Dissemination of the unit watt in airborne sound: aerodynamic reference sound sources as transfer standards

Spyros BREZAS[1]; Patrick CELLARD[2]; Håkan ANDERSSON[3]; Claudio GUGLIELMONE[4]; Cafer KIRBAŞ[5]

[1] Physikalisch-Technische Bundesanstalt (PTB), Germany

[2] Laboratoire national de métrologie et d'essais (LNE), France

[3] Technical Research Institute of Sweden (SP), Sweden

[4] Istituto Nazionale di Ricerca Metrologica (INRIM), Italy

[5] TÜBİTAK Ulusal Metroloji Enstitüsü (TÜBİTAK UME), Turkey

ABSTRACT

In the process aiming at the establishment of both traceability and transparent uncertainty budgets for airborne sound power, the dissemination of the unit watt ensures the correct relation between the sound power of a stationary primary standard and the sound power of transportable transfer standards. The paper reports on a detailed study to qualify aerodynamic reference sound sources (RSSs) as transfer standards. The temporal stability of RSSs has been determined for both narrow and broad frequency bands. Specially designed scanning apparatuses have provided directivity results. Remaining room reflections and near field effects have also been studied. The dissemination also requires the prediction of sound power under meteorological (static pressure, ambient temperature) and operating (rotational speed) conditions different from calibration conditions. These influences have been investigated and a correction is proposed. Finally, interlaboratory measurement results of the sound power of an aerodynamic reference sound source are reported.

Keywords: Sound power, dissemination, directivity, correction, substitution
I-INCE Classification of Subjects Number(s): 72.4

1. INTRODUCTION

The current lack of traceability concerning the quantity sound power is responsible for the differences in sound power determination according to different methods (1-9). The differences can be attributed to the assumptions each method follows. The establishment of traceability would lead to the minimisation of these differences, since the sound power of a source under measurement would be traced to a sound power of a primary source (10). The chain of traceability starts with the realisation of the unit watt in airborne sound utilising the aforementioned primary standard. Dissemination follows, which is the stage where the sound power under calibration conditions (in a hemianechoic or a reverberant room) is related to the in situ sound power. Dissemination requires the use of transfer standards, which are easily transportable sound sources of emission characteristics investigated in detail. Earlier studies focused on aerodynamic reference sound sources (RSSs) as the major candidates for transfer standards (11-12).

The contribution is related to the qualification of RSSs as transfer standards. The temporal stability of the emitted sound power has been measured for both broadband (one-third octave bands) and narrow band (FFT) frequency bands. The state-of-the-art sound power measurements are performed in

[1] spyros.brezas@ptb.de
[2] Patrick.Cellard@lne.fr
[3] hakan.andersson@sp.se
[4] c.guglielmone@inrim.it
[5] cafer.kirbas@tubitak.gov.tr

one-third octave band analysis from 100 Hz up to 10 kHz (13). Among the major aims of this contribution is the widening of the frequency interval with finer resolution. For the extension of the lower frequency limit, measurements have been performed in order to quantify near field effects and remaining room reflections. The use of the spiral method (4) for the sound power determination of a sound source has two main drawbacks. First, the sound power is determined over a virtual hemisphere, since the spiral path includes the movement of the microphone along a quarter circle, while the source is rotated by a turntable. Second, the analysis is performed in one-third octave bands. A scanning apparatus has been constructed for the measurement of a stationary RSS and the directivity characteristics of RSSs of the same type have also been measured, since they are strongly related to the sound power determination.

Dissemination relates the sound power under calibration conditions to the in situ sound power, which is affected by the changes in the conditions that influence the emitted sound power by RSSs. Measurements focusing on each of these conditions (atmospheric pressure, ambient temperature and fan rotation speed) have been performed and used for a proposed correction. The substitution method for the reference of the RSSs with the primary sources has been implemented based on interlaboratory measurements of a RSS specimen, which has been sent to participant laboratories for sound power determination using different measurement setups.

