

# FINAL PUBLISHABLE JRP REPORT

JRP-Contract number	SIB56			
JRP short name	SoundPwr			
JRP full title	Realisation, Dissemination and airborne sound	Dissemination and Application of the unit watt in		
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: V1.0 Annex Ib: V1.0			
Period covered (dates)	From 01 June 2013	To 31 May 2016		
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The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union



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## 1 Executive Summary

#### Introduction

Noise pollution is among the most important detrimental effects of modern industrialised societies. Protection from noise requires the ability to measure sound emission with sufficient precision in a wide frequency range. The path towards a measurement technique is paved by the results of this project.

#### The Problem

Measuring the sound emitted from an object is required for consumer information on domestic and industrial products. It enables potential purchasers of machines to compare products of the same type, and take the sound emissions into consideration. As a result, manufacturers should be able to demonstrate that their product complies with European legislation on noise emissions and fewer people should be affected by hearing impairment. The three primary directives of interest are the Machinery Directive 2006/42/EC, the Outdoor Noise Directive 2000/14/EC and the Eco Design of Energy Related Products Directive 2009/125/EC; which cover noise emission. Manufacturers are not allowed to market their products in Europe if they do not meet these noise emission requirements. Therefore, manufacturers as well as notified bodies which carry out or supervise the conformity assessment procedures require traceable results with small uncertainties.

The measurement of sound power is currently based on the measurement of field quantities like sound pressure, which is measured under specified conditions. This approach and the lack of a reference procedure are the basic reasons why the currently 10 different standardised procedures give different results and why uncertainties easily reach several decibels (dB).

A further need arises from the replacement of centralised large fossil fuel power stations by decentralised energy conversion devices like heat pumps or small combined heat and power plants. These sources emit low frequency sounds (< 100 Hz), which are not covered by measurement guidelines at present.

#### The Solution

To address these needs, this project aimed to develop primary sound power sources, measure the acoustic field generated by these sources, develop calibration techniques and make practical recommendations for the use of these standards for measuring sound power.

#### Impact

The results of this project enable the traceable measurement of airborne sound power, the major descriptor for the sound emission from sources. It furthermore fosters the extension of the frequency range towards lower frequencies since current methods are restricted to a lower frequency limit of 100 Hz. This extension is of utmost importance since the increased use of renewable energy sources leads to more low frequency noise sources which are often located in the immediate vicinity of living environments. Examples are decentralised heat pumps or small combined heat and power plants.

Considering the sound emission of a source to be the result of the combination of a source with a surrounding sound field is a revolution in the measurement of sound power. It will, in principle, change the way sound power and quantities derived thereof are measured, predicted and supervised.

#### 2 **Project context, rationale and objectives**

## 2.1 Context

Sound power is the rate at which sound energy from a source or object is emitted per unit time, and is measured in watts (W), the SI unit of power. Until now, the sound power was considered to be independent of the environment and of the distance from the source, and could therefore be used to describe the acoustic output of both domestic and industrial technical products. But in practice, sound power can only be determined from other measurements such as sound pressure at a certain position, which is measured in pascals (Pa). There are many different ways to determine the sound power of a particular source, but results



can vary widely. Even worse, uncertainties can only be compared if the measurement procedures were the same, and not for an individual measurement result. This makes it difficult to compare the measured sound power levels for regulatory compliance with noise protection legislation.

The main goal of the project is the improvement of the quality of life with respect to noise – a task concerning the whole European society. This concern is reflected by the European directives 2000/14/EC "Outdoor Directive", 2006/42/EC "Machinery Directive" and 2010/30/EU " Energy Labelling Directive" which are directly linked to the quantity sound power and thus to this project.

The Outdoor Directive is related to the noise emission in the environment by equipment for use outdoors. Sound power levels from such equipment must be determined and declared. For some machines, e.g. lawnmowers and earth moving machinery, permissible sound power levels are defined. Manufacturers are not allowed to market their products in Europe if they do not meet these requirements. Therefore, manufacturers as well as notified bodies which carry out or supervise the conformity assessment procedures require traceable results with small uncertainties and a transparent uncertainty budget. At current, "Measurement uncertainties are not taken into account in the framework of conformity assessment procedures in the design phase." (Annex III of the Outdoor Directive) and measurement results of the sound power level are not traceable at all. This reflects the difficulties to establish an approved uncertainty budget for the sound power level and clearly indicates the need for improved measurement methods ensuring traceability of the results.

The Machinery Directive 2006/42/EC supports the free movement of goods in the European internal market. As a Directive under Article 114 of the Treaty on the Functioning of the European Union, prepared to avoid trade barriers, it poses essential requirements on safety issues which have to be observed by all machinery manufacturers and machine importers in Europe. As noise is one of the important hazards addressed by the Machinery Directive, essential requirements on noise are included. Most important is the minimisation requirement that postulates a noise control at the source by design which has to aim at reaching lowest noise emission levels. As a consequence it is necessary to assess whether the applied noise reduction measures are sufficient with regard to the state of the art of noise reduction. The emission values must be given in the instruction manual of the respective machine and in the sales literature describing the machinery. The intention is to allow potential purchasers of machines to compare machines of the same type but of different brand in order to choose the quietest machine on the market. As a result, the noise exposure of workers will be reduced by using more quiet machines at work places, thus leading to less people with hearing impairment. Hearing impairment is one of the most prevalent occupational diseases today. The whole concept of the Machinery Directive is closely linked to the measurand sound power. The implementation of the Machinery Directive thus benefits considerably from the establishment of a sound power standard resulting in traceable sound emission measurements with a clear uncertainty budget.

