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Traceability of the unit watt in airborne sound: an overview

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ABSTRACT

Sound power is a key acoustic parameter, which is widely used for the characterisation and labelling of sound sources. The up-to-date determination methods are valid for frequencies above 50 Hz and for broadband sources. To extend the lower frequency limits and to include sources with narrow band spectral content an extensive study for the establishment of traceability of the unit watt in airborne sound has been performed and an overview of the results is presented in this contribution. The traceability concept is introduced and the dissemination process is explained. The investigation included theoretical models, measurements under calibration conditions and in situ, and results are presented. After exploring and validating the dissemination parameters, the really emitted sound power of sources under test in realistic acoustic environments was referred to their free field sound power. For the inclusive establishment of traceability, the related uncertainty was also determined in a transparent budget, which allows the decomposition of the factors contributing to the uncertainty.

Keywords: sound power, substitution, uncertainty
I-INCE Classification of Subject Number: 72
(see `http://i-ince.org/files/data/classification.pdf`)

1. INTRODUCTION

The acoustic properties of a source are described by its radiated sound power. This quantity is widely used and documented. Sound power use as a source descriptor is a fundamental asset towards a quieter environment and well-informed buyers of machinery or household appliances. The importance of sound power can be illustrated by the outdoor

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[1], the new machinery [2] and the labelling directive [3]. The measurement of sound power cannot be directly performed and thus, indirect determination is used instead. The effects of sound power are measured in sound pressure and sound intensity. The ISO 3740 series ([4], [5], [6], [7], [8], [9], [10]) describes the sound power determination based on sound pressure measurements and the ISO 9614 series ([11], [12], [13]) based on sound intensity. ISO 3740 [14] contains the requirements and specifications for each measurement method. Although the insight gained for sound power, the measurements are influenced by conditions of the sound field at which they are performed. In practice, this means that deviations are observed among the sound power determination methods in spite of using state-of-the-art measurement techniques.

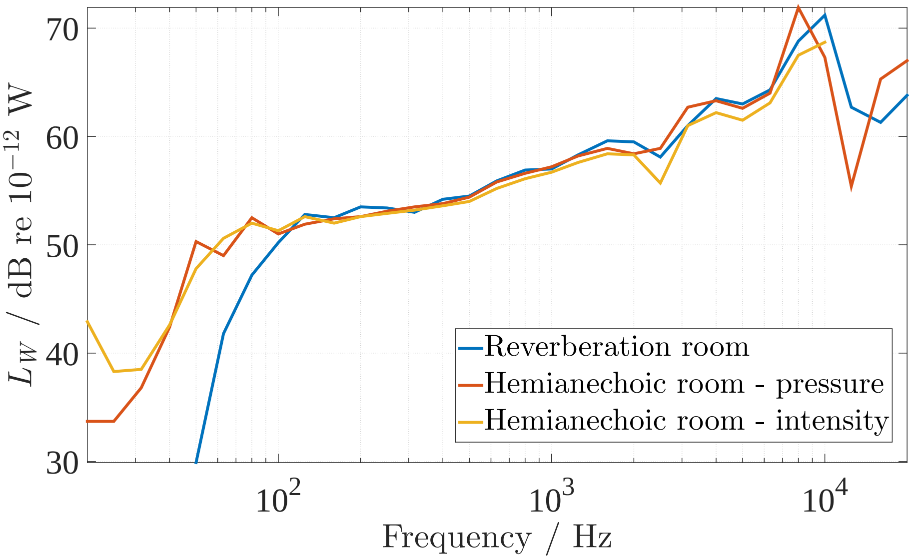

Figure 1: Sound power level of the same source for three different measurement methods

Figure 1 illustrates the sound power level of a source determined by both sound pressure and sound intensity at different sound fields. As it may be observed, the sound power deviations are large for frequencies below 100 Hz. Profound disadvantages of the up-to-present sound power determination methods is the low frequency limitation (100 Hz for sound pressure and 50 Hz for sound intensity) and the broadband frequency analysis (one-third octave bands). Apart from the sound power itself, the corresponding uncertainty is also described in the standards using the standard deviation of reproducibility. Therefore, different uncertainty contributions cannot be distinguished or quantitatively assessed.