2. TEMPORAL STABILITY

The up-to-date temporal stability requirements concerning the calibration of RSSs are described in ISO 6926 (14) in terms of standard deviation. For the case of random signals, the standard deviation of the signal is related to the signal duration T (in s) and bandwidth B (in Hz) by (15):

$$\sigma = \frac{4.34}{\sqrt{BT}} \tag{1}$$

The performed temporal stability measurements can be divided into two groups. The first one includes sound pressure measurements using a stationary quarter circular metallic arc, along which ten microphones were positioned enabling a measurement surface of 2 m. Six RSSs were used (3 of the same type, 3 of different types) and the measurements lasted 2 months (11). The second group includes measurements performed using PTB's scanning apparatus (16). The apparatus consists of a metallic arc, which can host up to 24 microphones and enables sound pressure measurements at different measurement radii. For the measurements, the maximum number of microphones was used. Three RSSs of different type were measured at three different radii (1.45, 1.70 & 2 m). The measurements were performed during a period of 6 months. The measurement duration for the first measurement group was 600 s and for the second 1200 s.

Based on the sound pressure measurements, the sound power was determined according to:

$$L_W = 10\lg\left(\sum_i S_i \times 10^{L_{pi}/10}\right)\mathrm{dB} - 10\lg D\,\mathrm{dB} \tag{2}$$

where L_{pi} and S_i is the sound pressure level measured and the surface covered by the i-th microphone respectively and $D = \rho c / \left(400\,\mathrm{N \cdot s/m^3}\right)$, with ρ the air density and c the sound speed in air (17).

The standard deviation calculation was performed in one-third octave bands and in FFT bands (3.125 Hz). ISO 6926 (14) indicates the limit of the standard deviation for a RSS in one-third octave bands. The same limit values were used for the narrow band analysis. Figure 1 shows the standard deviation of the measurement results along with the limit values according to ISO 6926. As it can be seen, the standard deviation does not significantly change by changing the measurement method. The large values located at 10 kHz for the one-third octave band analysis and at more frequencies for the FFT analysis are due to the tonal characteristics that are exhibited by some RSSs.

The tonal characteristics are more profound at finer frequency resolutions. For this reason, the number of signal samples, which comply with the ISO 6926 standard deviation limits have been calculated for the signals used in Figure 1 for various FFT bandwidths (3.125, 6.25, 12.5 & 25 Hz). The standard deviation for the 3.125 Hz bandwidth has been used to calculate the standard deviation for other bandwidths. For each available standard deviation, the mean value was calculated by:

$$\overline{\sigma} = \sqrt{\frac{1}{n}\sum_{i}^{n}\sigma(f_i)^2} \tag{3}$$

Figure 2 shows the percentage of standard deviation samples, which comply with the ISO 6926 requirements for different FFT bandwidths.

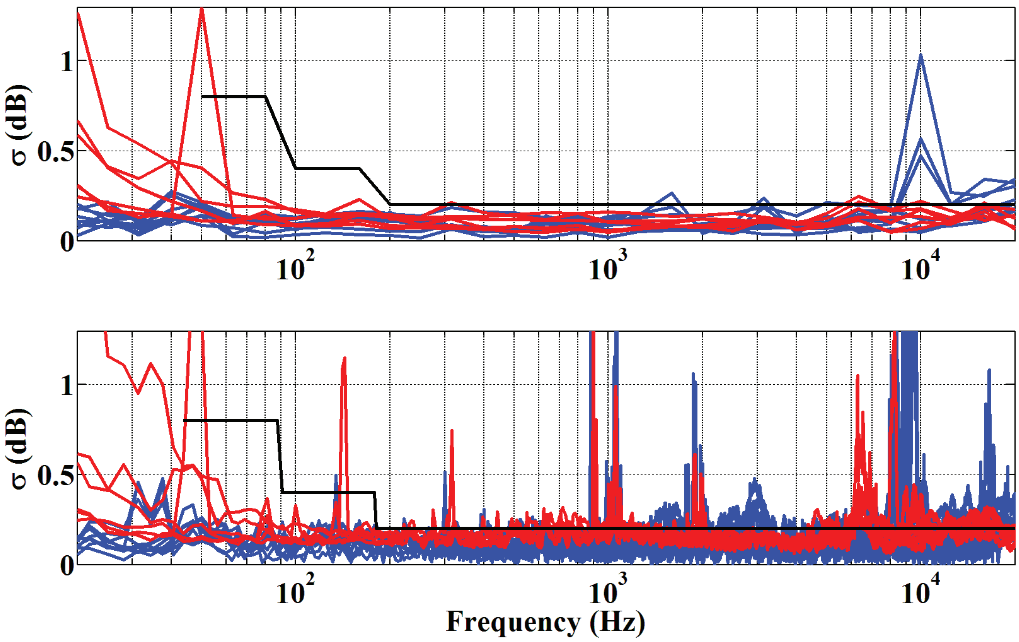

Figure 1 – Standard deviation of reference sound sources sound power levels for moving (blue) and stationary (red) microphones and limit according to ISO 6926 (black). Top: one-third octave band analysis. Bottom: FFT analysis (3.125 Hz).

