Primary sound power sources for the realisation of the unit watt in airborne sound

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ABSTRACT
At present, airborne sound power is not a directly measurable quantity. It is calculated from sound pressure measurements performed in special environments, e.g. free or diffuse fields or from sound intensity measurements using 2-microphone probes. All the different methods are lacking traceability and transparent uncertainty budgets. These deficiencies are finally based on the lack of a primary standard for sound power as the metrological basis. In the joint research project funded by the European Metrology Research Program, primary sound power standards were established on the base of the Rayleigh Integral Method where the sound power is calculated from measured velocities on a baffled vibrating body. Different reference sound power sources were designed in different Institutes. The construction of the primary sources was mainly focused on the piston; its material, shape and friction during its movement. Primary sound power sources were installed in hemi anechoic and reverberant environments, and characterisation measurements were performed to see the effect of different environments on the sound power output. Comparison measurements were performed to compare the new and present methods for the primary sound power source.

Keywords: Sound Power, Primary Sound Power Source, Rayleigh’s Integral

1. INTRODUCTION

Sound power is the only parameter which measures and shows the capability for the generation of sound by sources. It is also a correct metric for reporting noise data for products which can be household appliances like refrigerators, vacuum cleaners etc. Products producing noises at high levels have negative effect for the health and they threaten human health in daily life. Because of this, EU has taken precautions with its directives to protect people from the products having high sound power levels. Many research has been done by manufacturers to reduce the sound power of their products under the permitted levels by EU directives and to provide more comfortable products to their customers. It is important to determine the sound power level of the products precisely from a metrological point of view. More precise measurements mean safer products or a better protection of people from noise. Therefore it is important and necessary to determine the sound power of the products with a small uncertainty.

In metrology, primary standards are used for the establishment of the quantities, for instance, primary standard microphones (1) are used for the establishment of the unit pascal for sound in air (2) and the traceability for secondary or working standard microphones is taken from the primary standard for acoustical measurements. However this is not the case for sound power in air. At present, sound

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power is determined from sound pressure and sound intensity. There are different standards (3,4,5) for the
determination of sound power levels from sound pressure measurements. The main differentiator
among these standards is the type of the environment in which the measurements are made. Free field,
reverberant field and in-situ environments are used for the measurements. Sound power is calculated
from averaged sound pressure measurements over an enveloping surface covering the sound source.
Sound power determination using sound intensity involves integrating the normal component of the
intensity over the surface enclosing the source. There are three international standards available
(6,7,8) for this type of sound power determination. The accuracy of the determination of sound power
changes for different measurement methods and this causes a large uncertainty in the determination of
sound power levels of sound sources. In consequence, this large uncertainty complicates resolving
discrepancies among measurement results and legal requirements. In order to improve this situation, it
is inevitable to establish a primary sound power standard for sound power as for other quantities in
metrology.

The purpose of the present study is to establish traceability for the unit watt in airborne sound from
a primary standard which is based on a vibrating baffled solid body. The investigation was performed
within a joint research project funded by the European Metrology Research Program (EMRP JRP
SIB56). The sound power output of this device is determined from the vibration velocity of the body’s
surface and several additional quantities like static pressure and temperature. In particular,
measurements in the airborne sound field as well as restricting assumptions on the nature of the sound
field are not required. The uncertainty of these primary sound power sources is aimed to be below 1 dB.
For these purposes, four participating institutes have designed and constructed their primary sources.
The vibrating piston is the main component for producing the sound field, and then focused research
has been done on the piston to find optimum parameters. The sound power level of primary sources
was calculated by velocity measurements on the piston from Rayleigh’s Integral. Some
calibration measurements with respect to the near field and the linearity were done for the
primary sources. The results are presented and discussed in this contribution.

2. THEORY OF A VIBRATING CIRCULAR BAFFLE

The setup for primary reference sources consists of a shaker and a piston embedded into the floor of
a hemi anechoic environment. A laser scanning vibrometer is mounted in a position that it is directly
across the piston surface. Thus, the vibrometer is able to measure the velocity along the surface of the
piston. The setup is shown in Figure 1.