2. TRACEABILITY

A new concept on the sound power determination was the subject of a research presented in this contribution. The new concept is the reference of the in situ sound power of a real source (e.g. machinery, equipment etc.) to its free field sound power. In metrology terms, this is described by traceability, which is defined as the property of a measurement result when it can be related to a reference following a documented unbroken chain of calibrations [15].

Figure 2 shows the traceability chain for the unit watt in airborne sound. Traceability includes three categories of sources. Firstly, the primary source, whose free field sound

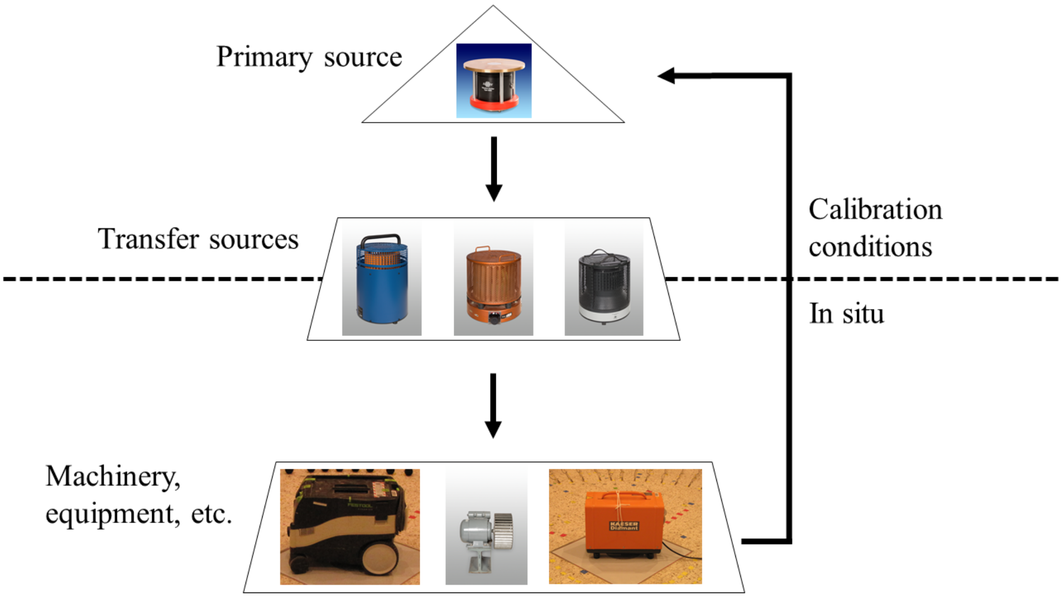

Figure 2: Traceability chain for the sound power determination in airborne sound

power is known and constitutes the reference for all other sound power values. For this reason the primary source is positioned in controllable calibration conditions. The second category are the transfer sources, whose main use is to disseminate (transfer) the unit from calibration conditions (e.g. a hemianechoic room) to real environments (e.g. factory room). The last part of traceability includes any sound source to be described in terms of sound power.

The tool to establish traceability is the substitution method (also termed comparison method), which determines the unknown sound power of a source by comparing it to the known sound power of another source. The substitution method is used in sound power determination based on sound pressure measurements ([4], [5], [6], [10]). It is described by

$$L_{W,\ \mathrm{unknown}} = L_{W,\ \mathrm{known}} + \overline{L_{p,\ \mathrm{unknown}}} - \overline{L_{p,\ \mathrm{known}}} \tag{1}$$

where L_W is the sound power level and $\overline{L_p}$ the time and surface averaged sound pressure level of the sources involved.

3. SOUND POWER NOVELTIES

The use of the substitution method will enable the in situ sound power level to be referred to the free field sound power level. Low frequency effects such as near field and room remaining modes could be avoided if sound intensity was used instead of sound pressure. Therefore, the substitution method based on sound intensity measurements was also part of this study. For this reason, Equation 1 was modified to

$$L_{W,\ \mathrm{unknown}} = L_{W,\ \mathrm{known}} + \overline{L_{I,\ \mathrm{unknown}}} - \overline{L_{I,\ \mathrm{known}}} \tag{2}$$

where $\overline{L_I}$ is the time and surface averaged sound intensity level.

The overcoming of the current limitations will enable the sound power determination below 50 Hz. To broaden the method applicability to tonal sound sources, a finer frequency resolution was also investigated (FFT, 3.125 Hz).