The Energy Labelling Directive establishes a framework for the harmonisation of national measures on enduser information, particularly by means of labelling and standard product information, on the consumption of energy and where relevant of other essential resources during use, and supplementary information concerning energy-related products, thereby allowing end-users to choose more efficient products. It is supplemented by commission delegated regulations with regard to several household appliances. Such regulations exist e.g. for dishwashers, washing machines and refrigerators. The label of the mentioned household appliances must contain the "airborne acoustical noise emissions expressed in dB(A) re 1 pW and rounded to the nearest integer". It is expected that future regulations for further household appliances will also contain the noise emission which is quantified by the sound power level. Manufacturers as well as consumers are therefore interested in traceable sound power measurements with small uncertainties.

Besides these needs from European Legislation, the necessity of a primary power standard in airborne sound becomes furthermore obvious when other disciplines with wave fields are considered. In ultrasound, a radiation force balance is used as a primary power standard. For the measurand power of an electromagnetic field, traceability is ensured e.g. by substitution of d.c. power in a bolometer element. These examples show that a closed metrological system in the case of wave fields requires on the one hand sensors for the field quantities and on the other hand a power standard. Whereas the former is available in airborne sound, the development of the latter is pursued by this project.



## 2.2 Objectives

The project addresses the following scientific and technical objectives:

- 1. To develop a reference sound power source with a calculable sound power based on measurements of vibration velocity, dimension and the environmental properties of air with an uncertainty of 0.5 dB.
- To measure the output of this reference sound power source with sound intensity instruments calibrated in accordance with IEC 61043 and explain any deviations from the predicted behaviour. This is necessary to distinguish the phase shift between the sound velocity and the sound pressure on the enveloping surface.
- 3. To develop methods for the calibration of non-calculable sound sources by comparison with the reference sound power source. One major focus will be on broadband sources, which generate sound aerodynamically. Another aspect addressed is the development of a new concept for tonal sound power sources.
- 4. To develop qualification procedures for measurement setups, analyse uncertainties of sound power determinations in practice and develop a substitution method using sound intensity for machinery noise.

## 3 Research results

#### 3.1 Development of a primary sound power source

The primary standard for the quantity sound power is based on a baffled vibrating solid body. The vibration velocity of this device is measured by a laser vibrometer whereby the velocity distribution on the source's surface including the phase is considered. The sound power output of this device is calculated directly by Rayleigh's Integral from measured velocity, dimension and environmental properties of air assuming a free sound field. All the necessary quantities are measured with a sufficient accuracy keeping traceability. Design goals for the primary sound power source are to have an embedded solid body, high temporal stability, flat frequency response, high sound power and monopole behaviour.

PTB and INRİM developed an analytical lumped parameter model comprising the elements power amplifier, electrodynamic vibration exciter, vibrating plate and sound power emitted into a free sound field. By using the results of this study, PTB investigated the influence of major design parameters like plate velocity, plate mass, diameter of the rigid piston and electrodynamic vibration. The results are given as follows:

- Of all investigated variations, the piston velocity has the largest impact, maximum velocity emits maximum sound power.
- Increasing plate mass leads to a decrease in sound power output.
- The influence of plate radius was investigated for PMMA and radii of 1, 3, and 5 cm, larger piston radii lead to more sound power output. The overall shape of the sound power output curve is not influenced by piston radii.
- Three different materials, aluminium, PMMA and Teflon, were tested under the assumption of identical geometries for a rigid piston. Aluminium and Teflon display almost identical sound power output, whereas PMMA emits 2 dB more sound power and the general behavior of all three materials is very similar.
- An electrodynamic vibration exciter was proposed because of the ease of monitoring its output. However, the electrodynamic vibration exciter may not be the most efficient solution for high frequencies. For instance, it may be possible to extract the magnet/moving coil assembly from a high frequency loudspeaker and connect it to the smaller discs for high frequencies.

After evaluating the results from the analytical study of PTB, the construction of primary sound power sources started. The sizes of primary sound power sources were mainly determined by the geometric restrictions of the space, where the primary sound source is mounted. As a source of vibration generation, PTB, SP and TÜBİTAK UME used vibration exciters whereas INRIM used a loudspeaker. Institutes have done their own designs and they have improved their designs many times to obtain a higher stability and flat



spectrum in a wide frequency range. The final construction of primary sound power sources is shown in Figure 1 for different institutes.



INRIM TÜBİTAK UME Figure 1 - Primary sound power sources developed at PTB, SP, INRIM and TUBITAK

PTB has produced several versions of their primary sound power source. The 8th version, which is introduced here, has a cone shaped piston of 60 mm diameter made of aluminium which is excited by an electrodynamic shaker. The primary sound source was mounted in the center floor of PTBs hemianechoic room or of the reverberation room.

INRiM used a loudspeaker as an exciter in the primary source. They connected the piston made of hi-tech polymer Celazole to the center of the loudspeaker with a polymer rod glued to the loudspeaker voice coil (coice coli) as shown in Figure 1 for INRiM. The baffle is a multi layer made of steel and brass with vibration damping adhesive tape. It was located in the center of INRiMs hemi anechoic room.

At SP, the piston material is made of an acrylic glass, and it has a diameter of 60 mm. The piston is coneshaped. The baffled disc is made of steel and there is a clearance of 0.2 mm between the piston and the baffle disc. In order to decrease the risk of friction, contact surfaces between the piston and the baffle are highly polished. They used a vibration exciter in the source. They placed the primary reference source in their hemi anechoic room.