![Figure 1- Setup for the primary reference source](image)

The vibration of the piston causes a displacement of the air volume at the interface. The total sound
power generated by the piston is represented by a summation (9);

\[ P = \sum_{i=1}^{N} \frac{\rho c}{2\pi} k^2 \nu_i^2 S_i + 2 \sum_{i=1}^{N} \sum_{i'=i+1}^{N} \frac{\rho c}{2\pi} k^2 \nu_i \nu_i' S_i S_{i'} \frac{\sin(k d_{ij})}{k d_{ij}} \cos(\varphi_i - \varphi_{i'}) \]  

(1)

With the number of surface elements \( N \), the density of air \( \rho \), the speed of sound in air \( c \), the wave
number \(k\), the velocity of the \(i\)-th element \(v_i\), the surface of the \(i\)-th element \(S_i\), the distance between the \(i\)-th and the \(l\)-th element \(d_{il}\) and the phases of the vibrations of the \(i\)-th and the \(l\)-th element \(\varphi_i\) and \(\varphi_l\). This equation is known as the discretised Rayleigh’s Integral.

Rayleigh’s Integral can be applied to a rigid plane circular piston of radius \(a\) that is surrounded by an in-plane infinite rigid baffle. The ability of the piston to radiate sound power in air is given by:

\[
P = \pi \rho c a^2 V^2 \left(1 - \frac{J_1(2ka)}{ka}\right)
\]

\(J_1\) is the Bessel Function, \(a\) is the radius of the piston. Power is related to the velocity of the piston, the radius of the piston and environmental factors indirectly. Therefore by using this equation, the sound power of a vibrating baffled piston is calculated.

3. PRIMARY SOUND POWER SOURCES

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 Equation 1 or 2 from measured velocity, diameter 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.

3.1 The Investigation of the influence of major design parameters

PTB and INRiM developed a lumped parameter model comprising at least 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 (10). The results are given as a summary,

- 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 acrylic glass (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.

3.2 Construction of Sound Power Sources

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 2 for different institutes.
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, and it is made of aluminium. A vibration exciter was used in the source. The primary sound source was mounted in the floor of the hemi anechoic or 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 as shown in Figure 2 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 cone-shaped. The baffle 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 teflon coated. 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 plate type 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.
3.3 The Investigation on the Piston

A piston connected to an exciter was designed as a baffled vibrating circular solid body in the primary sound power sources. Since the goal is to have a flat frequency spectrum in a wide frequency range for the primary source, a good and optimum design is necessary. Two types of piston designs, planar and cone shaped were selected by institutes in the construction of sources as shown in Figure 3.

TÜBİTAK UME used the planar piston shape in the primary sound power source shown in Figure 3 and in this investigation. In order to examine the behaviour of the piston under vibration and to find the optimum design parameters for the piston, an investigation has been done by TÜBİTAK UME. The main focused parameters in the investigation were sizes and material of the piston. To evaluate these effects, the pistons with different diameters (60 mm, 50 mm, 30 mm, 28 mm, 25 mm, 22 mm and 15 mm) and materials (aluminium, polyamid and teflon) were manufactured. The results are given in Figure 4.

Figure 4 – a) Velocity on the piston having 50 mm diameter for different materials, b) Velocity on the piston made of aluminium material for different piston diameters

Figure 4a shows the material effect of the piston on the vibration velocity. It is obviously shown that there are peaks at certain frequencies for each material. To be able to understand the reason of these peaks, a theoretical modal analysis (11) of the same aluminium piston with 50 mm diameter was conducted. It proved that that the peaks in the plots of sound power level are due to the longitudinal resonances of the materials. The vibration mode and resonance frequencies obtained from modal analyses are given in Table 1. Since aluminium had the highest resonance frequency in the graph, it was determined the most suitable material among the materials.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Resonance Frequency, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bar Bending</td>
</tr>
<tr>
<td>2</td>
<td>Torsional</td>
</tr>
<tr>
<td>3</td>
<td>Bar Bending</td>
</tr>
<tr>
<td>4</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>5</td>
<td>Plate Bending</td>
</tr>
<tr>
<td>6</td>
<td>Plate Drum Mode</td>
</tr>
</tbody>
</table>

From Figure 4b, the effect of diameter on vibration velocity is seen. As it is expected, while diameter decreases, the resonance frequency of the material increases. However, in this case, a decrease in sound power occurs and this is an undesirable result. After evaluating the results, the optimum diameter was selected as 50 mm.
4. SOUND POWER LEVEL OF PRIMARY SOUND POWER SOURCES

4.1 Vibration Velocity Measurement on the Piston Surfaces

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 6.