The source directivity is a further important factor for the sound power determination. The current measurement techniques cover a virtual hemispherical measurement surface [8] due to the rotation of the source under measurement in combination with moving a microphone on a quarter circle. For this study, a specially designed apparatus enabled the sound pressure or intensity measurement over a physically hemispherical surface.

At each traceability step, the related uncertainty was determined in parallel. This determination may ultimately provide a transparent uncertainty budget for the determined sound power, which based on Equations 1 and 2 can be generally written as

$$u^2(L_{W,\text{ unknown}}) = u^2(L_{W,\text{ known}}) + u^2(\overline{L_{p/I,\text{ unknown}}} - \overline{L_{p/I,\text{ known}}}) \tag{3}$$

where, according to GUM [16], u^2 is the variance of the probability distribution of the quantity in parenthesis. It is to be emphasised here that the sound pressure level differences or the sound intensity level difference are considered to be the input quantities and not the levels themselves.

4. THEORETICAL INVESTIGATIONS

The substitution method was initially theoretically investigated [17]. Calculations were performed in free field conditions and for geometries including a reflecting plane. For the reflections both spherical and plane waves were considered. The number and the positioning of the receivers was investigated and the determination of the time and surface averaged sound pressure and sound intensity level was studied in terms of calculation time. The substitution included different order of sources. The known-unknown source pairs that were investigated are: monopole-monopole, dipole-dipole and monopole-dipole. The source of the unknown sound power was vertically and horizontally translated compared to the stationary other source. The sound power level determined by the substitution method was compared to the corresponding free field level in order to determine the method limitations. Figure 3 shows the case of a monopole over a reflecting plane. As it may be seen, for the plane wave approach, the mirror source model was used.

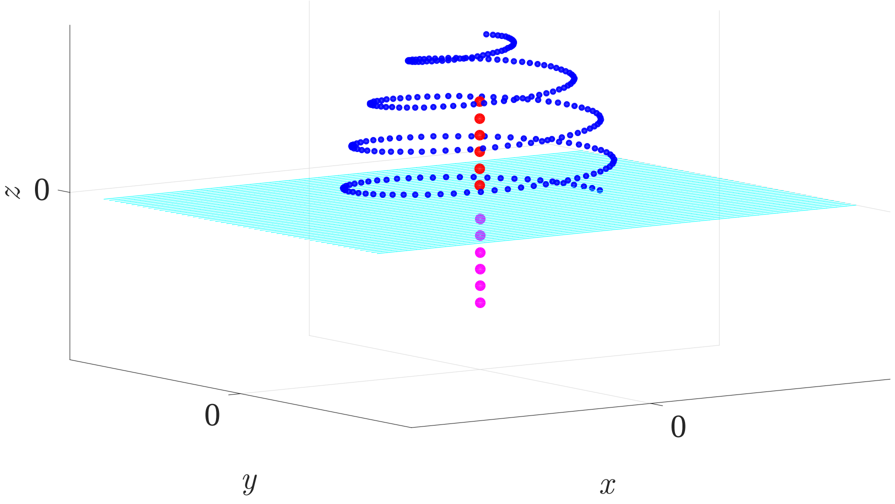

Figure 3: Model for the study of vertical translation of a monopole over a reflecting plane

The boundary impedance is also of importance and a part of the investigation. Figure 4 shows the deviation from the free field sound power level when the sound power of a vertically translated monopole was directly determined based on sound intensity and when the substitution method was applied. For the reflections, the spherical wave approach was used. As it may be seen, the direct determination yields overestimated sound power levels. This is not the case for the substitution method. Figure 4 validates the use of sound intensity to the substitution method.

