Uncertainty in the realization of the standard of sound pressure in low ultrasonic frequency range by the free-field reciprocity technique

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Introduction

Recent years have seen an increased use of ultrasound in medical and industrial applications, such as medical therapy and diagnosis, material characterization, cleaning, welding of metal and plastic, measuring distance in buildings, in robotics, etc. Therefore there is a significant risk of exposure to high level airborne ultrasound, which may be harmful for the hearing or may have negative bio-effects on man [1]. To ensure safety of persons against this exposition, ultrasound levels in air must be measured with calibrated devices traceable to the national standard. Current measurement standards for airborne sound are realized by means of the sensitivity of half-inch laboratory standard microphones, calibrated with the reciprocity method in the frequency range from 20 kHz to 40 kHz [2]. At present the Physikalisch-Technische Bundesanstalt is developing a free-field reciprocity calibration technique permitting the realization of the sound pressure unit in the frequency range from 20 kHz to 160 kHz by using quarter-inch working standard microphones [3]. In this paper, the measurement procedure is described and an approach for the determination of the uncertainty of the free-field sensitivity is discussed.

Measurement Technique

Free-field reciprocity calibration of condenser microphones is a well-developed primary method for obtaining the free-field sensitivity of condenser microphones. When two microphones M_1, M_2 are coupled acoustically, the product of their free field sensitivities M_1 M_2 can be calculated from the electrical transfer impedance, which represents the ratio of the open-circuit output voltage of the receiver $U_{R,2}$ to the transmitter driving current $I_{T,1}$, the effective distance between the microphones d_{12}, the density ρ, the absorption of air α, and the frequency f is given by Eq. (1):

$$M_1 M_2 = \frac{2 d_{12}}{\rho f} \cdot e^{\alpha d_{12}} \cdot \frac{U_{R,2}}{I_{T,1}} \qquad (1)$$

In order to minimize reflections, measurements are performed in an anechoic chamber of 15 m^3 net volume, installed in an audiometric container shielded against electromagnetic interference. U_R is measured by means of the insert voltage technique. A new insert voltage preamplifier had been constructed for the calibration of quarter-inch microphones, which is mounted on a tubular rod having the diameter of the microphone. The transmitter current is determined from measurements of the driving voltage U_T and the capacitance of the transmitter microphone C, given by the formula:

$$I_T = 2\pi f \cdot C \cdot U_T \qquad (2)$$

Measurements are performed for three quarter-inch Brüel&Kjaer microphones type 4939, combined in three pairs. So, three products of sensitivities M_1M_2, M_2M_3, M_3M_1 can be obtained. The sensitivity of each microphone can then be deduced from the combination of the three products, e.g. the sensitivity M_1 can be obtained from:

$$M_1 = \left(\frac{U_{R,1} \cdot U_{R,3}}{U_{R,2} \cdot U_T} \frac{d_{12} \cdot d_{31}}{d_{23}} \cdot \frac{C_2}{C_1 \cdot C_3} \cdot \frac{1}{\rho \pi f^2} \cdot e^{\alpha (d_{12} - d_{23} + d_{31})} \right)^{1/2} \qquad (3)$$

Measurements are performed in a distance range from 10 cm to 30 cm between the transmitter and receiver microphones.

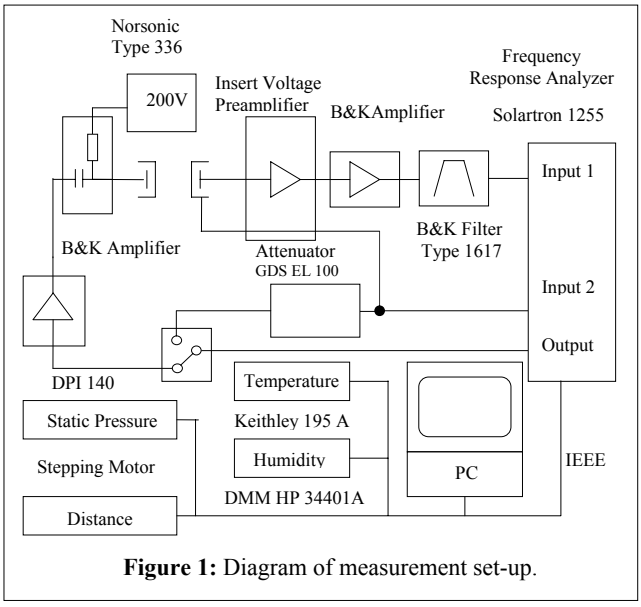

Figure 1: Diagram of measurement set-up.