As it can be seen in Figure 2, the lowest compliance is apparent for the 3.125 Hz resolution and the RSS with tonal characteristics at high frequencies (see Figure 1). The compliance increases for all studied RSSs as the bandwidth is enlarged.

3. DIRECTIVITY

The qualification of the RSSs is also related to the directivity characteristics. The directivity is quantified by the directivity index, which can be calculated by measurements in a hemianechoic room by:

$$D_{\mathrm{I}i} = L_{pi} - \overline{L}_p \tag{4}$$

where L_{pi} is the sound pressure level recorded by the i-th microphone and $\overline{L}_p$ the time and surface average sound pressure level (14). Directivity measurements were performed by the National Metrology Institutes (NMIs), which are participating in the European Metrology Research Programme (EMRP) part of which is this contribution. The Project is entitled “Realisation, dissemination and application of the unit watt in airborne sound” and the NMIs having provided directivity data are: INRIM (Italy), PTB (Germany), SP (Sweden) and TUBITAK (Turkey).

The directivity measurements were performed by either stationary or moving microphones. For the moving microphones, a scanning apparatus has been constructed by some NMIs. These devices are described in detail in another contribution (18). TUBITAK and PTB performed measurements with stationary microphones the former according to ISO 6926 and the latter as described in chapter 2. PTB also performed directivity measurements utilising a scanning apparatus. A first comparison was performed by measurements of RSSs of the same type. TUBITAK, INRIM and SP measured a specimen, while PTB has measured three specimen with stationary microphones and one specimen with the scanning method. Figure 3 shows the directivity index as calculated by each method. It can be seen that the overall patterns are revealed by all approaches. On the contrary, the more complex directivity characteristics (side lobes) are revealed much better by moving microphones due to the finer angular resolution they provide.

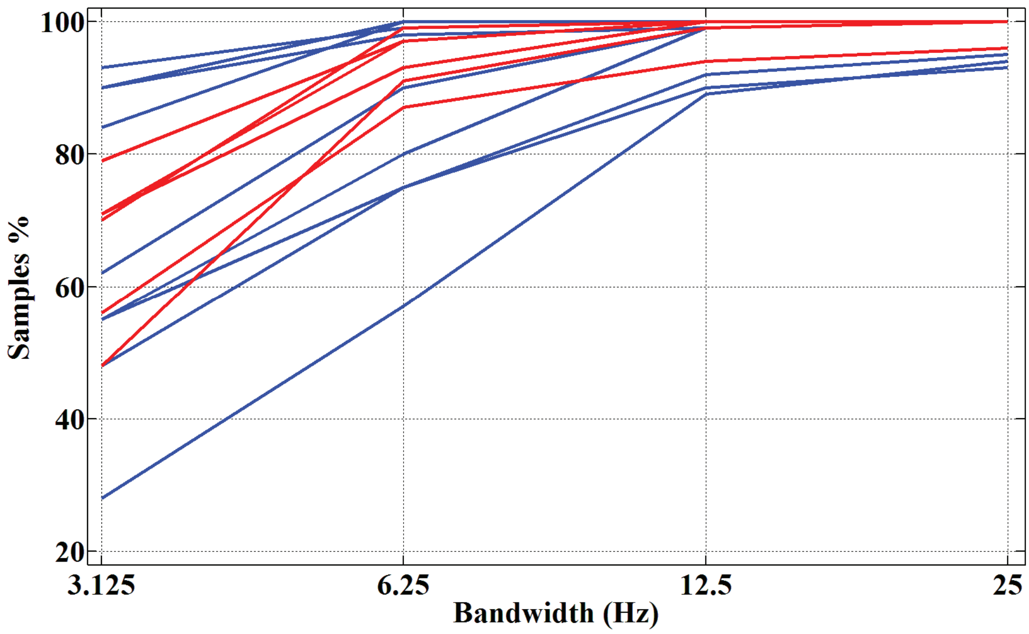

Figure 2 – Percentage of standard deviation samples complying with ISO 6926 requirements for various bandwidths for moving (blue) and stationary (red) measurement microphones.