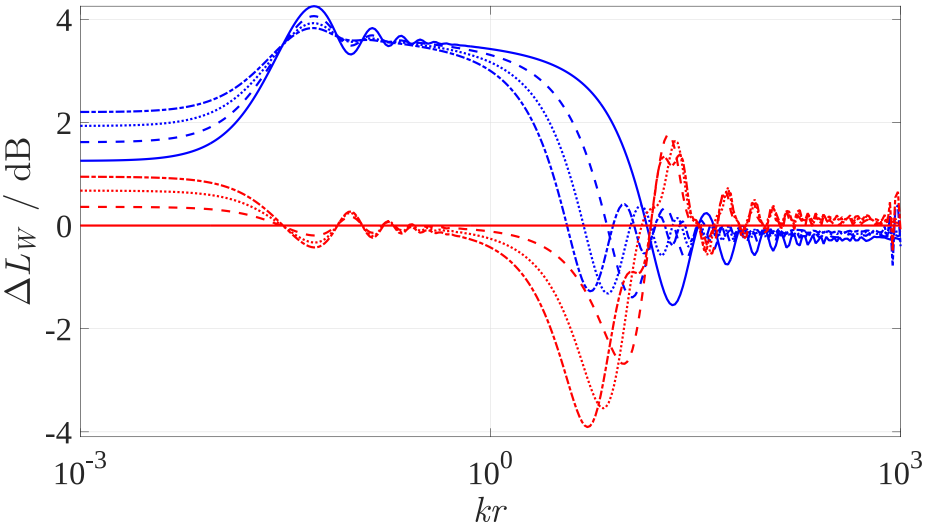

Figure 4: Difference between the directly determined sound power level of a monopole and its free field sound power level (blue) and between the level after the substitution method and the free field level (red). Vertical translation over a highly reflecting floor. The same line pattern corresponds to the same translation

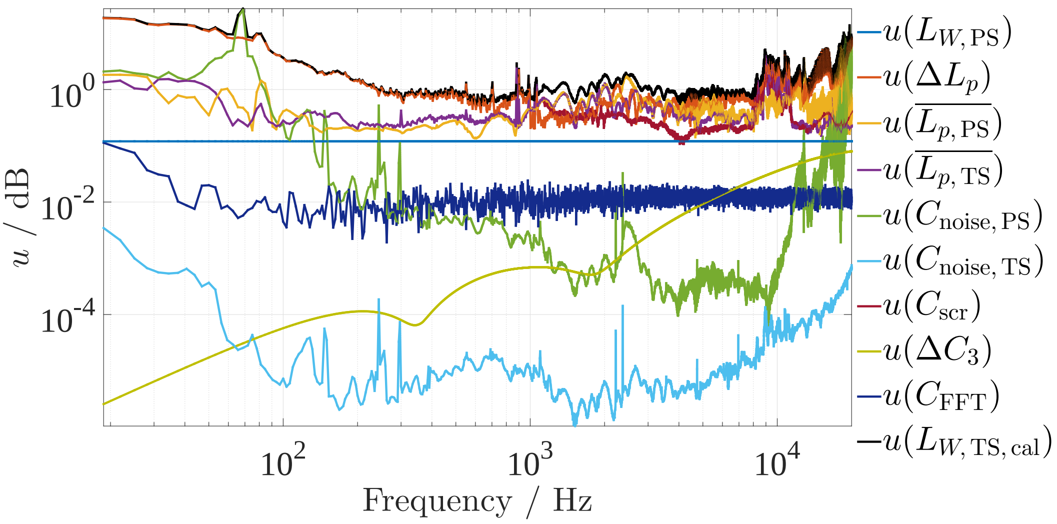

Figure 5: Uncertainty analysis for the sound power level of the transfer standard under calibration conditions

5. EXPERIMENTAL INVESTIGATIONS

5.5.1. Transfer standards under calibration conditions

As it has already been mentioned, a specially designed scanning apparatus was assembled for the purposes of the project [18]. The scanning apparatus enable the measurement of the sound pressure or sound intensity over a hemispherical surface of various radii. Special attention was paid to the stability of the scan, the background noise and the repeatability of the results. An important advantage of the substitution method is the cancellation of effects (due to the opposite sign of the time and surface averaged level) that otherwise would influence the sound power, such as the reflections from the arc.

