5 Sound Intensity Measurements

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Fig. 5.1 (previous page): A USP (three dimensional pu sound intensity probe) surrounded by a pp sound intensity probe.

5.1 Summary

In general there are two possible configurations to measure sound intensity. A combination of a pressure microphone and a Microflown, the pu probe and a configuration where two pressure microphones are closely spaced, the pp probe.

The pp probe has become a well-known and established method, described in several standards, the pu probe is relatively new and no standards have been written for this probe yet.

The quality of the methods depend on the sound field. The pp method has difficulties with large values of the pressure-intensity index (caused by reflections, diffuse sound fields or extraneous sound sources), but not to high values of the reactivity.

By contrast the pu method is sensitive to high values of the reactivity (caused by sound fields with a high phase shifts, e.g. in the near field of a sound source), but not to large values of the pressure-intensity index. Both limitations can be serious in practical measurements, and one cannot conclude from these considerations that one method is superior to the other.
The size of the probes is different. The pp probe is very much larger than a pu probe. The size of a pp probe is in the order of 10cm and a pu probe can be as small as several millimetres. Small size is essential if the measurement space is small (measurement in small cavities) or the sound source is small (e.g. a hearing aid).

The calibration of a pp probe is easier than the calibration of a pu probe.

The bandwidth of a pu probe is higher (20Hz-20kHz) than the bandwidth of a pp probe. The pp probe can normally be used in a 100Hz-10kHz bandwidth. In most applications this is sufficient.

The self-noise of a pu probe is better than a pp probe. This is only an issue with very low level noise sources.

Unlike the pp method, it is easy to construct a three dimensional broad banded pu sound intensity probe. Such 3D probe only requires 4 measurement channels (the pp method requires 6 channels).

Most of the information in this chapter is based on or copied from the papers [2], [4], the refereed AES paper [1] and the refereed JASA paper [3]. The knowledge that the pu method is not influenced by the pressure-intensity index is a key element for the source-path analysis application.

5.2 Introduction

Sound intensity is useful for measurement of sound power, identification and ranking of sources, visualisation of sound fields, measurement of transmission loss, identification of transmission paths, etc. In the pioneering days in the 1970s and 1980s sound intensity was a hot research topic, but since then it has become a well-known and established method, described in several standards. The conventional measurement technique employs two matched condenser microphones. However, a particle velocity transducer called the ‘Microflown’ and an intensity probe based on this transducer combined with a small pressure microphone have recently become available.

In the general case measurement of sound intensity requires the use of at least two transducers. Sound intensity is traditionally measured with the pp method, which combines two pressure microphones and makes use of a finite-difference approximation to the pressure gradient. The alternative pu method involves combining a pressure transducer with a particle velocity transducer. This chapter examines and compares the pp and pu measurement principles.

Sound intensity is associated with the product of sound pressure and particle velocity and quantifies the amount of sound energy that propagates in a certain direction though a unit area. Sound energy density (E), which is related to the sum of the sound pressure and particle velocity, quantifies how much energy is “stored” in an acoustic wave, sound intensity quantifies how much sound energy is transported. The intensity measurement enables to determine the amount of radiated sound power of a source without the
need for a special acoustic environment (such as a reverberant room or an anechoic room).

First some examples are shown to get a feeling what sound intensity actually is. After this the focus will be on the differences between both probes.

5.3 Sound intensity measurements

Sound intensity measurements are quite complicated to understand so first the concept sound intensity is introduced in this paragraph before the pros and cons of both methods are discussed.

In an experiment two loudspeakers are positioned on one line, with the intensity probe in the middle, see Fig. 5.2. The two loudspeakers are excited by two uncorrelated noise sources. When the excitation strength of the two loudspeakers is equal, the net energy flow (i.e. the sound intensity) should be zero, but both the sound pressure and the particle velocity level are 3dB higher than when only one loudspeaker is excited. The sound pressure, particle velocity and sound energy increases if the second loudspeaker is switched on, and the sound intensity becomes smaller.

![Fig. 5.2: Measurement set-up: two loudspeakers positioned on one line and the sound probe in the middle.](image)

The loudspeakers are excited with uncorrelated noise, where the excitation of loudspeaker 1 is fixed \( s_1 \) and of loudspeaker 2 is variable \( s_2 \). In the figure Fig. 5.3 \( (s_2/s_1)^2 \) is plotted horizontally. The relative intensity is plotted vertically; \( I_0 \) is the measured intensity when loudspeaker 2 is switched off and only loudspeaker 1 is excited.

![Fig. 5.3: Measurement performed in the anechoic room at 125 Hz in a 1/3-octave band. The measurement results should be on a line from (0,1) to (3,-2). The 12mm and the 50mm pp probe have the expected results. The pu probe performs also well, from [1].](image)
The straight line in Fig. 5.3 corresponds to the expected behaviour, i.e. \( I/I_0 \propto (s_2/s_1)^2 \) with \( I=0 \) for \( s_2=s_1 \). Three intensity probes were used: the pu and the traditional pp probes with spacers of 12mm and 50mm.

**Definition of sound intensity**

Sound intensity is the average rate at which sound energy is transmitted through a unit area perpendicular to the specified direction at the point considered.

In a free progressive sound wave the sound intensity equals the sound energy times the speed of sound \((I=cE)\). The speed of sound is the maximum velocity of sound energy to travel.