TÜBİTAK UME constructed a 2nd version of the primary reference source. Three types of piston materials in different diameters were tested and the piston having a 50 mm diameter made of aluminium was selected to be used in the primary sound power source. An adaptor was integrated in the baffle disc to be able to use different types of pistons in the primary source. A B&K type 4809 exciter was employed to generate the vibration. In order to isolate the vibration between the exciter and the main body, vibration isolators and sealing rings were used. TÜBİTAK UME has a full anechoic room but it was converted to a hemi anechoic room by covering the floor of the room with a chip board with a thickness of 30 mm. The size of the cover is 5 m x 5 m. The primary sound source was placed in the hole having a height of 21 cm at the center of the room. For the measurements performed in a reverberation room, it was moved to the reverberation room of TÜBİTAK UME.



After constructing the primary sound power sources, they were all installed in hemi anechoic rooms to determine sound power levels. First, measurement points were defined on the piston surface, which are shown in Figure 5 and vibration velocity measurements were performed at each point. 25 points on the surface of the piston were determined in the measurements at TÜBİTAK UME. The measurement setups are shown for different institutes in Figure 2.



Figure 2 - Vibration velocity measurements on the primary sound power sources

Vibration velocity measurements were performed generally in the frequency range from 20 Hz to 20 kHz using the laser vibrometer in 1/3 octave or FFT bands. TÜBİTAK UME and PTB have used scanning laser vibrometers, INRiM and SP have used single point laser vibrometers for the measurements. The measurements were performed on the piston surface at each point. SP, INRiM and TUBITAK assumed a rigid piston and calculated the sound power whereas PTB used the discretised Rayleigh-integral for this purpose.

The sound pressure was additionally measured on enveloping surfaces where PTB, SP und UME TUBITAK used specially designed scanning mechanisms. At PTB, it consists of a 24 microphone array mounted on an arc (Figure 3). It can be tilted to cover a hemispherical measurement surface by two wires which are moved by a stepper motor outside the room. Two different arcs can be used for different measurement radii.



Figure 3 – PTB's scanning apparatus

At LNE, only one microphone is used, which is moved on each position by an automatic device, controlled by software that will manage both the scanning apparatus and the acoustic signal analyser acquisition. One movement is along a rail describing a vertical arc of 90°. The second movement is to move this arc around a vertical axis to cover the entire hemispherical surface. A third movement displaces the microphone on the radius by 1 cm to evaluate the intensity by two steps (Figure 4).





Figure 4 – LNE's scanning apparatus, basic design and detail

SP uses automatic scanning along a single meridional arc about a horizontal axis, as proposed by the third proposal of microphone arrangements given in the ISO 3745 standard. The scanning apparatus has to be manually turned around the vertical axis. The scan can be running continuously (path) or stop at predefined heights. The scanning speed and spatial resolution of the measurement points can be set freely. The scan is accomplished by a string pulling the frame of the apparatus. The string is winded by a stepper motor mounted on the roof of the hemi-anechoic chamber.



Figure 5 – SP's scanning apparatus

INRIM used a 20 point array of discrete microphone positions for this purpose. PTB and UME TUBITAK also measured the sound pressure level in their reverberation rooms. Additionally, the reverberation times were determined which permitted a calculation of the sound power level according to the diffuse field method.

Sound power comparisons are reported in Figure 6. Due to the different designs and test setups different results are yielded in all four institutes. The sound power comparison is excellent with INRiMs source between about 2 kHz and 7 kHz. At lower frequencies parasitic vibrations of the supporting plate change the sound power output of the device. The overall agreement between both sound powers is quite excellent for SP. The whole frequency range between 50 Hz and 10 kHz is well covered with deviations reaching 2 dB around 1 kHz and at the lowest and highest end of the frequency range. The reason for the excellent performance is probably the separate founding of the source. The air gap does not seem to be of relevance. The source of UME TUBITAK shows a good agreement between all three sound power levels between 200 Hz and about 8 kHz. At lower frequencies, the floor installed in the fully anechoic chamber is not sufficiently rigid and the reverberation room does not provide a diffuse sound field. At the highest frequencies, the rigid piston assumption does not really hold. The agreement between the three different sound power levels at PTB is very good between 125 Hz and 1.6 kHz. At lower frequencies, discrepancies



indicate that the sound power emitted by the source into the different sound fields is different. Differences above 1.6 kHz can not be explained yet. Since results from the free-field and diffuse field agree quite well one possible explanation are parasitic airborne sound sources.

The uncertainty associated with the realisation of the unit watt by the primay sound power sources was investigated by TÜBİTAK UME assuming a rigid piston. The velocity of the piston is the largest uncertainty contribution with about 0.25 dB whereas the other components like frequency measurement, air density, speed of sound and piston radius can nearly be neglected. The expanded uncertainty of the sound power level is between 0.5 and 0.6 dB according to this calculation.

PTB performed a detailed uncertainty calculation. It considered the uncertainty contributions by velocity, phase, discretisation and barometric parameter misidentification that are due to the uncertainty of the measurement equipment. This uncertainty calculation showed that an uncertainty budget of  $\pm 0.2$  dB is attainable considering just the measurement equipment influence used to obtain the data input for Rayleigh's integral.

This value was confirmed by a second uncertainty calculation by PTB: a Monte Carlo simulation. This simulation consisted of  $10^6$  runs of sound power calculations using the discretised Rayleigh integral. For each run, each measured input data item (geometry, velocity, barometric pressure and speed of sound) was modified by a random number drawn from a uniform distribution of width  $\pm 3^\circ$ . The measured phase values were modified in the same way using a uniform distribution of width  $\pm 3^\circ$ . These values were chosen in accordance with the manufacturer's data sheet for the laser-scanning vibrometer in use. For each measured point and each frequency, the random numbers chosen were varied. The analysis was performed at single frequencies corresponding to the midband-frequencies of one-third octave bands between 20 Hz and 20 kHz.