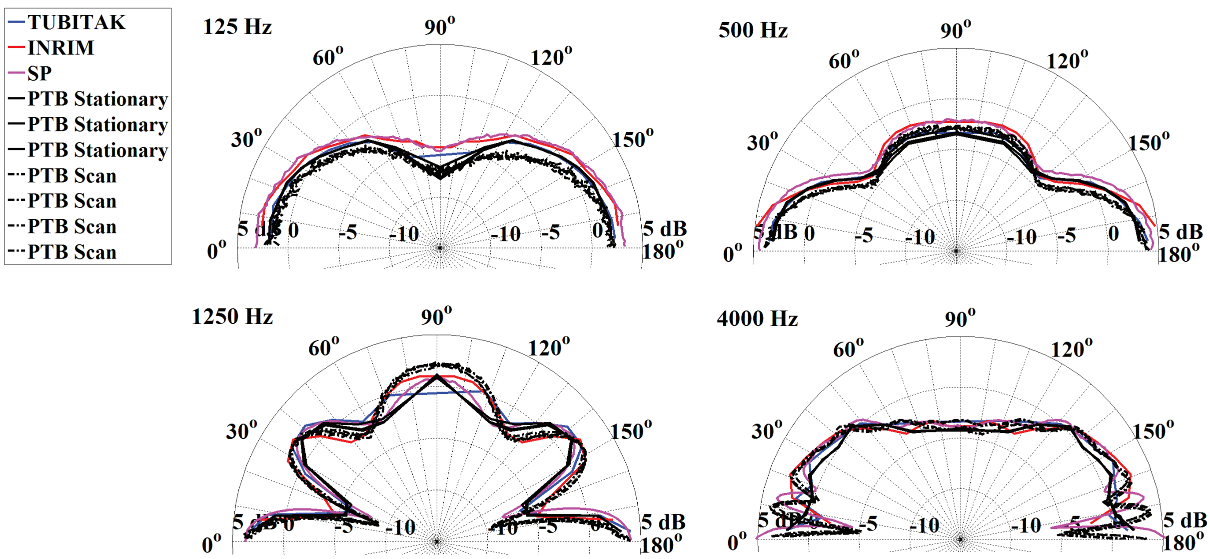

Figure 3 – Directivity index for RSSs of the same type. Measurements performed using different setups.

In Figure 3, the results correspond to a single measurement trajectory over the measured RSS and were performed in one-third octave band analysis. The PTB's scanning apparatus was used for directivity measurements for a physically covered hemisphere over three RSSs in both one-third octave and FFT bands. Figure 4 shows the directivity patterns for 1600 Hz and 1.45 m measurement radius. The stripes of the plots correspond to the surface covered by each microphone. The different directivity patterns are revealed by the scanning apparatus for all sources and frequency analyses.