As can be seen in the example with the two loudspeakers (see Fig. 5.2), the intensity becomes zero if both loudspeakers generate the same amount of noise and thus an equal amount of energy travels in an opposite direction. In contrast to that, the sound pressure level, the particle velocity level and sound energy are not zero in this situation. According to the definitions this may be understood but below the mathematic mechanisms are explained.

In other acoustic environments also situations exist where the energy, pressure and velocity are not zero but the intensity is. In a standing wave tube the amount of intensity that is put in the tube is reflected at the end, and thus an equal amount of energy propagates in the opposite direction. Therefore the sound intensity is zero. In a pure diffuse sound field components of a sound field propagate in all directions. Therefore the sound intensity in a certain area (i.e. the sound power) is zero.

Sound intensity is a vector quantity (it has a magnitude and direction); defined as the time averaged product of the sound pressure (scalar) and the corresponding particle velocity (vector) at the same position.

\[
I = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} p(t)u(t)dt \quad [W/m^2]
\]

(5.1)

If for example the sound pressure is taken \( p(t) = \hat{p}\cos(\omega t) \) and the particle velocity (with a certain phase shift \( \varphi \) compared to the pressure signal) \( u(t) = \hat{u}\cos(\omega t + \varphi) \) Eq. (5.1) can be written as:

\[
I = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} p(t)u(t)dt = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \hat{p}\cos(\omega t)\hat{u}\cos(\omega t + \varphi)dt
\]

\[
= \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \frac{1}{2} \hat{p}\hat{u}\left(\cos\varphi + \cos(2\omega t + \varphi)\right)dt
\]

\[
= \frac{1}{2} \hat{p}\hat{u}\cos\varphi + \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \frac{1}{2} \hat{p}\hat{u}\cos(2\omega t + \varphi)dt = \frac{1}{2} \hat{p}\hat{u}\cos\varphi
\]

(5.2)
As shown in Eq. (5.2) this time averaged intensity is a DC (non-time dependent) value. If both pressure as velocity have a certain frequency, the non-averaged output equals a DC value depending on the phase shift, plus a signal of double frequency. This double frequency part of the equation is time-averaged to zero.

If the intensity of a certain bandwidth has to be determined, first the sound pressure and the particle velocity signal have to be filtered (with a band pass filter of that specific bandwidth) and then multiplied and averaged. The DC result represents the sound intensity of that particular bandwidth. Modern techniques apply FFT methods to determine the intensity.

So apart from the amplitude of sound pressure and particle velocity, the phase between sound pressure and particle velocity contains important information for the sound intensity is determination, see Fig. 5.4.

A quite loud sound has for example 1Pa pressure variation, if the sound wave is relatively far from the source and when no reflections are present, the accompanying particle velocity then is 2.4mm/s. In such case the phase difference between sound pressure and particle velocity of the sound field is zero degrees. The sound intensity is the mean value of the lower left plot of Fig. 5.4. As can be seen, it values 2.3mWm\(^{-2}\).

If the phase shift alters in to 60 degrees, the sound intensity will be half compared to the zero-degrees (free field) situation. If the phase shift is 90 degrees, the sound intensity will be zero and if sound pressure and particle velocity are out of phase (phase shift equals 180 degrees) the sound intensity values -2.3mWm\(^{-2}\). So, even when the amplitude of sound pressure and particle velocity is not changing, the sound intensity can vary strongly.

![Fig. 5.4: Upper plots: sound pressure and particle velocity. Lower plots: instantaneous sound intensity and sound intensity (straight lines) as function of the phase shift between particle velocity and sound pressure.](image-url)
In the example of the two loudspeakers (see Fig. 5.2), the intensity became zero if loudspeaker 2 was turned on with the same volume as loudspeaker 1. Both sound pressure and particle velocity increase 3dB so one could conclude that the phase shift between sound pressure and particle velocity is 90 degrees. After all if \( \hat{p} \neq 0 \) and \( \hat{u} \neq 0 \) and \( I = \frac{1}{2} \hat{p} \hat{u} \cos(\phi) = 0 \) one has to conclude that \( \cos(\phi) = 0 \) and thus \( \phi = \pm 90 \) degrees. This is however not true.

Because both loudspeakers generate uncorrelated noise, the phase shift becomes time dependent and can take all values. For a random varying phase shift between sound pressure and particle velocity Eq. (5.2) alters in:

\[
I = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} p(t)u(t)dt = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \hat{p} \cos(\omega t) \hat{u} \cos(\omega t + \phi(t))dt \\
= \frac{1}{2} \hat{p} \hat{u} \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \cos(\phi(t)) dt = 0
\]

(5.3)

If both loudspeakers would generate the same signal, the phase shift would be constant. The value of the sound pressure would be 6dB higher and the amplitude of the particle velocity would be zero. Again, the intensity is zero.

If both loudspeakers would generate a similar signal but with a certain phase shift, sound energy would be transported and the intensity would not be zero.

In the standing wave tube the sound intensity is also zero. This is because the phase shift between sound pressure and particle velocity is 90 degrees.

In a diffuse sound field the situation is again different. A diffuse sound field can be found in a reverberant room; a large room that has hard sound reflecting walls that are not parallel or perpendicular to each other. In a pure diffuse sound field sound is propagating in all directions with the same magnitude. Similar as in a standing wave tube, in a pure diffuse sound field the sound energy has a value and the intensity is zero: the sound energy is not propagating.

In a diffuse sound field the phase shift is a random value. It takes all values, and when the position or frequency is changed it will change in an unpredictable manner. In a diffuse field the sound pressure level and the particle velocity level do not vary in space, in a standing wave the sound pressure and particle velocity do vary much.