In this way a measurement uncertainty of the input quantities of  $\pm 3\%$  was modeled. From the distribution of the calculated sound power levels for the  $10^6$  runs, a mean and an expanded uncertainty corresponding to a 95% confidence interval (k=2) was calculated for the midband-frequencies of every one-third octave band in the range between 20 Hz and 20 kHz. This expanded uncertainty is about 0.2 dB and shows some scatter over frequency.





Figure 6 Comparison between sound powers determined from vibration velocity and from ISO 6926

In addition to these experimental investigations, numerical calculations were performed by POLITO and by PTB. The complexity of the simulations was increased step by step starting with an ideal piston in an ideal free field ending with the real piston in PTBs hemianechoic room. The latter was simulated by a sponge layer with an absorption coefficient of the wedges as measured in PTBs large Kundt's tube. The final result is that the real piston behaves very well like a monopole in terms of directivity and near-field effects and that PTBs hemianechoic room provides a sufficiently free field.

The discrepant results from PTB at low frequencies, a frequency range where the source should work properly, lead to further theoretical investigations on the nature of the quantity sound power. Using existing theoretical approaches, the amount of sound power emitted into a room by a monopole of constant volume flow was calculated. This room was PTBs rectangular reverberation room. The calculation uses the first 10000 room modes, i.e. the results are valid up to about 500 Hz. The results for different source positions clearly demonstrate that the sound power changes considerably with position in the room (Figure 7).



Figure 7 – Sound power of a constant volume flow point source emitted into a 200 m<sup>3</sup> reverberation room for 50 randomly chosen source positions relative to the sound power emitted into a free sound field in dB



Figure 8 – Expected value and standard deviation for the sound power emitted by a monopole of constant volume flow at different source positions into a 200 m<sup>3</sup> reverberation room calculated with the Monte-Carlo method

In a next step, Monte-Carlo-Simulations were performed at individual frequencies to determine whether the expected value of the ratio between really emitted sound power and free-field sound power is about one. For frequencies around 100 Hz this is not the case whereas for frequencies around 400 Hz this seems to be more valid (Figure 8). The conclusion from this is that the sound power emitted by a source depends on the outer sound field, in general. A worst case scenario is a point source in a highly reflecting environment. In practice, these influences are often reduced by spatially distributed sources (i.e. high frequencies) and by averaging over source positions and bandwidths.

As a consequence these findings lead to the proposal to characterise a source by its **free-field** sound power by introducing the concept of traceability into sound power measurements. For the quantity sound power this is a complete change in philosophy.

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It can thus be stated that the major objectives were achieved. Primary sound power sources were developed. Different source designs result in different frequency ranges where the aim of an uncertainty of 0.5 dB is reached.

#### 3.2 Investigations on near-field effects and remaining room reflections

For the calibration of transfer standards it is of utmost importance to decide at which distance to the sources the enveloping surface is to be situated. Very small distances to the sources may be prone to the near-field effect whereas very large distances to the source show larger influences of the remaining room influences. The absence of near-field effects and remaining room influences would be demonstrated by a sound power level, which is measured by the sound pressure enveloping method and which is independent from the distance to the source. To test this, the sound power level differences measured at different distances are calculated (Figure 9) where the sound power measured at the largest difference was used as the reference. Between 63 and 1000 Hz, all differences are very close to 0 dB. Thus, there is no measurable influence at these frequencies. At higher frequencies, the influence of the scanning apparatus is observed which is different radii. At frequencies below 63 Hz, sound pressure level differences deviate significantly from 0 dB. The reason is the occurrence of room modes, i.e. spatial inhomogenities of the sound field. Whether they are caused by the room or by the source cannot be distinguished from this measured data.



Figure 9 – Difference between sound power levels measured by the sound pressure method at distance r to the sound power level measured at r = 2.75 m

Another common feature of near-field effects and remaining room influences is a significant difference between measured sound pressure and sound intensity levels. Therefore, this difference was calculated for the enveloping surfaces used in PTBs hemianechoic room (Figure 10).

At medium frequencies between 100 Hz and 10 kHz, all curves are about 0 dB. This means that there are no significant near-field effects or remaining room reflections. At higher frequencies, deviations of several dB are observed which are mainly caused by the arc reflections and by the spatial sampling. Whereas 24 microphone positions were used for the sound pressure measurements, only 3 positions were used for the intensity. Due to the directivity of the primary source, deviations occur. For the question to be investigated here, the distances between the source and the measurement hemisphere and between the measurement hemisphere and the room boundaries are quite large. Thus, the frequency range above 1 kHz will be free from reflections from room boundaries and near-field effects.

The opposite is expected for frequencies below 100 Hz. Nevertheless, measured differences between sound pressure and sound intensity levels are around 0 dB and tend to become even negative at low frequencies. Significant near-field effects or room reflections would be indicated by a positive difference



between sound pressure and sound intensity level. This is not observed. It remains open how negative differences between sound pressure and sound intensity levels can be explained.

The major goal within this objective was the performance of intensity measurements which clearly was achieved. Deviations to the predicted behaviour could be explained at frequencies above 100 Hz whereas results below 100 Hz are still to be explained.