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 and averaged. Measurement results are given in Figure 7 for TÜBİTAK UME, and no deviations were observed in velocity values among the points, it can be easily said that piston was moving as a rigid plate at measured frequencies.
The results of the vibration velocity measurements on the piston surface are plotted in Figure 8 for different Institutes. It is seen that the vibration velocity decreases with increasing frequency and, there is a resonance peak in measured velocity spectra. As it is explained in 3.3, these peaks are caused from the resonances of the pistons.
4.2 Calculation of Sound Power Level of Primary Sound Power Sources

By using the measured vibration velocity values, the sound power levels, $L_{w\text{-Rayleigh}}$, of primary sources were calculated according to Rayleigh’s Integral in Equation 1 (PTB) or 2 (other institutes). The calculated $L_{w\text{-Rayleigh}}$ of primary sound sources are shown in Figure 9 for the institutes.

![Sound power levels of primary sources](image)

Figure 9 - Sound power levels emitted by primary sources calculated from vibration velocities according to Rayleigh’s Integral.

For PTB’s primary sound source, there are two spectra, in 1/3 octave bands and in FFT bands. The source emits a relatively flat spectrum with some resonance peaks at higher frequencies starting at about 3 kHz. For TÜBİTAK UME, it has a flat frequency spectrum up to 3 kHz and there is a peak caused from the resonance of the pistons at about 4 kHz. INRiM’s last prototype has an axial resonance around 3 kHz for the larger source (50 mm diameter) and 8 kHz for the small 25 mm source. Low friction of piston materials ends up in undamped resonance (high and narrow peak), that can be reduced by increasing the damping in the voice coil driver. For SP’s primary sound source the spectrum of the driving signal was adjusted to yield an approximately flat 1/3 octave band sound power spectrum up to 10 kHz.

4.3 Linearity of Primary Sources

PTB and TÜBİTAK UME tested the linearity of their primary reference sources. At TÜBİTAK UME, the voltages at the input terminal of the exciter were selected as 0.5 V, 1.0 V, 1.5 V, 2.0 V and 2.5 V. In the primary source, the piston having a diameter of 60 mm was used. A sine signal was applied at every 1/3 octave band center frequencies from 20 Hz to 20 kHz. The desired voltage level was adjusted at each frequency by observing the monitor of the multimeter. Vibration velocity measurements were performed at every 1/3 octave band center frequency at 25 different points on the piston surface. The
measured velocities were averaged over all 25 points. By using the vibration velocity values, the sound power levels of the primary source were calculated according to Equation 2. Overall, the calculated sound power levels are plotted in Figure 10 for TÜBİTAK UME. At PTB, the linearity was tested by voltage versus acceleration and the results are plotted in Figure 10.

![Figure 10- Linearity test results of the primary source of TÜBİTAK UME and PTB](image)

The linearity of the primary sound power source of TÜBİTAK UME can be seen from Figure 10. By increasing input voltages from 0.5 to 2.5 V, the sound power levels increase. Doubling the input voltage causes 6 dB more sound power level which shows the linear relation between input voltage and emitted sound power. Another comment from Figure 10 is that the changes in the levels for velocity and sound power are constant up to 8 kHz. Above this frequency, there is no change in sound power.

The linearity of PTB's source was tested by measuring the piston acceleration by an accelerometer and increasing the input voltage into the shaker in 5 dB steps. The results shown in Figure 10 relate to an earlier version of the primary source. The voltage range was 40 dB and the same range is observed in the entire frequency range for the acceleration.

5. DETERMINATION OF SOUND POWER LEVEL FROM SOUND PRESSURE LEVEL MEASUREMENTS

5.1 Measurements in Hemianechoic Room.

Sound pressure level measurements were performed in accordance with ISO 3745 and ISO 6926 (12) for hemianechoic chambers. A hemispherical measurement surface was set up having a radius of 2.0 m enclosing the primary source. Measurements were conducted at 1/3 octave or FFT bands with center frequencies in the frequency range from 20 Hz to 20 kHz. Each participating institute determined the sound power level ($L_{w-Hemianechoic}$) of their primary sources. TÜBİTAK UME and INRiM used a 20 microphone array. SP and PTB used their scanning mechanisms which are given in Figure 11.