The situation for a diffuse sound field is somewhat similar to the example with the two opposite loudspeakers (see Fig. 5.2) but a little different. Due the reflections in a reverberant room only one loudspeaker can generate a diffuse sound field. At one position and at one frequency the phase is not varying in time. The sound intensity is only zero if Eq. (5.2) is integrated over a certain frequency band and/or area.
Therefore the proper way to use intensity probes is to integrate over a certain frequency band (normally 1/3 or 1/12 octaves) and to integrate over a certain area. If the intensity is integrated over a certain area the result is sound power in Watts.

5.4 Operation principle of sound intensity probes

In this paragraph it is explained how the two possible (pp and pu) intensity probes operate and what properties influence the accuracy of performance.

**pp probe**

The *pp* measurement principle employs two pressure microphones. The particle velocity component in the direction of the axis of the probe is obtained by a finite-difference approximation to the pressure gradient in Euler’s equation of motion (see also chapter 2):

\[
 u(x,t) = -\frac{1}{\rho_0} \int \frac{d}{dx} p(x,t) dt = -\frac{1}{\Delta x \cdot \rho_0} \int p(x + \Delta x,t) - p(x,t) dt
\]

(5.4)

The sound pressure is simply the average of the two pressure signals. The intensity is obtained by:

\[
 \hat{I} = \langle \hat{p} \hat{u} \rangle = \left\langle \frac{p_1(t) + p_2(t)}{2} \int_0 \frac{p_1(\tau) - p_2(\tau)}{\rho \Delta r} d\tau \right\rangle
\]

(5.5)

where the caret \(^\hat{}\) indicates an estimated quantity, \(\langle \rangle\), indicates averaging over time, \(\rho\) is the density of air, and \(\Delta r\) is the microphone separation distance. The most important limitations of this measurement technique are caused by the finite difference approximation, scattering and diffraction, the size of the probe and instrumentation phase mismatch.
Fig. 5.5: A size comparison of a pu-mini and pp sound intensity probe.
The accuracy of the finite-difference approximation obviously depends on the separation distance. For a plane wave of axial incidence the finite difference error can be shown to be:

\[ \frac{\hat{I}_r}{I_r} = \frac{\sin k \Delta r}{k \Delta r} \]  

(5.6)

where \( k = 2\pi f/c \) is the wavenumber and \( I_r \) is the “true” intensity (unaffected by phase mismatch).

It is evident that the effect of scattering and diffraction depends on the geometry of the microphone arrangement. Several configurations are possible, but in the early 1980s it was shown experimentally that the face-to-face configuration with a solid spacer between the two microphones is particularly favourable.

Much later it was discovered that the effect of scattering and diffraction not only tends to counterbalance the finite-difference error but in fact for a certain length of the spacer almost perfectly cancels it under virtually any sound field condition encountered in practice. A practical consequence is
that the upper frequency limit of a sound intensity probe based on two \( \frac{1}{2}'' \) microphones separated by a 12mm spacer in the face-to-face arrangement is about 10kHz, which is about an octave higher than the frequency limit determined by the finite-difference approximation. The combination of \( \frac{1}{2}'' \) microphones and a 12mm spacer is now regarded as optimal, and longer spacers are only used when the focus is exclusively on low frequencies.

Unless the measurement is compensated for phase mismatch the microphones for measurement of sound intensity with the \( pp \) method have to be phase matched extremely well, and state-of-the-art sound intensity microphones are matched to a maximum phase response difference of 0.05\(^\circ\) below 250Hz and a phase difference proportional to the frequency above 250Hz (say, 0.2\(^\circ\) at 1kHz). The latter is a consequence of the fact that phase mismatch in most of the frequency range is caused by differences between the resonance frequencies and the damping of the two microphones.

It can be shown that a small phase mismatch error \( \varphi_{pe} \) gives rise to a bias error that can be approximated by the following expression:

\[
\hat{I}_r \approx I_r - \frac{\varphi_{pe}}{k\Delta r} \frac{p_{rms}^2}{\rho c} = I_r \left( 1 - \frac{\varphi_{pe}}{k\Delta r} \frac{p_{rms}^2}{\rho c} \right) \tag{5.7}
\]

where \( I_r \) is the “true” intensity (unaffected by phase mismatch), \( p_{rms} \) is the rms value of the sound pressure and \( c \) is the speed of sound. This expression shows that the effect of a given phase error is inversely proportional to the frequency and the microphone separation distance and is proportional to the ratio of the mean square sound pressure to the sound intensity. If this ratio is large then even the small phase errors mentioned above will give rise to significant bias errors. Because of phase mismatch it will rarely be possible to make reliable measurements below, say, 80Hz unless a longer spacer than the usual 12-mm spacer is used.

The ratio of the phase error to the product of the frequency and the microphone separation distance can be measured (usually in the form of the so-called “pressure-residual intensity index”) by exposing the two pressure microphones to the same pressure in a small coupler. Modern sound intensity analyzers automatically determine the ratio of the mean square pressure to the intensity during the intensity measurements. Thus one has a clear indication of whether the bias error is serious or not.

Calibration of \( pp \) sound intensity measurement systems involves calibrating the two pressure microphones with a pistonphone in the usual manner and determining the pressure-residual intensity index in a small coupler driven by a wide-band signal as mentioned above.