The scanning apparatus was used for the measurement of the time and surface averaged sound pressure or intensity level of the primary source [19] and the transfer sources. For the up-to-present sound power determination methods using substitution, aerodynamic reference sound sources are used. This was the reason for these sources to be investigated as transfer standard candidates [20]. Initially, the transfer standards were qualified according to the current requirements [21]. By detailed investigation and analysis, the sound power level of the transfer standards $L_{W,\,\mathrm{TS,\,cal}}$ and the related uncertainty $u(L_{W,\,\mathrm{TS,\,cal}})$ were derived following GUM [16]. Figure 5 shows the uncertainty along with its contributing factors for narrow band analysis. Following the Figure 5 notations, the contributing uncertainty factors are: the uncertainty of the primary source sound power level $u(L_{W,\,\mathrm{PS}})$, the uncertainty of the time and surface averaged sound pressure level difference $u(\Delta L_p)$, the uncertainty of the time and surface averaged sound pressure level of the primary source $u(\overline{L_{p,\,\mathrm{PS}}})$, the uncertainty of the time and surface averaged sound pressure level of the transfer source $u(\overline{L_{p,\,\mathrm{TS}}})$, the uncertainty due to the background noise for the primary source $u(C_{\mathrm{noise,\,PS}})$, the uncertainty due to the background noise for the transfer source $u(C_{\mathrm{noise,\,TS}})$, the uncertainty due to windscreen use (to suppress the influences of the wind generated by the reference sound sources) $u(C_{\mathrm{scr}})$, the air absorption uncertainty $u(\Delta C_3)$ and the FFT windowing uncertainty (the FFT analysis for the primary source was performed with Uniform window and for the transfer source with Hanning) $u(C_{\mathrm{FFT}})$. As it may be seen, the mostly contributing factors are this for the sound pressure level difference, which is related to near field and room mode effects and the background noise for the primary source, which is expected to decrease by improving the primary source frequency response.

5.5.2. Transfer standards in situ

Figure 2 shows that sound power level of the transfer sources is to be determined in both calibration conditions and in situ. Apparently, a correction must be applied for the factors affecting the sound power of the reference sound sources. These factors are: the atmospheric pressure, the ambient temperature and the fan rotation speed [22]. Figure 6 shows the variations of the directly determined sound power level of a transfer source at various temperatures. The observed frequency pattern is due to reflections in the measurement setup. This could be compensated from analysis by normalisation with respect to wave number. For the influence of each parameter special measurements were performed and the corresponding correction factor was determined [22]. The proposed correction was found to provide better results compared to an existing one [23]. As it was shown by the theoretical investigation, the order of the sources involved in the substitution method is of great importance, especially for the case where the two sources are of different order (monopole-dipole). The correction factor analysis revealed that the order of the transfer sources is frequency dependent. For a better insight into the source order, the transfer source radiation pattern was analysed in terms of spherical harmonics transform [20]. The order frequency dependence was also revealed, without full coincidence with the results based on both investigations. The near field effects were also studied theoretically [22] and the dipole behaviour of the transfer sources was revealed.

At this stage, an uncertainty analysis was performed [23] as for the in situ conditions. Figure 7 shows that the uncertainty of the in situ sound power level of the transfer sources is excessively influenced by the uncertainty of the sound power level of the same source under calibration conditions. The correction factors contribute to a non-significant extent.

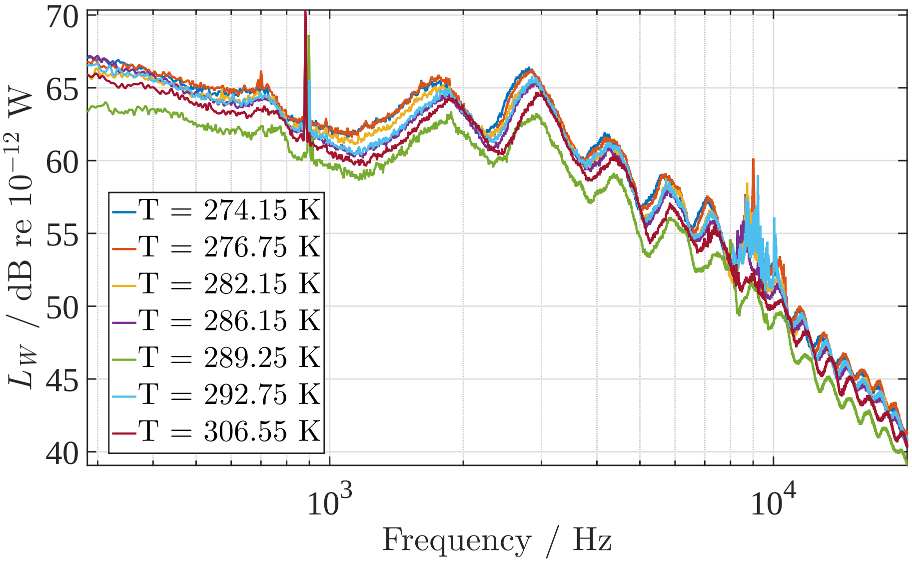

Figure 6: Sound power level of a transfer source at various ambient temperatures

5.5.3. Real sources in situ

The last stage of traceability is the in situ sound power level determination of real sources such as machinery and equipment. This was performed using both sound pressure and sound intensity [24]. The investigation focused on both the measurement surface (scanning or discrete points) and the surrounding environment (different rooms of various volume and absorption). Some of the tested sources had tonal spectral characteristics. The comparison of the sound power level after the substitution method and the level directly determined based on the sound pressure and sound intensity revealed that the directly determined levels deviate by more than 20 dB from the free field sound power level at frequencies below 60 Hz. The uncertainty of the real sources sound power level after the substitution method using sound pressure is presented in Figure 8. The mostly contributing factor is the sound pressure level difference between the transfer and the real source. The same factor influences the uncertainty when the substitution is based on sound intensity.