Figure 10 – Difference between sound pressure and sound intensity level measured at different distances r to the primary sound power source in PTBs hemianechoic room

#### 3.3 Calibration of non-calculable sound sources

Before the development of calculation procedures, appropriate transfer sound sources had to be identified. Aerodynamic fan-type sound sources are already used for this purpose, but only for one-third octave bands. A thorough investigation of these sources in terms of temporal stability, directivity and frequency content lead to the conclusion that they can also be used in narrow frequency bands. Then they are equivalent to tonal sources.

Two further concepts for realising tonal sources have been investigated. The first is to use an electrodynamic loudspeaker with a microphone in the near-field to control the output. This device can be excited with tonal or multisine signals and the input current and input voltage are measured as a cross-spectrum. Test measurements with this device revealed that it cannot be expected that the volume-flow is constant for different outer sound fields due to a different vibrational behaviour of the loudspeaker membrane. Therefore, the first concept was not followed. The second concept is to use a tube excited by a compression driver. The volume flow of this device can then be measured by two microphones. Such a device has been developed but showed a major parasitic sound radiation from the body of the compression driver. Thus a similar commercially available device has been purchased. The volume flow of this device can be determined by a pair of microphones inside the compressed volume. This device has also been tested. Nevertheless, the sound power emitted by the device as measured in a hemi-free field and diffuse field is not identical to the one calculated from the volume flow. Nevertheless, changes in the emitted sound power, e.g. due to placing the orifice close to a reflecting boundary, are reflected by changes in the volume flow measured by the two microphones.

These findings lead to the decision to use the fan-type aerodynamic sound sources in narrow frequency bands and to develop a calibration procedure for this type of source.

The sound power level of the transfer standard is determined from the sound power level of the primary sound power standard  $L_{W,PS}$ , and the sound pressure levels on enveloping surfaces induced by the primary and the transfer sources  $L_{p,PS}$  and  $L_{p,cal}$  according to



$$L_{W,TS,cal} = L_{W,PS} + L_{p,TS,cal} - L_{p,PS} - 101g \frac{B_{TS,cal}}{B_{PS}} dB + 51g \frac{T_{TS,cal}}{T_{PS}} dB - L_{Hanning}.$$
 (1)

The sound pressure levels are in this context measured by the scanning apparatus. The influence of data analysis is considered by the term *L*<sub>Hanning</sub>. The background of this correction is that the primary source is excited with a fixed phase multisine signal which exactly matches the time window of the analysis. Therefore, a uniform window is applied for the FFT analysis for the vibration measurement and for the sound pressure measurement. From the former, the sound power level is calculated in FFT bands, from the latter the averaged surface sound pressure level. For the measurement of the transfer standard, the analysis window can not be matched to the signal due to its broadband nature. Thus, a Hanning-window is applied. For a white noise, the Hanning window adds 1.78 dB to the total level and also to the individual frequency lines due to the existence of sidelobes. The correction was experimentally determined to be

$$L_{\text{Hanning}} = 1.78 \text{ dB} \,. \tag{2}$$

The uncertainty of this correction is considered to be negligible in the context of this report. The calibration is performed in PTBs hemianechoic room. It is to be noted here, that the sound power level of the primary source is calculated from the discretised Rayleigh integral for the static pressure and temperature which prevail at the calibration of the transfer standard. The sound pressure measurements for the primary source were performed at static pressure  $B_{PS}$  and temperature  $T_{PS}$  whereas the transfer source was measured at  $B_{TS,cal}$ . The uncertainty of the transfer standard sound power level at calibration conditions is

$$u^{2}(L_{W,TS,cal}) = u^{2}(L_{W,PS}) + u^{2}(L_{p,TS,cal} - L_{p,PS}) + \left[\frac{10 \text{ dB}}{\ln 10} \frac{B_{PS}}{B_{TS,cal}} u\left(\frac{B_{TS,cal}}{B_{PS}}\right)\right]^{2} + \left[\frac{5 \text{ dB}}{\ln 10} \frac{T_{PS}}{T_{TS,cal}} u\left(\frac{T_{TS,cal}}{T_{PS}}\right)\right]^{2}.$$
 (3)

The ratio of static pressures and temperatures for laboratory measurements at the same location is in the range

$$\frac{B_{\rm TS,cal}}{B_{\rm PS}} = 0.94...1.06, \quad \frac{T_{\rm TS,cal}}{T_{\rm PS}} = 0.96...1.04$$
(4)

and the uncertainty for the measurement of both ratios is estimated to be 0.1 % since measurements are performed with the same instruments. The corresponding uncertainty contributions are thus smaller than 0.0046 dB.

The uncertainty of the sound pressure level difference measured on the enveloping surface depends on several major aspects. These are the temporal stabilities of both sources, the data analysis and the reflections in the room including those from the scanning apparatus. The latter depends on the radius chosen. Therefore, radii of 1.45 m, 1.70 m and 2.00 m were used. The measurement of the sound pressure level of the primary source was performed 4 times and the measurement of the transfer standard once for each radius. From these results, 12 different sound pressure level differences were calculated (Figure 11, Figure 12). Below a frequency of 100 Hz, systematic deviations occur which are caused by nearfield effects and remaining room influences. Thus, the uncertainty of the sound pressure level difference is expressed by the sum of a statistical effect, expressed as the standard deviation of all 12 measured differences and systematic effects between the mean value for a given radius and the mean value for all radii

$$u^{2}(L_{p,\text{TS,cal}} - L_{p,\text{PS}}) = \sigma^{2}(L_{p,\text{TS,cal}} - L_{p,\text{PS}}) + \sum_{i=1}^{3} \left[ (L_{p,\text{TS,cal}} - L_{p,\text{PS}})_{r,i} - (L_{p,\text{TS,cal}} - L_{p,\text{PS}})^{r} \right]^{2}.$$
 (5)

The uncertainty of the sound power level of the transfer standard at calibration conditions turns out to be dominated by the uncertainty of the sound pressure level difference (Figure 13). The influence of static pressure and temperature is negligible. The combined uncertainty is about 0.25 dB in the central frequency region. It increases slightly towards larger frequencies. At low frequencies, the uncertainty reaches very large values of several dB. In this range, further research could decrease the uncertainty considerably.