\textbf{pu probe}

A pu sound intensity measurement system combines two fundamentally different transducers. The sound intensity is simply the time average of the instantaneous product of the pressure and particle velocity signal,
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\[ I_r = \langle pu_r \rangle = \frac{1}{2} \text{Re}\{pu_r^*\} \]  

(5.8)

where the latter expression is based on the complex representation of harmonic variables. Quite apart from the particulars of the Microflown transducer it can be shown that any sound intensity measurement system based on the combination of a pressure microphone and a particle velocity transducer is sensitive to reactive sound fields; if the reactivity (the ratio of the reactive to the active intensity in logarithmic form) takes a high value, as for example in the near field of a source, then even a very small phase mismatch error between the two transducers gives rise to a considerable bias error, as can be seen from the expression:

\[ \hat{I}_r = \text{Re}\{ S_{pu} e^{i\phi_e} \} = I_r \cos \phi_e - J_r, \sin \phi_e = I_r \left( 1 - \frac{J_r}{I_r} \right) = I_r \left( 1 - \phi_e \tan \phi_{\text{field}} \right) \]  

(5.9)

where \( \hat{I}_r \) is the measured intensity, \( S_{pu} \) is the ‘true’ cross spectrum between the sound pressure and the particle velocity, \( \phi_e \) is a small phase error between the measured and the ‘true’ particle velocity, \( I_r \) is the ‘true’ intensity, and \( J_r \) is the ‘true’ reactive intensity. The phase \( \phi_{\text{field}} \) is the phase shift of the sound field. The reactive intensity is given by:

\[ J_r = \frac{1}{2} \text{Im}\{pu_r^*\} \]  

(5.10)

 Whereas the (active) intensity describes the net flow of sound energy the reactive intensity describes the non-propagating part of the energy that is merely flowing back and forth, corresponding to the instantaneous particle velocity being in quadrature with the sound pressure. Many sources have strongly reactive nearfields at low frequencies where they mainly generate evanescent waves. Near such a source the air is essentially moving back and forth as if it were incompressible.

The rightmost approximation of Eq. (5.9) is valid if \( \phi_e << 1 \). If \( J_r >> I_r \), as for instance very near a source, then even a fairly small phase error will give rise to a considerable bias error.

On the other hand it also shows that substantial \( pu \) phase errors can be tolerated if \( J_e << I_e \). For example, even phase mismatch of 35° gives a bias error of less than 1dB under such conditions. In other words, the phase calibration is critical when measurements are carried out under nearfield conditions, but not at all critical if the measurements are carried out in the far field. The “reactivity” (the ratio of the reactive to the active intensity) indicates whether this source of error is of concern or not.

Calibration of \( pu \) sound intensity systems involves exposing the probe to a sound field with a known relation between the pressure and the particle velocity, for example a plane propagating wave, a standing wave tube or a simple spherical wave.

5-12
5.5 The phase error of pp and pu probes

As shown in the previous paragraph the phase matching error causes a measurement error. The pp method is sensitive to large values of the pressure-intensity index, but not to high values of the reactivity. By contrast the pu method is sensitive to high values of the reactivity, but not to large values of the pressure-intensity index. Thus pu intensity measurement systems are potentially less affected by extraneous noise but more affected by reactive near fields than pp intensity measurement systems. Both limitations can be serious in practical measurements, and one cannot conclude from these considerations that one method is superior to the other.

In measurements with pp probes the acceptable pressure-intensity index depends on how well the two microphones are matched, that is, on the 'pressure-residual intensity index' of the probe. With state-of-the-art equipment a pressure-intensity index exceeding 10dB is ‘high’ in most of the frequency range; below 200Hz even an index of 5dB is ‘high’. Such high values of the pressure-intensity index will occur if there is strong background noise from other sources than the one under test, in particular if the measurement takes place in reverberant surroundings (like inside a car or aeroplane). If the pressure-intensity index is unacceptably high possible countermeasures include moving the measurement surface towards the source under test, shielding the extraneous sources with temporary screens, and introducing more absorption in the room.

The pp method is more sensitive for a phase matching errors than a pu method. This is because the phase error of the pp probe is divided by a value $k\Delta r$, see Eq. (5.7). The value of $\Delta r$ is normally 12mm and $k=2\pi f/c$ so the product $k\Delta r$ is frequency dependent and much smaller than 1 for frequencies lower than 1kHz. At 100Hz the value $(k\Delta r)^{-1}$ equals 45 and at 20Hz the value $(k\Delta r)^{-1}$ equals 225.

![Fig. 5.7: Reactivity as function of the phase shift of sound pressure and particle velocity.](image-url)
In measurements with pu probes the acceptable reactivity depends on the accuracy of the phase calibration of the device. A reactivity of more than 5dB is ‘high’, but values of up to 25dB can occur, see paragraph 5.8. Since the phenomenon is associated with near fields of sources the only remedy is to use a measurement surface further away from the source under investigation.

The phase shift of a sound field is not difficult to measure. The relation between reactivity and the phase shift of the sound field is depicted in Fig. 5.7. As can be seen, a reactivity of 5dB equals a phase shift of 70 degrees; a reactivity of 25dB equals a phase shift of almost 90 degrees.

The measurement error of the intensity determination due to the phase matching error between the pressure microphone and the Microflown is a function of the reactivity of the sound field, see Eq. (5.9). The relation between the measurement error and the phase shift of the sound field and the phase matching error is depicted in Fig. 5.8. A phase matching error of 5 degrees will cause a sound intensity measurement error of ½dB if the phase shift of the sound field is 50 degrees.