Uncertainty of Measurement

The uncertainty of the measured free-field sensitivity is estimated from the uncertainties of the variables used for its calculation given in Eq. (3). The combined standard uncertainty is the root of the sums of the squares of the standard uncertainty components [4], given by the formula:

$$\left(\frac{\delta M}{M}\right)^2 = \left(\frac{\delta M}{M}\right)^2_{\text{Pol}} + \left(\frac{\delta M}{M}\right)^2_{\text{St–Pr}} + \left(\frac{\delta M}{M}\right)^2_{\text{Repr}} + \left(\frac{\delta f}{f}\right)^2 + \left(\frac{1}{4}\right)\left(\frac{\delta U_T}{U_T}\right)^2 + \frac{3}{4}\left[\left(\frac{\delta U_R}{U_R}\right)^2 + \left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta d}{d}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2 + \left(\alpha d \frac{\delta \alpha}{\alpha}\right)^2 + \left(\alpha d \frac{\delta d}{d}\right)^2\right] \qquad (4)$$

Component	Type	Distribution	Standard uncertainty contribution of	Standard uncertainty in % at frequency (kHz)									
				20	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
$\left(\frac{\delta U_R}{U_R}\right)$	A	normal	Receiver voltage due to crosstalk and standing waves	0.47	0.22	0.13	0.17	0.17	0.28	0.18	0.15	0.13	0.46
	B	rectangular	Receiver voltage due the measuring analyzer	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$\left(\frac{\delta U_T}{U_T}\right)$	B	rectangular	Driving voltage	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$\left(\frac{\delta C}{C}\right)$	B	rectangular	Capacitance	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$\left(\frac{\delta d}{d}\right)$	B	rectangular	Distance	0.35	0.35	0.35	0.35	0.25	0.25	0.20	0.20	0.20	0.20
$\left(\alpha d\frac{\delta\alpha}{\alpha}\right)$	B	rectangular	Absorption	0.06	0.07	0.09	0.11	0.18	0.22	0.35	0.45	0.60	0.86
$\left(\frac{\delta M}{M}\right)_{Pol}$	B	rectangular	Polarization voltage	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$\left(\frac{\delta M}{M}\right)_{S-Pr}$	B	rectangular	Static pressure dependency of sensitivity	0.00	0.03	0.09	0.18	0.26	0.28	0.32	0.36	0.18	0.06
$\left(\frac{\delta M}{M}\right)_{Rep}$	A	normal	Reproducibility	0.10	0.18	0.14	0.21	0.13	0.09	0.22	0.40	0.07	0.29
$\left(\frac{\delta M}{M}\right)$			Combined uncertainty of sensitivity	0.53	0.42	0.39	0.46	0.46	0.51	0.58	0.73	0.62	0.93
$\left(\frac{\delta M}{M}\right)_{Exp}$			Expanded uncertainty of sensitivity in % (k=2 , confidence level 95 %)	1.07	0.85	0.79	0.93	0.93	1.03	1.17	1.46	1.25	1.87

Table (1): Uncertainty of free field sensitivity for microphones B&K 4939 values shown are in percent for frequencies from 20 to 160 kHz.

The uncertainty of each component was obtained by statistical methods, such as repetition of the measurement (type A) or by other methods (called type B), e.g. from a certificate of an instrument [4]. Uncertainty components are expressed as relative uncertainties and listed in Table (1) in percent (%) for each frequency from 20 kHz to 160 kHz.

Standard Uncertainty (SU) of the receiver voltage:
The uncertainty of the open circuit voltage of the receiver microphone results from acoustic interference (standing waves and reflections), or from electrical interference (crosstalk). In order to minimize the uncertainty, special care to the instrumentation has been taken during the realization of the set-up. Crosstalk is mainly effective at lower frequencies (below 40 kHz), where the signal-to-crosstalk ratio is low. Thus, a distance range from 10 cm to 20 cm has been chosen (signal-to-crosstalk ratio decreases with increasing distance). At higher frequencies (above 80 kHz) the effects of standing waves are dominant, therefore a larger distance range (20 cm to 30 cm) is used for measurements to minimize this effects. The standard uncertainty of the receiver voltage (type A) is calculated as standard deviation from the linear interpolation over distance of the inverse of the open circuit voltage corrected for the absorption of air. The uncertainty of the open circuit voltage of the receiver microphone also results from the accuracy of the frequency response analyzer (type B).

SU of the measurement distance:
The effective distance between the microphones is deduced from the measured physical distance between the two microphone diaphragms and the acoustic centre calculated from the linear interpolation of the open circuit voltage corrected for absorption as a function of distance. The maximum standard uncertainty of the distance is estimated to be 0.5 mm.

Combined uncertainty of the free field sensitivity:
The combined uncertainty was obtained by using Eq. (3). The expanded uncertainty was calculated as

$$(\delta M / M)_{Exp} = k(\delta M / M)$$

where k is the coverage factor. For k = 2 (confidence level 95%) the expanded uncertainty according to Table (1) is less than 0.2 dB in the frequency range from 20 kHz to 160 kHz.

Conclusion

The free-field sensitivity of quarter-inch microphones has been measured with the reciprocity method in the frequency range from 20 kHz to 160 kHz. Components of the measurement uncertainty were calculated following the GUM rules with a model based on the free-field sensitivity formula, and then the expanded uncertainty was deduced.

References

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