify which configuration they are going to use the transducers to the calibration laboratory.

Another issue that can be relevant when measuring in a free field is whether the microphone has been calibrated with or without the protection grid on. At primary level, the membrane of the microphone is fully exposed to the sound field (without grid). In practical measurements, it will be difficult to argue with and convince the measurement engineer to use the microphone without grid. The influence of the grid can be significant in the frequency range of interest. Figure 6 shows the free-field response of a some microphones commercially available, also with and without grid.

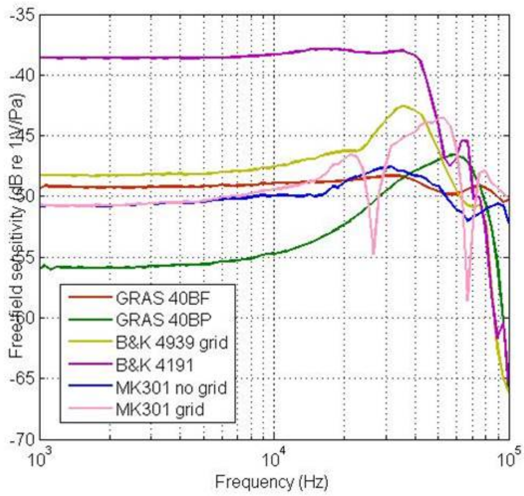


Figure 6. Free-field sensitivity level of a variery of WS2 and WS3 microphones.

A last matter that must be taken into account is that the higher the upper frequency limits are set for free-field comparison, the more difficult to find sound sources that are stable and with a well defined frequency response. It is no trivial task to find a source that can be used up to 150 kHz.

Pressure comparison calibration at frequencies above 20 kHz is rather unexplored, mainly because of the lack of references above 30 kHz, and comparison couplers for higher frequencies. The standard IEC 61094-5 includes some suggestions to calibrate WS3 microphones but the scope is limited to one type of microphone. Hence the need to further validate the electrostatic actuator method with primary calibration of WS3 microphones.

5 CONCLUSIONS

The current state of the art concerning the establishment of measurement references at frequencies that cover Airborne Ultrasound has been described, and discussed. Major advances are concentrated in free-field calibration. Laboratories have described procedures and results from free-field reciprocity calibration of Working Standard type 3 microphones.

Pressure reciprocity calibration has also been investigated. The main goal being the validation of the pressure response obtained by other measurement methods such as electrostatic actuator.

Dissemination of the accuracy of primary methods can be carried out using comparison methods. Further investigation of comparison calibration is needed in order to establish a solid traceability chain to primary standards. Furthermore, formal comparisons among NMIs under the auspice of the BIPM-CCAUV need to be run in order to formalise the publication of CMCs covering the airborne ultrasound area.

Figure 7 shows what an expectedly updated traceability CMC status should look like once further investigations and comparisons are completed.

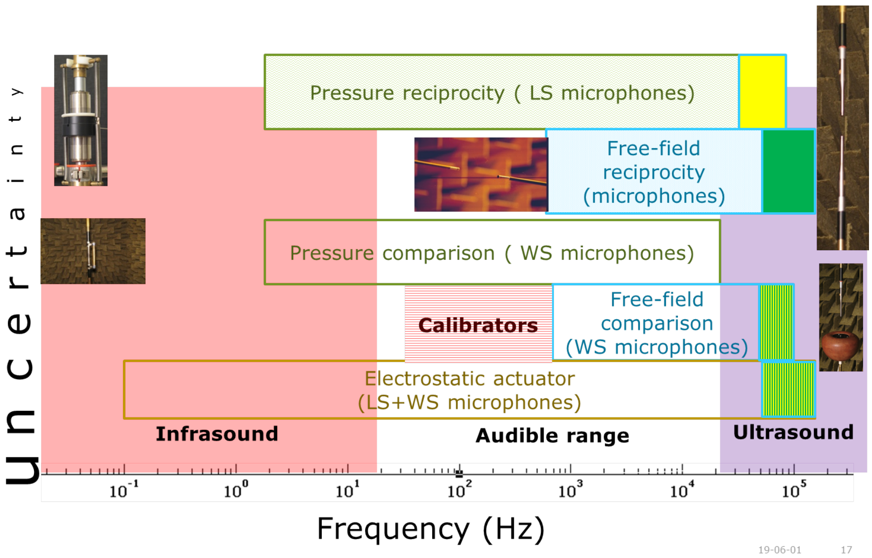


Figure 7. Updated status of the CMCs covering primary and secondary methods for airborne ultrasound measurements.

ACKNOWLEDGEMENTS

This paper was written with the support of the European Metrology Programme for Research and Innovation(EMPIR) under the Joint Research Project HLT02 Metrology for modern hearing assessment and protecting public health from emerging noise sources (EARSII). The EMPIR is managed by the European Association of National Metrology Institutes, EURAMET. The project is also supported by funds from the The Danish Agency for Higher Education.

REFERENCES

[1] IEC International Standard 61094-1:. Measurement microphones part 1: Specifications for laboratory standard microphones, 2000.

[2] IEC International Standard 61094-2 2nd Ed.:. Measurement microphones part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique, 2009.

[3] IEC International Standard 61094-3 2nd Ed:. Measurement microphone part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique, 2016.

[4] Appendix C of the Key Comparison Data Base (KCDB) - Calibration and Measurement Capabilities (CMC) https://kcdb.bipm.org/AppendixC/default.asp.

[5] Metrology for a universal ear simulator and the perception of non-audible sound, European Metrology Research Programme (EMRP), EURAMET https://www.ptb.de/emrp/ears.html.

[6] Metrology for modern hearing assessment and protecting public health from emerging noise sources, The European Metrology Programme for Innovation and Research (EMPIR), EURAMET http://www.ears-project.eu/emrp/ears.html.

[7] The Journal of the Acoutical Society of America, Special Issue on Ultrasound in Air, Vol UIA2018, Issue 1, October 2018, Editor, Tim Leighton http://asa.scitation.org/toc/jas/UIA2018/1.

[8] S. Barrera-Figueroa. Free-field reciprocity calibration of measurement microphones at frequencies up to 150 khz. *The Journal of the Acoustical Society of America*, 144:2575, 2018.

[9] H. Takahashi and R. Horiuchi. Uncertainty analysis on free-field reciprocity calibration of measurement microphones for airborne ultrasound. *The Journal of the Acoustical Society of America*, 144:2584, 2018.

[10] IEC International Standard 61094-4:. Measurement microphones part 4: Specifications for working standard microphones, 1995.

[11] IEC International Standard 61094-6:. Measurement microphones part 6: Electrostatic actuators for determination of frequency response, 2002.

[12] S. Barrera-Figueroa. Pressure calibration of ws3 microphones. In *Conference Proceedings of the 25th ICSV*, 2018.

[13] G. Behler and M. Vorlander. Reciprocal measurements on condenser microphones for quality control and absolute calibration. *Acta Acustica*, 90:152–160, 2004.

[14] S. Barrera-Figueroa, F. Jacobsen, and K. Rasmussen. On determination of microphone response and other parameters by a hybrid experimental and numerical method. *The Journal of the Acoustical Society of America*, 123(5):3229–3229, May 2008.

[15] IEC International Standard 61094-8 1st ed:. Measurement microphones part 8: Methods for free-field calibration of working standard microphones vy comparison, 2012.

[16] IEC International Standard 61094-5 1st ed.:. Measurement microphones part 5: Methods for pressure calibration of working standard microphones by comparison, 2002.