Measurements show that a phase matching of 1 degree is possible with a calibration based on a short standing wave tube method or the piston on a sphere method. The enhanced calibration based on the sound power ratio technique (see chapter 4, Calibration) a phase matching error of 0.15 degrees can be obtained [3], [4].

One can state that if the measured phase of the sound field is less than 80 degrees (less than 7dB), a calibrated pu probe has a measurement error less than 0.5dB.
If the sound field is more reactive, the probe has to be calibrated with a more advanced technique or move the probe away from the source.

Below the relation between the phase shift of the sound field and the measurement error is depicted for the various calibration techniques.

![Graph showing the relation between phase shift and measurement error for different calibration techniques](image)

**Fig. 5.9:** Sound intensity measurement error as function of the phase shift of the sound field and the phase matching error.

### Reactive intensity

The reactive intensity, when combined with the active intensity describes the sound field. A high value of the ratio of reactive to active intensity shows a near field where the pressure and the particle velocity are in quadrature. This knowledge is useful because sound (intensity) measurements are affected by such conditions.

### 5.6 Size

The size difference is one of the most obvious differences between a pp and pu probe. A small physical size of the sound probe is important for two reasons.

1) If the measurement space is limited or hard to reach the physical size of the probe is an important property. If for instance the sound power output of a dashboard in a car has to be determined, the part where the windscreen comes close to the dashboard is impossible to reach with a traditional pp probe. A pu probe is the only option then.

2) To determine the sound intensity (or sound energy, etc.) of small objects (like hearing aids, cell phones components on printed circuit boards, etc.). The sound probe must be small to get any special resolution of these small noise sources.
5.7 Sound fields with a high pressure intensity index

A pp probe fails at sound fields with a high pressure intensity index; i.e. sound fields where the sound pressure is high and the sound intensity low. A diffuse sound field is an example of this: sound waves propagate in all directions with the same magnitude so the intensity is low and the sound pressure is not. A high pressure intensity index may be expected in environments with multiple sound sources or close to a reflecting surface.

Particle velocity is traditionally determined by measuring sound pressure at two closely spaced places, see Fig. 5.13. The so-obtained pressure gradient is used to calculate particle velocity. The sound pressure is calculated by averaging the two pressure signals.

The pressure transducers have to be closely spaced; the spacing must be much smaller than the wavelength. At lower frequencies the pressure gradient is very small so a larger sensor spacing is required than at higher frequencies. A sound intensity probe consist normally of two sets of matched microphones, half inch probes for lower frequencies and quarter inch probes for higher frequencies. However recent research showed that $rac{1}{2}$” probes and a 12mm spacing can be used from 80-200Hz up to 10kHz (the lower frequency limit depends on the reactivity index of the sound field).
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Fig. 5.11: A traditional three dimensional pp probe. Because of its size it is impossible to measure high frequencies.

If the experiment with the two loudspeakers is repeated (see Fig. 5.2) in a reverberation room, a sensor spacing of 12mm appears to be too small to get reliable results with a traditional sound intensity probe. In the experiments in the reverberation room the reactivity index \((L_\alpha)\) when \(s_2 = 0\) \((I=I_0)\) was about 7dB. The pu probe is not affected by a large pressure-intensity index.

At high frequencies (say \(f>10\text{kHz}\)) the traditional probe is limited because the spacing can not be infinite small and scattering and diffraction problems occur at higher frequencies.

A pu probe is not affected by a diffuse sound field because the polar pattern of both pressure and particle velocity determination is as it should be: the pressure determination is omni directional which means that the sensitivity is the same for sound waves from all directions. The polar pattern of the particle velocity determination with a Microflown is also what it should be: a figure of eight.
Fig. 5.12: Measurement performed in a reverberant room at 125Hz in a 1/3-octave band. The measurement results should be on a line from (0,1) to (2,-1). As can be seen it is not possible to use a 12mm pp probe, this is due to the diffusivity of the sound field. The 50mm pp probe and the pu probe are performing well, from [1].

Since both sensors have their expected angular response the intensity contribution of a diffuse sound field is zero. In a diffuse field sound waves propagate in all directions with similar magnitude. Each sound wave ($W_a$) from one direction is canceled by a sound wave in the opposite direction ($W_b$). The exact figure of eight of the Microflown in combination with the omnidirectional behavior of the pressure microphone causes that the intensity contribution of $W_a$ cancels $W_b$.

Fig. 5.13: Photograph of a traditional sound acoustic intensity probe.

With a pp probe, the particle velocity is calculated by a pressure gradient calculation. If the pressure transducers do not have any phase difference, the differential pressure signal is zero if the sound wave enters perpendicular to the probe and the polar pattern is an exact figure of eight. If the phase response of both pressure transducers is not similar, the polar pattern of the pressure gradient is not a figure of eight anymore. Due to this the pp intensity probe will produce a signal in a diffuse sound field. The contribution of a sound wave from one direction ($W_a$) is not canceled by a sound wave with the same magnitude from the opposite direction ($W_b$).
5.8 Sound intensity probes reactive sound fields

In the previous paragraph it is shown that a pp probe has difficulties to measure the intensity accurately if the sound field has a high pressure intensity index. In this paragraph the accuracy of the intensity probes is examined for reactive sound fields, i.e. sound fields that have a phase shift between sound pressure and particle velocity in the order of 90 degrees. This is a difficult situation for a pu probe.

In pure standing waves the phase shift is ±90 degrees and also near a sound source the phase shift is in the order of 90 degrees.

In reactive sound fields the active intensity \( I \) is low compared to the reactive intensity \( J \).