For the calculation of the sound power level of the transfer standard at calibration conditions, the mean sound pressure level difference is used, i. e. the average over all 12 sound pressure level differences.





Figure 11 – Difference of sound pressure levels produced by the transfer standard and the primary standard measured on hemispherical measurement surfaces at different distances r in one-third octave bands



Figure 12 – Difference of sound pressure levels produced by the transfer standard and the primary standard measured on hemispherical measurement surfaces at different distances r in FFT bands





Figure 13 – Uncertainty budget for the calibration of a transfer standard according to eq. (3) in one-third octave bands



Figure 14 – Uncertainty budget for the calibration of a transfer standard according to eq. (3) in FFT bands

The main goal of developing calibration methods for non-calculable sound sources has been achieved. This holds for broadband and tonal sources, whereby the latter have been approximated by a narrowband calibration of broadband sources.

## 3.4 Applications in machinery noise

Sound power measurements are performed in setups which may be in the field or in laboratories. The main features of such a setup are the acoustic environment, i.e. (approximated) free or diffuse fields, the exact choice of microphone positions on an enveloping surface or in a diffuse field and the measurement device consisting of microphones, cables and analyser. The idea is now to qualify such a complete setup by injecting a known amount of sound power into it. The result of the qualification procedure is the constant of proportionality between sound power level and sound pressure level for this particular setup. It is assumed that this is identical for different sound sources.

Starting point is the determination of the known sound power. For the aerodynamic sound sources, the influence of temperature and rotational speed on the sound power output has been measured within the project. The influence of barometric pressure is sufficiently known. So, from the sound power level of the



source under calibration conditions (temperature, rotational speed, barometric pressure), the sound power level under in-situ conditions and its uncertainty is to be calculated.

The next step is then the application of the usual measurement procedure in the setup to be qualified using the transfer source. This was performed in approximated free and diffuse fields within the project.

For the (approximated) diffuse field, a complete sound power determination was performed, i.e. the reverberation times were included to measure the sound power level. This was compared to the calculated in-situ sound power level. At high frequencies (appr. 1.6 kHz) the in-situ sound power as determined by calibration of the transfer standard against a primary sound power standard shows discrepant results compared to the sound power determined by the diffuse field method. In this range, the primary sound power sources used seem to have potential for improvements. At medium frequencies (appr. 100 Hz to 1.6 kHz), both results agree sufficiently well. At low frequencies (below 100 Hz), some results indicate that the free-field sound power of the transfer standard is larger than the sound power level determined in the rooms with approximated diffuse fields. Of course, the diffusity of the field is very poor in this frequency range. Nevertheless, it is interesting to notice that for other results the opposite is observed. Future investigations must show whether this difference is a part of the measurement uncertainty or whether the sound power level itself changes.

For the (approximated) free fields, the result of the qualification procedure is the constant of proportionality between sound power level and sound pressure level for this particular setup. So, the procedure has been applied to the different setups and the constant of proportionality was determined including its uncertainty.

In a next step, realistic small sound sources (vacuum cleaner, compressor, angle grinder, ...) were tested in the qualified environments. They are denoted as devices under test – DUT. Whether the traceability concept really improves the current situation was investigated by the difference of sound pressure levels

$$\Delta L_p = L_{p,\text{DUT}} - L_{p,\text{TS}} \,. \tag{6}$$

whereby sound pressure levels are measured either on an enveloping surface or randomly distributed in a volume. A constant sound pressure level difference for one particular device under test indicates that the major assumption for the traceability concept holds.

The very promising results are shown in Figure 15. It is clearly seen that the sound pressure level difference can be considered to be suffuciently constant. In particular, there is no systematic shift observed between sound pressure level differences in free or diffuse fields. Observed deviations at low frequencies can partly be attributed to a special test room where a floating floor was excited by some of the tested devices. Some other tested sources did not have a sufficient stability in time, especially the tapping machine which was mounted on a steel plate and the grinding machine.

The standard deviations of these sound pressure level differences are used as an indicator for the uncertainty of the final sound power level. For the stable source, it is about one to two dB at frequencies between 100 Hz and 10 kHz. Towards lower frequencies, it increases considerably.





Figure 15 Sound pressure level differences of different sources in different environemnts

A further main objective for the application in machinery noise was the analysis of uncertainties of sound power determinations in practice. Within the project, two major aspects to this were investigated. These are different directivities and a different spectral content of the device under test and the transfer standard.



For the influence of the directivity, the worst case was considered. This is a free-field situation since room reflections decrease the directivity of a source. Starting point for the analysis was the sound field of an aerodynamic transfer standard measured in PTBs anechoic room by the scanning apparatus. The distribution of about 2000 sound pressure levels was used as a reference. Then, a sound field of a source under test with a certain maximum directivity index was randomly chosen. By applying Monte-Carlo-simulations it was calculated what the difference between using all about 2000 measurement points and a realistic number of measurement positions is and what the standard uncertainty due to the undersampling is. Maximum directivity indices of the device under test covered a range from 0 to 10 dB. It turned out that the standard uncertainty decreases with the number of microphones and increases with the maximum directivity index. It is between 0.8 and 1.3 dB for 10 microphone positions and between 0.6 and 0.9 dB for 20 microphone positions. This is a very interesting result since it gives clear hints on the required number of measurement positions.