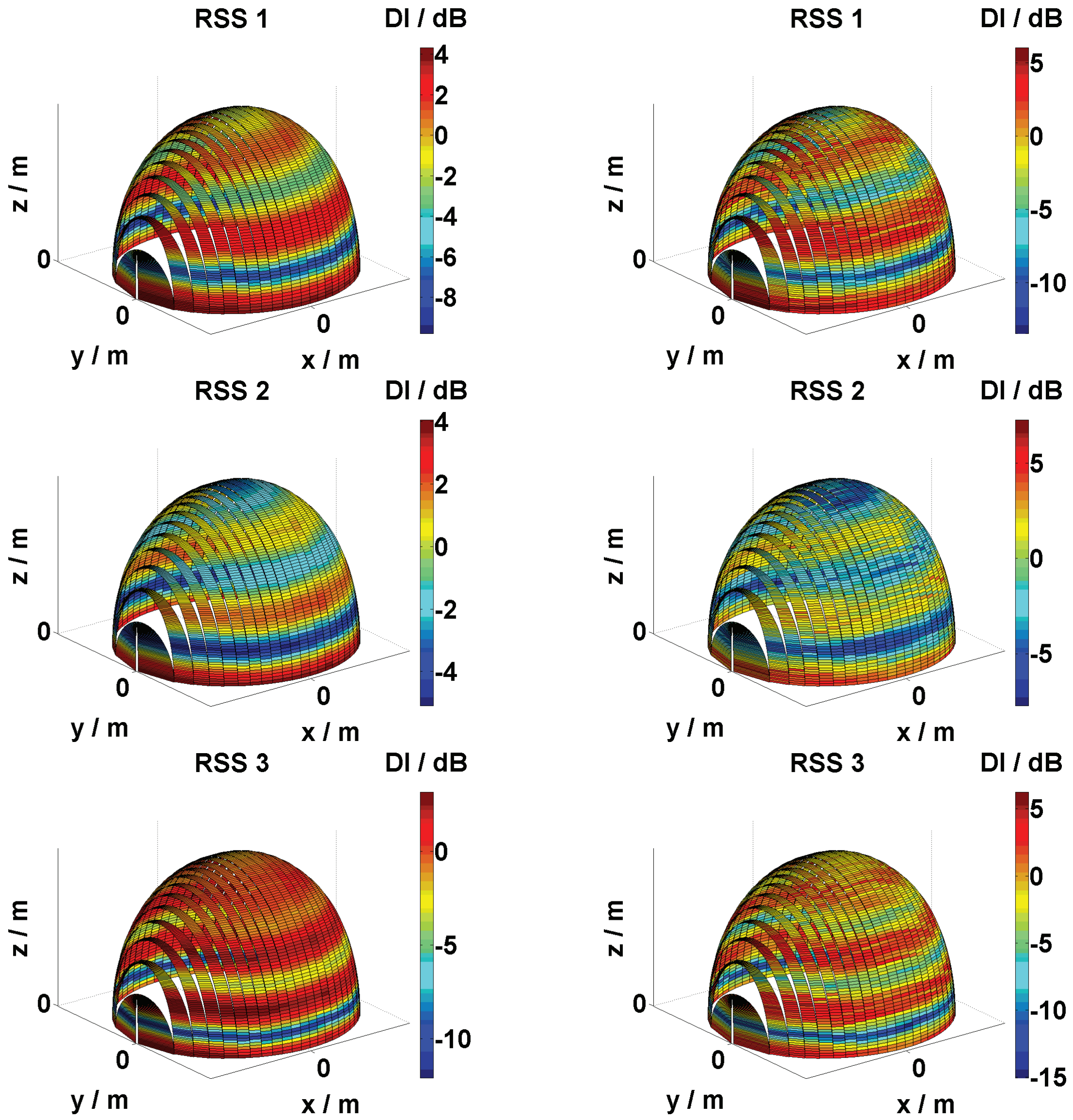

Figure 4 – Directivity index for 3 RSSs of different types for a measurement radius of 1.45 m. Left: one-third octave bands. Right: FFT bands (3.125 Hz).

4. NEAR FIELD EFFECTS

Sound power is determined by either sound pressure or sound intensity measurements, allowing different levels of accuracy for different assumptions, mainly related to the acoustic environment the measurements take place. Consequently, different sources of errors affect the measurement uncertainty. For measurements in hemianechoic rooms an error source are the near field effects, which are related to the measurement distance from the source and the type of the source (spherical etc.). The near field error of a concentric sphere measured at a distance r is according to Huebner (19):

$$\Delta_{theo} = 10\lg\left(\frac{2}{\pi kr\left|H_{n+\frac{1}{2}}^{(2)}(kr)\right|^2}\right)\text{dB} \tag{5}$$

where $H^{(2)}_{n+\frac{1}{2}}(kr)$ is the normalised Bessel function of the third kind and n is the order of the source (0 for monopole, 1 for dipole etc.).