The next experiment shows that the pp probe is less influenced by reactive sound field than the pu probe.

First the pu probe was calibrated in an anechoic room at two meters from the sound source, see Fig. 5.15. It was assumed that the specific acoustic impedance is: \( z=\rho c \). So the phase shift between sound pressure and particle velocity was assumed 0 degrees. This was a wrong assumption because at lower frequencies the loudspeaker at 2 meters distance is not far from the probe anymore. If the loudspeaker is small the acoustic impedance is approximately given by (impedance of a point like source, see chapter 2):

\[
z(r) = \rho_0 c \left( \frac{ikr}{ikr + 1} \right) \tag{5.11}
\]

so at lower frequencies the acoustic impedance becomes complex. In first order a loudspeaker at two metres distance to the probe can be modelled as a point like source. Due to the nearfield effect that is described with Eq. (5.11) the phase shift occurs between the sound pressure and particle velocity. The phase shift is plotted in Fig. 5.15. As can be seen at 200Hz the phase shift is approximately 8 degrees, at 100Hz it is 17 degrees and so on.
So for lower frequencies the calibration error of the phase response is increasing.

The error made in the amplitude response is not very large.

![Phase shift of a point like source at two meters.](image)

The experiment took place in an ordinary room where the sound power of a 'sound source' of type B&K 4205 was measured by scanning over a surface enclosing the source with two different intensity probes, the Microflown probe and a pp probe of type B&K 3545 with microphones of type B&K 4181.

Two different measurement surfaces were used; one with an area of 5m², and a very small one with an area of about 0.43m², and each measurement was repeated using a different scanning pattern. The sound power, the intensity multiplied by the measurement surface should be the same at the two surfaces. The sound field however is more reactive at the smaller area than the larger.

Fig. 5.17 shows the level difference between the average intensity determined with the Microflown probe and with the B&K probe on the two measurement surfaces.

From the ratio of the areas one would expect a difference of 10.6dB, which is fairly close to what we see in the measurements with the Microflown probe above 200Hz; see Fig. 5.17. The level difference measured with the B&K probe is a little less, about 10dB. This is undoubtedly due to the fact that the centre of the B&K probe, which is more bulky than the Microflown probe, has been a few centimetres away from the nominal measurement surfaces during the measurements.

The difference between the Microflown data and the B&K data on the small measurement surface is about 1dB higher than on the large surface from 200Hz and upwards. This is due to the centre of the B&K probe being a few centimetres away from the nominal surface, as mentioned above.
Fig. 5.16: sound power measured at two surfaces.

However, the additional difference of up to 4dB below 200Hz is due to the fact that the sound field is fairly reactive on the small surface, see Fig. 5.18. Under such conditions, the phase correction is critical.

Fig. 5.17: Difference between the average intensities on the two surfaces.

Moreover, the distance to the source in the calibration experiment was not sufficient to give an accurate phase correction in this frequency range. As can be seen in the previous experiment the error in the calibration of the phase response results in an error in the determined intensity.
Sound intensity measurements

Fig. 5.18: Ratio of reactive to active intensity on two surfaces enclosing the B&K 4205 Sound source.

After proper calibration (with the anechoic calibration the near field effect is taken into account) of the sound pressure probe, particle velocity probe and their phase behaviour the measurements of the pp and pu measurement principle coincide, see Fig. 5.19.

Fig. 5.19: Sound power of the B&K 4205 sound source.

Measurement of a very reactive sound source

The reactivity very close to the sound (emitting) source can take higher values see Fig. 5.18. If that sound source is replaced by a dipole and an extremely small measurement surface with an area of 0.2m$^2$ is used, see
Fig. 5.20. The reactivity increases significantly, see Fig. 5.21. Such sound source does almost not radiate sound but generates a high particle velocity sound field around it and a small pressure field that is almost 90 degrees out of phase.

The dipole was constructed by mounting two loudspeaker units mounted against each other and driven in antiphase, see Fig. 5.20.

The calibration must now be extremely accurate and a calibration in an anechoic room is not sufficient anymore. A more accurate calibration method has to be used. This method (the sound power ratio method) is presented in [3] and in chapter 4. The effect of the adjusted calibration is shown in Fig. 5.22.

Fig. 5.20: Dipole sound source creating a very reactive sound source.

Fig. 5.21: Ratio of reactive to active intensity on two surfaces enclosing the dipole.
As can be seen in Fig. 5.22, if the phase is calibrated with the sound power ratio technique, the sound intensity can be determined properly in a highly reactive sound field. Even a reactivity of 25dB (measured at 50Hz, see Fig. 5.21) is not influencing the accuracy of the measurement. A 25dB reactivity is measured if the phase of the sound field is as high as 89 degrees, see Fig. 5.7.

![Estimation error of Microflown probe; dipole source](image)

**Fig. 5.22**: Estimation error with improved calibration: blue dashed line. The blue solid line represents the error of a sound probe that is calibrated in an anechoic room.

### 5.9 Bandwidth

The bandwidth of a pp probe is limited. The lowest frequency where the 12mm pp probe can be used is in the order of 100Hz. At high frequencies (say f>10kHz) the traditional probe is limited because the spacing can not be infinite small and scattering and diffraction problems occur.

The bandwidth of a Microflown based pu probe is limited at the lower side by the pressure microphone. A frequency of 0.1Hz is possible but the calibration at these frequencies is not trivial. At the high end scattering problems occur. The half inch probe has scattering effects (it becomes an obstacle) so therefore it upper frequency limit is in the order of 10kHz. For higher frequencies smaller pu probes, like the USP or pu match, have to be used.