The influence of the spectral content was investigated by assuming that the substitution method for sound power determination is once applied to the one-third octave band levels and once to the A-weighted levels directly. A-weighted levels obtained by the two methods were finally compared where the calculation from the band levels is considered to be correct. To simulate different rooms, a frequency dependent room correction factor of about 0 dB (free field), about 7 dB (partly free or partly diffuse field) and about 12 dB (reverberant field) was chosen. Different spectral shapes of the device under test were assumed including tonal sources and broadband sources with different spectral slopes. Monte Carlo simulations were then performed as to whether different methods for the determination of the A-weighted level lead to different results. It turned out that the direct measurement of A-weighted levels is appropriate in free field, since deviations are less than 0.2 dB and standard deviations are in the same order of magnitude. For more reflective environments, the direct determination of A-weighted levels can not be recommended. Systematic differences between both methods and standard deviations are up to several dB. So, the more reflecting the room is the less accurate the direct measurement of A-weighted levels becomes.

A major issue in practical sound power determination is the consideration of large sources and the effort associated with sound power determination. Within a researcher excellence grant attached to this project, an excessive measurement program was performed to investigate how existing sound power standards could be improved in this respect. For this, a transfer standard, a small compressor and a model machine have been measured in very different environments according to different standardised procedures. An in-depth analysis of the measured values revealed that systematic differences between measurement methods exist. The introduction of traceability can be considered to be a promising approach to reduce these effects.

So, from the three aims in the application in machinery noise, two have been reached so far. The third, the development of an intensity substitution method is still in the process of data analysis. Measurements have been performed with different realistic sources in several different environments. It is expected to finalise this work by the end of October 2016.

#### 3.5 Summary

- Primary sound power sources for the realisation of the unit watt in airborne sound have been developed, installed and tested at four NMIs. These devices are the first of their kind in the world. The devices work well in a limited frequency range which is different for each NMI. In principle, these devices enable a calibration of sound power transfer standards.
- A major finding of the project is that the sound power emitted by a source generally depends on the outer sound field. Only under certain circumstances can the sound power be considered to be a descriptor of the source only. For sources in rooms, these circumstances are a sufficiently large bandwidth with a sufficient modal overlap and/or non-compact sources which is equivalent to high frequencies. This finding leads to the proposal to characterise sound sources by their free-field sound power level.
- It is demonstrated that the free-field sound power level can be determined by ensuring traceability of measured sound power levels to the free-field sound power level of the primary sound power sources. This can be performed by the substitution method using sound pressure in approximated free or diffuse sound fields.



## 4 Actual and potential impact

#### Dissemination

Altogether 30 presentations on the project were given, 14 of them at leading international conferences. 23 proceedings have been published and two peer-reviewed papers are in preparation, one on the concept of characterising sound sources by a sound power level including the question of traceability and one on the use of aerodynamic reference sound sources as transfer standards for the quantity sound power. Two more peer-reviewed papers are planned about the primary realisation of the unit watt and about the numerical models describing the primary sound source.

A project workshop was held as a structured session at INTER-NOISE 2016 a leading international conference to disseminate the results to the stakeholders from industry, authorities and testing institutes. The standardisation committees ISO/TC 43 Acoustics SC 1 (Noise) and ISO/TC 188/ WG 28 (Measurement of airborne noise) were also at that conference and members were able to take part.

#### Impact on standards

The project has contributed presentations to the committees ISO/TC 43/SC 1 and ISO/TC 188/WG 28, AFNOR S30B (Acoustique, sources fixes, mesurage et déclaration du bruit) and NA 001-01-04 AA "Geräuschemission von Maschinen und Anlagen, Messung, Minderung, Datensammlung" (German standardisation committee on sound emission of machinery).

The development of a primary sound power standard and to derive secondary (transfer) standards has been discussed in the standardisation community, particularly with ISO/TC 43 SC 2, where power based methods for source characterisation have been implemented for structure-borne sound sources recently.

Future work also includes a new international standard for the primary realisation of the unit watt and proposed changes to the existing ISO 6926 on the calibration of reference sound sources, both of which will include results from this project. Furthermore, the results of the project will be considered in future revisions of the ISO 3740 series of standards covering the determination of sound power levels of noise sources.

#### Actual impact

A core group of European NMIs was established which are willing to develop a metrological system for the quantity sound power. A supplementary comparison within TC-AUV (the Technical Committee for Acoustics, Ultrasound and Vibration in EURAMET) is the next step. This comparison within TCAUV will be based on the primary sound power sources and calibration techniques developed in the project.

#### Potential impact

The project has led to a new level of understanding about sound power within the acoustic community. Previously, sound power was considered as a unique quantity describing the ability of a source to emit sound, but it is now clear that the sound power emitted by a source depends on the surrounding sound field. The assumption that the sound field does not influence the emitted sound power holds for broadband sources above 100 Hz. But for tonal frequencies below 100 Hz, this assumption is not true. This is a complete change in philosophy in sound power metrology and means that sound power levels at frequencies below 100 Hz can now be accurately determined in the future. This is particularly important as it demonstrates that the discrepancies currently observed between different measurement methods are not caused by systematic deviations between the methods, but by changes in the measured quantity itself.