Measurements at different radii (0.60, 0.70, 0.80, 0.90, 1.00, 1.45, 1.70, 2.00, 2.34 & 2.75 m) were performed using PTB's scanning apparatus for three RSSs of different type. To minimise influences from the wind produced by the rotating fan of the sources, wind shields were applied. The sound powers determined for each radius r were subtracted from the sound power for the largest radius to obtain an experimental estimate for the near-field effect:

$$\Delta_{meas} = L_W(r_{\max}) - L_W(r) \tag{6}$$

By this approach, it is assumed that the near-field effect vanishes for the largest distance. This is obviously not the case, nevertheless it provides the best available estimate for the time being. Intensity measurements at different measurement distances would be much more appropriate to describe near field effects. Nevertheless, due to the wind in the vicinity of the sources, these measurements did not provide meaningful results.

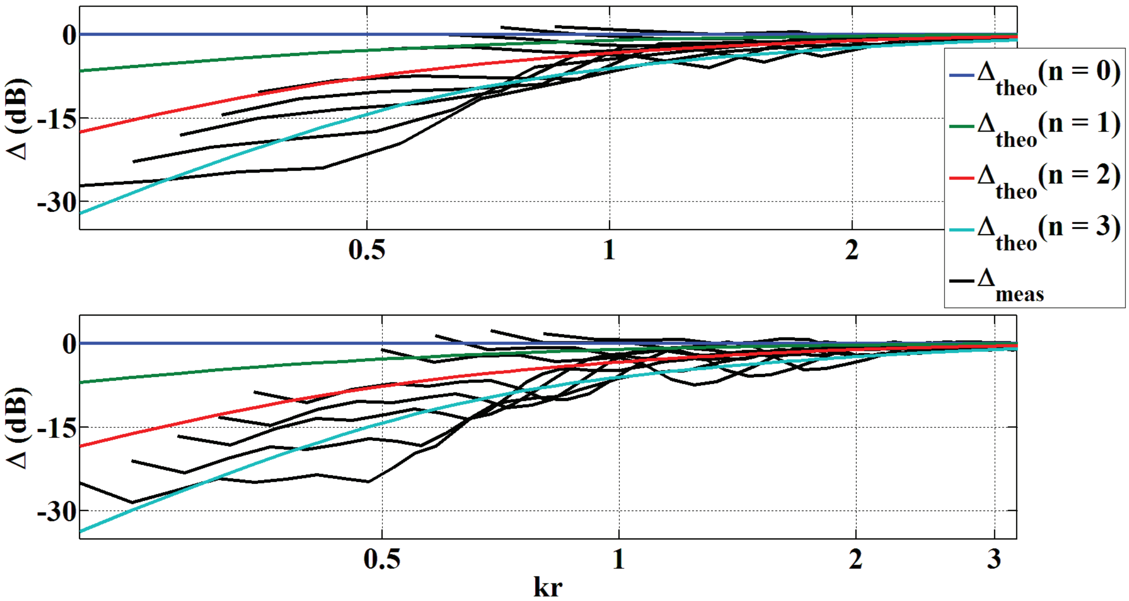

Figure 5 – Near field error investigation for sound power measurements at different radii compared to theoretical values for various orders of a concentric spherical source. Top: one-third octave band analysis. Bottom: FFT (3.125 Hz).

Figure 5 shows both Δ_{theo} for different orders and Δ_{meas} for a RSS. As it can be seen, it is not possible for the near field error to be attributed to a specific order behaviour (e.g. the source is not a dipole). Additionally, it must be stated that concerning the Δ_{meas} the wind has not been fully suppressed and there are also remaining room reflections influencing the difference.

5. SOUND POWER DETERMINATION UNDER DIFFERENT CONDITIONS

The sound power radiated by a rotating fan depends on atmospheric pressure, ambient temperature and fan rotation speed, according to the following equation (20):

$$P = K\, B^{n_B}\, T^{n_T}\, \omega^{n_\omega} \tag{7}$$

where P is the sound power in W, K a constant, B the atmospheric pressure in kPa, T the ambient temperature in K and ω the fan rotation speed in Hz. The n_B, n_T, n_ω values are determined by the emission characteristics of the source. Equation 7 may be the basis for the relation of the sound power of a RSS under calibration conditions to the in situ sound power. The relation can be described by:

$$L_{W,in\,situ} = L_{W,cal} + 10\,n_B \lg\left(\frac{B_{in\,situ}}{B_{cal}}\right)\text{dB} + 10\,n_T \lg\left(\frac{T_{in\,situ}}{T_{cal}}\right)\text{dB} + 10\,n_\omega \lg\left(\frac{\omega_{in\,situ}}{\omega_{cal}}\right)\text{dB} \quad (8)$$

The denominator values, which express the atmospheric pressure, ambient temperature and fan rotation speed under calibration conditions can be arbitrarily chosen. Measurements were performed for the determination of the n_B, n_T, n_ω values and have been previously described (12).