The reason why the ½” probe cannot be used at high frequencies is that it becomes non symmetric. Above the probe is air and below there is mounting of the probe. Only at high frequencies this asymmetry has an influence, i.e. the response of the ½” probe is different for a sound field from above instead of below the probe.

However for simple sound fields, a sound generated by a sound source in an environment with not so much reflections (a normal room such as depicted in Fig. 5.23), the intensity can be obtained rather accurate above 10kHz.
Fig. 5.23: Sound intensity measured in front of a loudspeaker in a normal room.

The sound intensity as determined in Fig. 5.23 is shown in Fig. 5.24. The intensity is determined by a 50mm pp probe for the low frequencies (20Hz-1250Hz), a 12mm pp probe for the frequency band 20Hz-6kHz and for the entire acoustic band with the ½” pu probe.

As can be seen in Fig. 5.24, the results are similar. At 32Hz there are huge differences between the three probes and at 250Hz there is an 8dB difference between both pp probes. Up to 6kHz the 12mm pp probe and the ½” pu probe have a similar response and for higher frequencies only the ½” pu probe can be used.

Fig. 5.24: Sound intensity determined with a 50mm pp probe, a 12mm pp probe and a ½” pu probe in front of a small loudspeaker.
5.10 Influence of wind

The Microflown is measuring particle velocity and wind can be seen as a very high level of particle velocity at a very low frequency. Therefore one can expect that wind affects the behaviour of the Microflown.

The frequency response of the Microflown however is not flat. At low frequencies the Microflown has a lower sensitivity than at frequencies of e.g. 100Hz. Therefore the effect of wind is not as bad as it could have been.

The pu probe Norsonic for example (see chapter 2) had a very high sensitivity at 0Hz and therefore it was difficult to use even at very low wind speeds.

Although the sensitivity of the Microflown drops at lower frequencies the effect of wind is considerable as can be seen in the following experiments.

In an anechoic room the intensity was determined using one sound source (loudspeaker) at a distance of 1.2m and a fan at a distance of 1.0m from the intensity probe; the loudspeaker and the fan were at opposite sides of the probe. When the fan was switched on the wind velocity at the intensity probe was about 3.4 m/sec. First the intensities were measured with a pp probe and a pu probe with the fan switched off. Then the same measurement was repeated with the fan switched on. Some experimental results are shown in figure 13. The abbreviations in the figure refer to the pp probe (BK) and the pu probe (pu). Horizontally the frequency in 1/3-octave bands is plotted, vertically the measured difference in intensity when the fan is switched on or off. Fig. 5.25 (left) shows a strong influence of the wind caused by the fan; this influence is stronger for the pu probe and is not acceptable. In order to diminish this influence a windscreen, as delivered by Bruel & Kjaer with the pp probe is used. In Fig. 5.25 (right) similar results are shown, but now with the windscreen around the pp or pu probe. This figure shows that the influence of wind is still stronger for the pu probe than for the pp probe, but that the effects are for frequencies above 100 Hz smaller than 1 dB and thus acceptable.

![Figure 5.25: Sound intensity determined with a pp probe and a pu probe with and without a windscreen](image-url)
5.11 Selfnoise of intensity probes

A ½” sound pressure probe is of a high quality and its selfnoise is low. As can be seen in Fig. 5.26, the selfnoise of the miniature pressure transducer (that is used in the Microflown sensor) is a few dB’s higher than the ½” sound pressure probe. The selfnoise of a Microflown packaged in a 1/2” housing is 10dB-20dB higher.

The selfnoise of a velocity determination by two pressure probes is much higher than the velocity measured by a Microflown, see Fig. 5.26. This is because the particle velocity determination is derived from the subtraction of two similar signals; the result is a small value. For lower frequencies the result of the subtraction becomes smaller and thus the selfnoise higher.

The selfnoise of sound intensity probes is normally not an issue because the intensity is determined by the cross spectrum (or average value). The selfnoise of the sensors is reduced with this technique.

![Fig. 5.26: Electrical noise of the Microflown in one-third octave bands compared with the noise the particle velocity measured with a two-microphone Brüel & Kjær sound intensity probe with a 12-mm spacer, and with the noise of a single pressure microphone of type B&K 4181.](image)

Transmission loss measurements is field where very low intensity values are required. The standard test methods for the transmission loss measurement uses two adjacent rooms with an adjoining transmission path. The treatment under test is placed between the two rooms in the adjoining transmission path. Sound is generated in one room and measurements are taken in both the source and receiver room to characterize the transmission loss.
Sound intensity measurements

Fig. 5.27: A typical transmission path measurement. Such measurements require low noise intensity measurements (courtesy General Motors).

Fig. 5.28: Comparison of a traditional intensity probe and a ½" Microflown PU probe. As can be seen, the selfnoise level is too high at frequencies higher than 3kHz.

The output of the PU intensity probe drops to the selfnoise if the source is switched off. The level that is reached when the probe is in an absolute silent environment is called the selfnoise level. As can be seen in Fig. 5.28, the selfnoise level is in the order of -10dB if measured in a 7Hz bandwidth.
5.12 Sound power measurements

Sound intensity probes are used to perform sound power measurements. Sound power equals the sound intensity integrated over a certain surface. The sound intensity itself is a time averaged value, so a value integrated over time. And usually the intensity is measured in third octave bands so the measurement values are also integrated over a certain bandwidth.