In a wider perspective, the project results will be the starting point for a change of philosophy for the experimental determination of those quantities in applied acoustics which are directly linked to sound power. These include sound insulation, sound absorption or impact noise levels. This will have major consequences for sound emission and building acoustics as major quantities in building acoustics are sound powers or sound power ratios.



## 5 Website address and contact details

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## 6 List of publications

- [1]. Wittstock, V., Schmelzer, M.; Bethke, C.: Establishing traceability for the quantity sound power, Internoise 2013, Austria, September 2013
- [2]. Brezas, S., Wittstock, V.: Properties of aerodynamic reference sound sources, DAGA 2014; Germany, March 2014
- [3]. Völkel, K., Schmelzer, M., Wittstock, V.: Analytical and Numerical Investigation of the Sound Power Emission of a Vibrating Baffled Piston Into a Hemi-Anechoic Room, DAGA 2014, March 2014, Germany, <u>http://2014.daga-tagung.de/de/</u>
- [4]. Brezas, S., Wittstock, V.: Detailed study towards the dissemination of the unit watt in airborne sound, FORUM ACUSTICUM, September 2014, Poland, The homepage is no longer available.
- [5]. Völkel, K., Bethke, C., Brezas, S., Wittstock, V.: First results in the realization of the unit watt in airborne sound, Internoise 2014, November 2014, Australia, <u>http://internoise2014.acoustics.asn.au/</u>
- [6]. Kurtz, P.: Is the sound power level of a source unambiguous ?, Internoise 2014, November 2014, Germany, <u>http://internoise2014.acoustics.asn.au/</u>
- [7]. Schmelzer, M.: Zur Schallleistung als Quellgröße, DAGA 2015, March 2015, Germany, http://www.daga2015.de/de/
- [8]. Brezas, S., Wittstock, V.: Factors that affect the sound power emitted by reference sound sources, German national congress on acoustics DAGA 2015, Nürnberg, ISBN 978-3-939296-08-9
- [9]. Brezas, S., Wittstock, V.: Study on the Dissemination of unit Watt in airborne sound, Internoise 2015, August 2015, United States, <u>http://internoise2015.com/</u>Guglielmone, C., Corallo, M.: II campione di potenza sonora dell'INRiM, 42° National Congress of Associazione Italiana di Acustica, Florence July 17
- [10]. Arendt, I., Berger, A.: Systematische Fehler bei der Anwendung verschiedener Verfahren zur Ermittlung des Schallleistungspegels, DAGA 2015, March 2015, Germany, <u>http://www.daga2015.de/de/</u>
- [11]. Kurtz, P., Arendt, I.: Airborne sound power level measurements revisited, Internoise 2015, August 2015, United States, <u>http://internoise2015.com/</u>
- [12]. Kurtz, P., Arendt, I.: Investigations for determining the sound power level by applying different measurement setups according to ISO 3744, Internoise 2015, August 2015, United States, <u>http://internoise2015.com/</u>
- [13]. Volker Wittstock and Claudio Guglielmone: Introducing the concept of traceability into sound power measurements, Internoise 2016, Hamburg, Germany, August 2016, Germany, <u>http://www.internoise2016.org/</u>
- [14]. Cafer Kirbas, Håkan Andersson, Claudio Guglielmone, Volker Wittstock and Eyup Bilgic: Primary Sound Power Sources for the Realisation of the Unit Watt in Airborne Sound, Internoise 2016, Hamburg, Germany, August 2016 Germany, <u>http://www.internoise2016.org/</u>
- [15]. Patrick Cellard, Håkan Andersson, Spyros Brezas and Volker Wittstock: Automatic sound field sampling mechanisms to disseminate the unit watt in airborne sound, Internoise 2016, Hamburg, Germany, August 2016, <u>http://www.internoise2016.org/</u>



- [16]. Heinrich Bietz, Volker Wittstock and Spyros Brezas: Investigations on the Suitability of an electroacoustic Sound Source as secondary Sound Power Standard, Internoise 2016, Hamburg, Germany August 2016, <u>http://www.internoise2016.org/</u>
- [17]. Håkan Andersson and Volker Wittstock: Traceable sound power measurements in essentially diffuse or free fields, Internoise 2016, Hamburg, Germany, August 2016, <u>http://www.internoise2016.org/</u>
- [18]. Katharina Voelkel and Volker Wittstock: Influence of Directivity and Spectral Shape on the Measured Sound Power Level, Internoise 2016, Hamburg, Germany, August 2016http://www.internoise2016.org/
- [19]. Claudio Guglielmone, Volker Wittstock, Cafer Kirbas and Håkan Andersson: Main achievements of the EMRP sound power project and future prospects, Internoise 2016, Hamburg, Germany, August 2016, <u>http://www.internoise2016.org/</u>
- [20]. Renzo Arina and Katharina Völkel: Numerical Modelling of the Primary Source in a Hemi-Anechoic Room, Internoise 2016, Hamburg, Germany, August 2016, <u>http://www.internoise2016.org/</u>
- [21]. Spyros Brezas, Patrick Cellard, Håkan Andersson, Claudio Guglielmone and Cafer Kirbas: Dissemination of the unit Watt in airborne sound: aerodynamic reference sound sources as transfer standards, Internoise 2016, Hamburg, Germany, August 2016, <u>http://www.internoise2016.org/</u>
- [22]. Ilka Arendt and Patrick Kurtz: Reasons justifying a revision of the existing sound power measurement standards, Internoise 2016, Hamburg, Germany, August 2016, <u>http://www.internoise2016.org/</u>