Figure 6 shows the values as calculated after the corresponding measurements and having used theoretical values (20) at the beginning of the calculation process.

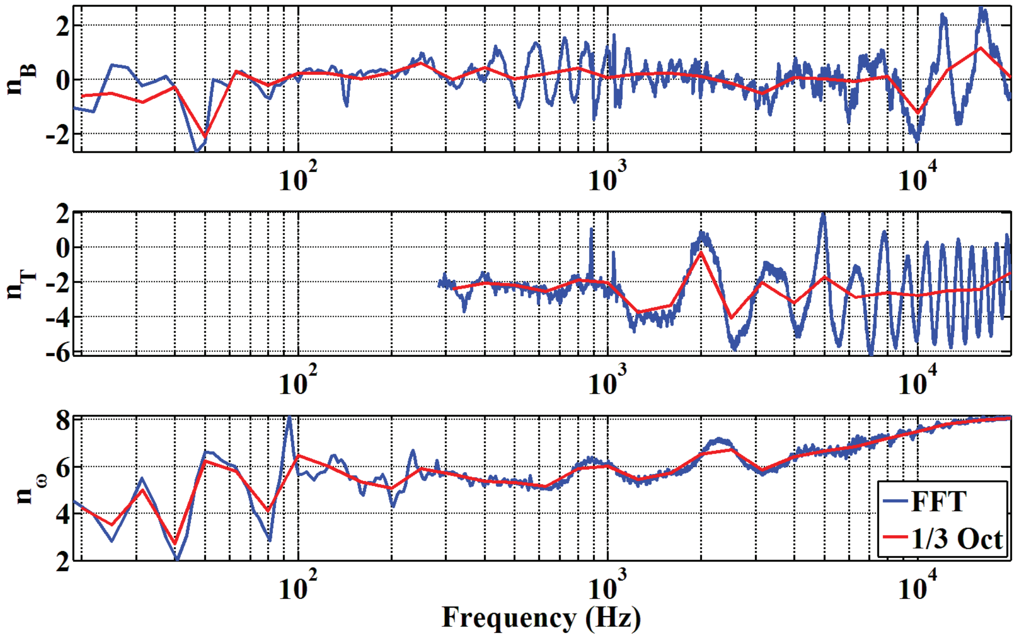

Figure 6 – Sound power level correction factors for (top to bottom) atmospheric pressure, ambient temperature and fan rotation speed.

Concerning Figure 6, the following remarks can be made: the small variations in the atmospheric pressure provide results within the limits of the related uncertainty and thus, larger variations are required for more robust results. The missing low frequency end for the temperature correction factor is attributed to the background noise during measurements. The mean value is close to the theoretical one for dipoles (-2.5) and the FFT ripples are due to arc reflections, which cannot cancel out, because of the spectrum frequency shift imposed by the temperature changes. The fan rotation variations have also led to a correction factor with values similar to the theoretical (6) up to approximately 1.5 kHz, which reveals dipole behaviour. The behaviour changes for higher frequencies towards this of a quadrupole.

6. INTERLABORATORY MEASUREMENTS

The relation between the sound power levels of the RSS and the primary source is established by the substitution method (2):

$$L_{W,\,RSS} = L_{W,\,PS} + \overline{L}_{p,\,RSS} - \overline{L}_{p,\,PS} \quad (9)$$

where $L_{W,\,RSS}$ and $L_{W,\,PS}$ are the sound power level of the RSS and the primary source respectively. Accordingly, $\overline{L}_{p,\,RSS}$ and $\overline{L}_{p,\,PS}$ are the average sound pressure level of the RSS and the primary source over the measurement duration and measurement surface. The substitution is intended to be performed for both one-third octave bands and FFT bands.