![Figure 11- Mechanism for sound pressure level measurements (12)](image)

The measurement results are given in Figure 12 for the determination of $L_{w-Hemianechoic}$ of primary sound sources at TÜBİTAK UME, PTB, INRiM and SP.
Sound power spectra obtained from two methods are given comparatively for TÜBİTAK UME in Figure 12. It is seen there is a good agreement between two methods above 200 Hz. Below 200 Hz, large deviations occur in sound power levels between the methods. $L_{w-Hemi\text{ Anechoic}}$ of TÜBİTAK UMEs primary source shows an unexpected behavior at low frequencies. Below 100 Hz, the increase in $L_{w-Hemi\text{ Anechoic}}$ is meaningless. The reason for this is considered to be the covering of the floor with a lightweight structure. The floor generates noise at low frequencies, and this causes an increase in the sound power level of the primary source. In Figure 12, the results of PTB for the two methods are shown. The results are overall in good agreement. There are major deviations below 100 Hz and above 2 kHz. Deviations at low frequencies are considered to be caused by room properties since the wedges are designed for a cut-on frequency of 90 Hz. Above 2 kHz, the reflections from the scanning apparatus are expected to cause the deviations. Nevertheless, they are observed in this absolute comparison. The later use of the measurement setup is for substitution measurements where the reflections will cancel to a large extent. $L_{w-Hemi\text{ Anechoic}}$ of INRiMs primary reference source, made on 1 m radius hemisphere, show a good agreement except around 200 to 300 Hz for unwanted radiation from the surrounding plate (measurements have been made before establishing the multi layer mounting plate). The measurements at SP, given in 1/3 octave bands in Figure 12, shows generally good agreement. The deviations at the highest frequencies is considered to be the result of the modes of the vibrating piston. The deviations of about 1 dB in the frequency range 1 to 2 kHz is not yet explained.

At TÜBİTAK UME, measurements were performed on hemispherical surfaces for different radii of 2.5 m, 2.0 m, 1.5 m, 1.0 m, 0.75 m and 0.5 m to study the effect of source distance on the sound power determination. In Figure 13, deviations from the measurement results performed at 2 m radius is shown. Below 100 Hz, large deviations in sound power levels are observed.
5.2 Measurements in Reverberation Rooms

The primary source was installed in a hole in the floor of the reverberation rooms at TÜBİTAK UME and at PTB. After that, measurements were performed in accordance with ISO 6926 (13). Sound pressure level measurements were performed at six different random microphone positions in the room. The reverberation time of the room was measured between 50 Hz and 10 kHz (TÜBİTAK UME) or 20 kHz (PTB). By using all these data, the sound power level ($L_{w\text{-Reverberation}}$) of the primary source was calculated. The results are shown for TÜBİTAK UME and PTB. In the graphs, there is a comparison to see the differences among the methods.

In Figure 14, for TÜBİTAK UMEs primary source, a good agreement among the results between 200 Hz and 8 kHz is observed. Below 200 Hz and above 8 kHz, larger differences occur between Rayleigh’s Integral and sound pressure level measurement methods. PTBs results show an excellent agreement at one-third octave bands between 125 Hz and 1.6 kHz. Deviations at lower frequencies are caused by insufficiencies of the reverberant or hemianechoic rooms which both have their cut on at about 100 Hz. At higher frequencies, the Rayleigh-integral seems not to deliver a good sound power estimate which may be caused by secondary airborne sound sources.

6. CONCLUSIONS

A new method different from present methods has been proposed to establish the sound power unit watt on the base of a vibrating solid body. In this method, a primary sound power source is needed for the traceability. Therefore, primary sound sources were constructed at different designs and the sound power unit has been realised by these sources.
From the theoretical approach of the Rayleigh integral, it has been concluded that the output sound power level of primary sources is affected by the main parameters; piston design (size, shape, material and mass), exciter and environmental parameters. The piston has been the most important element affecting the sound power of primary sources. It appeared that it caused friction problems in the primary reference source of PTB and some modifications were done to remove this problem. INRiM reported friction problems for their source as well. Other investigation by TÜBİTAK UME about the piston design also showed that different materials and different sizes have different modal behaviors resulting in distorted sound power spectra.

The sound power of primary sources was calculated from measured vibration velocities by using Rayleigh’s integral. In addition to this, sound powers of primary sources were determined from sound pressure level measurements in hemi anechoic and reverberation rooms. A comparison was performed to see the difference among the methods. For the different institutes, deviations between the different methods are observed. Nevertheless the major part of the deviations can be explained. Therefore, the results obtained from the new method were supported by present measurement methods.

Some important properties of primary sources were obtained from the measurements like near field effects and linearity. TÜBİTAK UMEs results showed, the radius of the hemisphere should be sufficiently large to get rid of the near field effect.

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