After having determined the uncertainty at each stage of traceability, the combined uncertainty for the real sources was determined after sound pressure and sound intensity

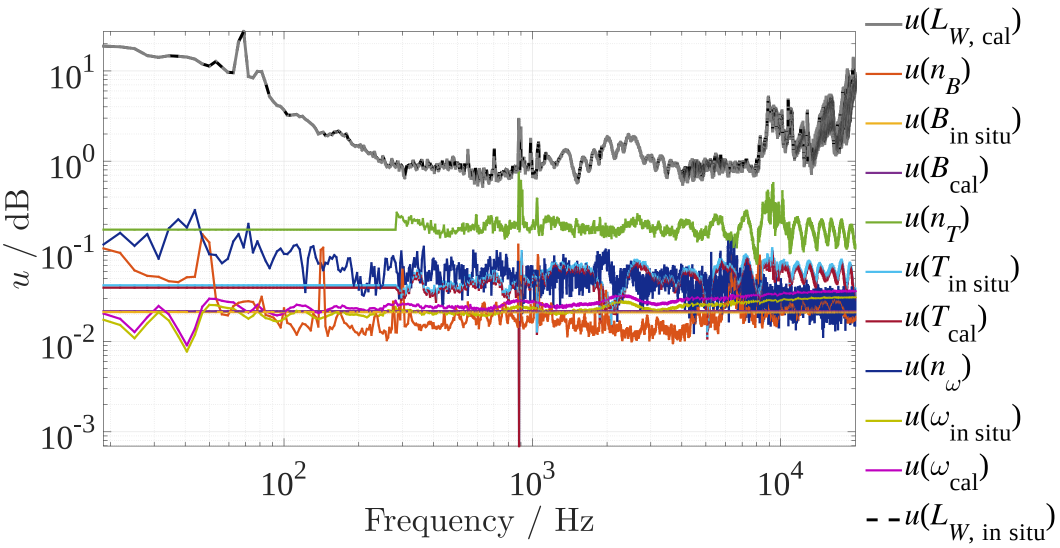

Figure 7: Uncertainty analysis for the in situ sound power level of the transfer standard

measurements and is shown in Figure 9. This uncertainty has been determined using the uncertainty of each real source measured at all different surroundings to generalize the results. The narrow band analysis reveals that the combined uncertainty is of the same level for frequencies above 300 Hz. This is not the case for lower frequencies, where the use of sound intensity for the substitution method provides lower uncertainty levels than sound pressure.

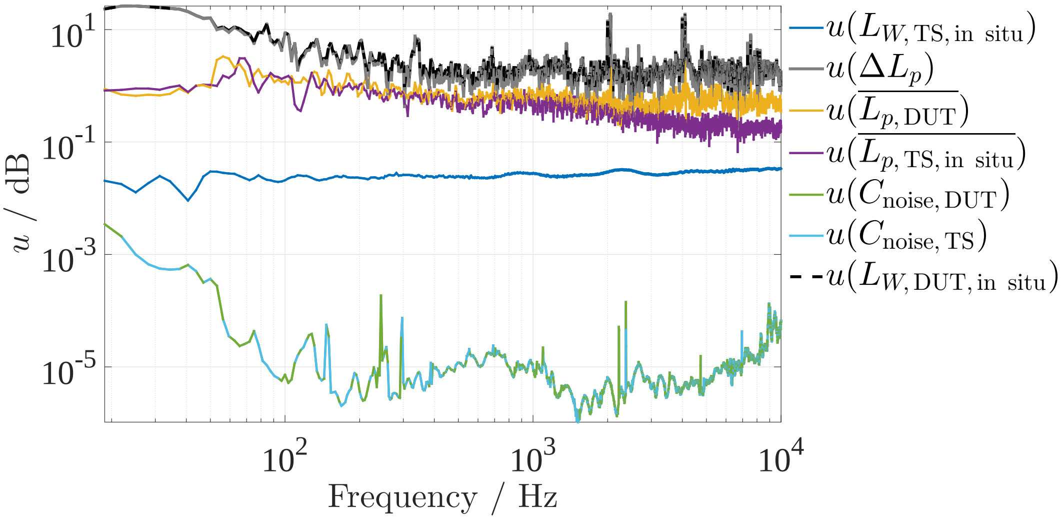

Figure 8: Uncertainty analysis for the in situ sound power level of the real sources after sound pressure measurements