Some NMIs participating in the project have assembled their own primary source. For the implementation of interlaboratory measurements of a RSS specimen, the sound power level of the RSS is referred to each primary source. Each NMI uses a different setup (either a scanning apparatus or stationary microphones) for the corresponding measurements. Figure 7 shows the RSS sound power levels according to equation 9 for three NMIs (the interaboratory measurements have not been concluded up to the present) and the sound power level differences between the NMIs results. The mean sound power level for each NMI has been calculated and for these three levels the mean value has been additionally calculated. The difference between the latter and the previously mentioned mean sound power levels are shown in Figure 7. The graph colours correspond to the same NMI for both plots. All measurements have been performed in hemianechoic rooms. SP and TUBITAK have performed their measurements at the same measurement radius (2 m), while PTB performed measurements at different radii (1.45, 1.70, 2.00 m).

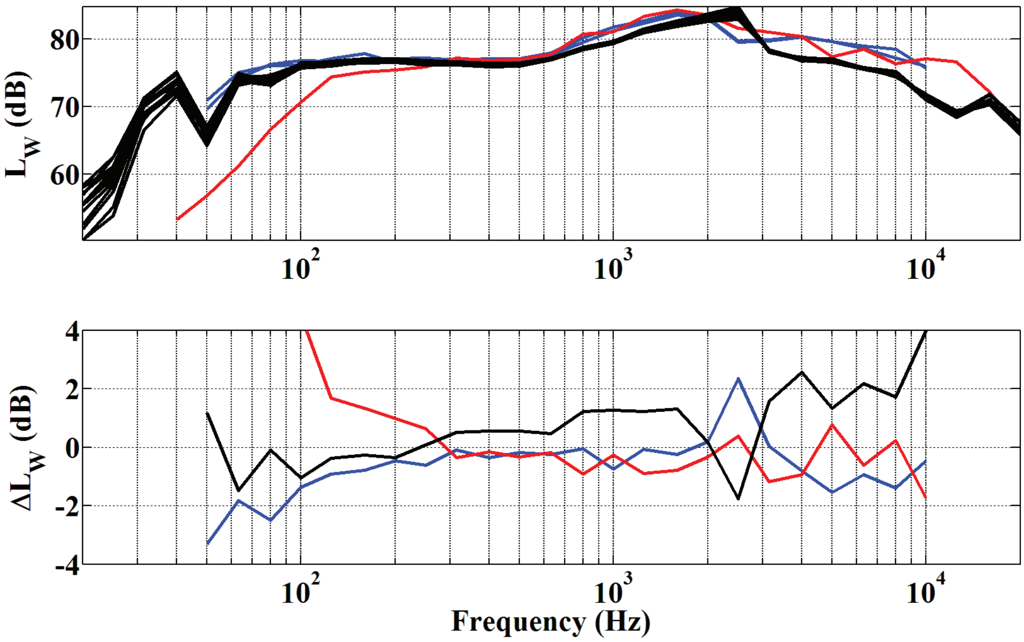

Figure 7 – RSS sound power level according to the substitution method for two NMIs (top) and sound power level differences between the NMIs results (bottom) for one-third octave band analysis.

For all NMIs the sound power level of the primary source has been calculated using Rayleigh's integral (10) and measured vibration velocity data provided by a laser doppler vibrometer. The smaller differences are located between 200 Hz and 1000 Hz. Room response and background noise affect the frequencies below 200 Hz. At frequencies above 1000 Hz, the frequency response of the primary source influences the substitution results. Alterations in the used primary sources are planned to improve their frequency response.

7. CONCLUSIONS

The intended use of aerodynamic reference sound sources as transfer standards for the dissemination of the unit watt in airborne sound has led to a series of relevant investigations. The temporal stability of such sources is sufficiently high for the majority of the studied sources for both measurements of stationary or moving microphones in terms of one-third octave band analysis. For narrow band analysis, it has been shown that the analysis bandwidth is strongly related to the degree of temporal stability. Directivity measurements with different setups have shown that the overall directivity pattern can be revealed by all setups. Nevertheless, the more prominent directivity characteristics are only seen in the results from scanning apparatus, which provide a finer discretisation of the measurement surface. Such apparatus can also provide the directivity along the total measurement surface for both broadband and narrow band frequency analysis.

When the sound power level of a particular reference sound source is determined by substitution with primary sound sources at different NMIs, the observed deviations are considerably larger than the standard uncertainties given in (14). This is due to the properties of the primary sources which have to be improved for a future introduction of traceability into sound power measurements.

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