6. SUMMARY

The contribution presents a range of research topics towards the establishment of traceability in sound power determination in airborne sound. The substitution method

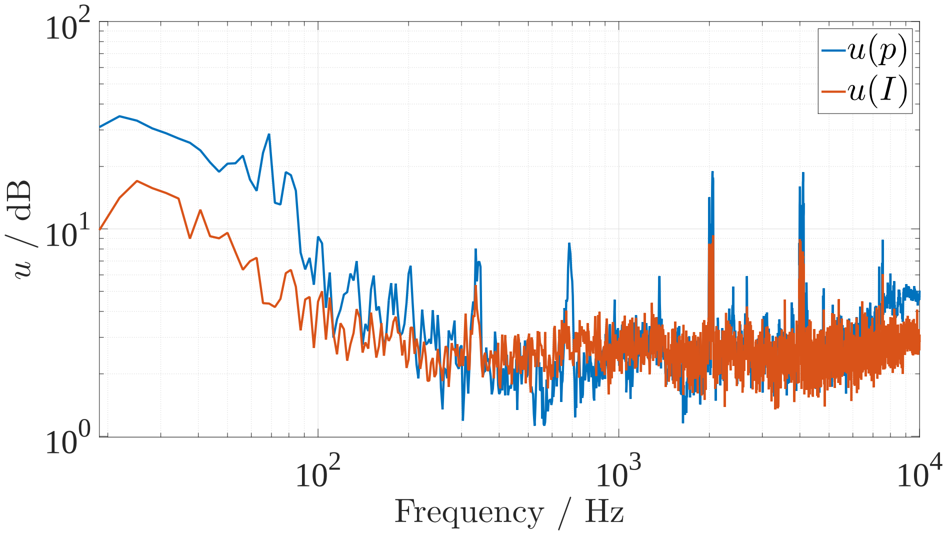

Figure 9: Combined uncertainty of real sources based on sound pressure and sound intensity measurements

is expected to be the main tool for this establishment. In order to avoid low frequency effects, which are related to sound pressure, the substitution method was also implemented using sound intensity levels. At first, a theoretical investigation was performed to study influential factors such as the sampling of the measurement surface, the presence of a reflecting plane and more importantly, the influence of the sources radiation order. The results support the use of sound intensity and provide acceptable deviations from the free field sound power level when the two sources are of the same order. In opposite case, the deviation becomes extremely high at low frequencies.

A scanning apparatus was assembled, which can be used for the measurement of the time and surface averaged sound pressure and sound intensity level and the directivity of the source. The fine sampling of the measurement surface can be used for the analysis of the radiation pattern of the source. The apparatus was also used to determine the uncertainty of the transfer source sound power level under calibration conditions. The transfer sources are intended to be used also for in situ measurements. For this, a correction must be applied to the results under calibration conditions. The influence of atmospheric pressure, ambient temperature and fan rotation speed was separately examined. The proposed correction was compared to an existing one revealing a higher degree of correctness. Although the factors are of great importance for the in situ sound power level determination, they do not contribute to the related uncertainty.

The substitution method was finally applied to real sources in order to conclude all traceability steps. The variance of the measurements in terms of measurement surface, surrounding environment and source spectral content provided results that validate the proposed sound power determination method. The sound power levels after the substitution method were closer to the free field ones compared to the directly determined levels. The uncertainty is mainly determined by the sound pressure or intensity level difference. The combined uncertainty of the sound power level of the real sources revealed lower values at low frequencies in case of sound intensity measurements, which is the main novelty of the proposed approach.

This paper presents a study on a new concept for sound power determination, which may be used in the future as a reference for the determination of the free field sound power level of sources and the related uncertainty budget.

7. ACKNOWLEDGEMENTS

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