Sound power is a time, space and frequency integrated value.

The sound power in a pure diffuse sound field is zero. In the example with the two opposing loudspeakers that generated uncorrelated noise (see Fig. 5.2.) equations Eq. (5.2) and Eq. (5.3) showed that the intensity was zero because the phase shift between sound pressure and particle velocity is time dependent.

In a diffuse sound field (e.g. generated in a reverberation chamber with only one loudspeaker), the phase shift between sound pressure and particle velocity is not time dependent. However the phase shift is random in frequency and place. It takes all values, and when the position or frequency is changed it will change in an unpredictable manner. So the intensity becomes zero in a diffuse sound field when it is integrated over a certain bandwidth or area.

Sound power based on near field velocity e measurements

ISO 3744:1994 Acoustics - Determination of sound power levels of noise sources using sound pressure -Engineering method in an essentially free field over a reflecting plane.

Pressure measurements are taken in a half sphere over a noise emitting source in a semi anechoic room (an anechoic room with a fully reflecting floor). The sound intensity can be calculated from the sound pressure signals in such acoustic environment because of the absence of reflections.
The transfer function from the pressure distribution on the sphere to the velocity distribution on the object under test can be derived with the reciprocity principle.

With this concept the sound intensity can be determined from the measured near field velocities and the measure transfer functions.

Step one is the measurement of the transfer function. A monopole sound source is moved around the object under test (that is not generating sound at that moment) and the sound pressure is measured at the surface.

Then the object is under test is switched on and the velocity distribution is measured close to the surface.

Each velocity measurement will result in a calculated signal on all virtual pressure points based on the set of transfer functions.

In this way the transfer function matrix will show the sound radiation of each velocity point.

The sound power is calculated as the sum of all calculated pressure signals squared divided by the acoustic impedance.

5.13 Example of 3D intensity measurements (I)

The noise level inside a vehicle is reduced with the use of damping materials. If the sound level is higher than expected the acoustic grommets in the firewall (the throughputs for the airco, electrical wiring, steering and peddles, etc) can be tested.

The standard way to measure this is to cut the car in pieces and place (and seal) the firewall in a wall that separates a reverberant room and an anechoic room. A diffuse sound field noise is generated in the reverberant room and the transmission through the firewall is measured in the anechoic room.

This type of measurement is very time consuming (12 days) and the infrastructure is very expensive.

It is also possible to put a very small three dimensional sound intensity probe close to the firewall before the car is cut to pieces. If the glove compartment is removed, the grommets in the firewall become accessible.

The Microflown based intensity method is not susceptible to background noise and reflections, so it is possible to measure the intensity in a confined space. A USP is very small but for this application a special USP match is designed.

The method to find out if the grommets in the firewall contribute dominantly to the noise level inside vehicle is the measurement of the three dimensional sound intensity. If the intensity vector is aiming towards the grommet in a broad frequency band, the grommet is not performing well.

This measurement can be done in situ, so in a working vehicle. This increases the quality of the measurements, it saves a lot of time and a car.
5.14 Example of 3D intensity measurements (II)

Prof. Stefan Weyna from the Faculty of Maritime Technology / Applied Vibroacoustics Department, Technical University of Szczecin, Poland did many extraordinary measurements.
In an anechoic room many (several thousands) three dimensional sound intensity measurements were done and the result is depicted in a way that allows one to see the direction and the magnitude of the three dimensional intensity values. The color of the lines represents the magnitude of the intensity and the path is shown by the lines.

In the first example one can see two loudspeakers mounted in a plate. Left the both loudspeakers are vibrating in phase and in the right pictures the loudspeakers are vibrating in antiphase.

Another example of this type of measurement is depicted below. Here the effect of a rigid obstacle placed in front of a loudspeaker in an anechoic room is shown. In Fig. 5.34 the sound field is shown that passes an obstacle.
at 155Hz. In Fig. 5.35 the sound field is shown that passes the same obstacle but now at 193.9Hz. One can see that the sound field starts to circulate.

These effects can only be measured with an intensity probe. With a sound pressure probe only scalar values can be obtained and with a velocity probe it is possible to measure the vector information but it is not possible to find out the (positive or negative) direction.

At the next page a detail of a rotating sound field in front of a rigid plate is shown.
5.15 3D sound intensity streamlines in a car interior

Based on [7]. Sound source localization techniques in a car interior are hampered by the fact that the cavity is governed by a high number of (in)coherent sources and reflections.

In the acoustic near field, particle velocity based (PU) sound intensity probes have been demonstrated to be not susceptible to these reflections allowing the individual contributions of these (in)coherent sources to be accurately determined. Panel noise contribution analysis based on PU measurements is becoming practice now.

In the acoustic far field (spherical) beam forming techniques are used that analyze the directional resolution of a sound field incident on the array. The method is applied both outdoors in the free field and, since recently, inside cars. In this case, it is assumed that the sound travels in a straight path from the source to the receiver and that there are no reflections.

To get a good insight in the true behavior of a sound field in a car, the 3D sound intensity streamlines are measured. A loudspeaker is used as a controlled sound source. For this purposes 900 intensity measurement points were taken in one day.

The three dimensional sound intensity data points are measured with a probe consisting three particle velocity sensors and one sound pressure microphone. The measurements show that even with a single source, the 3D sound intensity streamlines are strongly bending, suggesting that far field techniques do not point towards the sound source.

Visualisation techniques

The visualization of a three dimensional sound field (e.g. the SPL) is difficult because it concerns a volume of results. The visualization of a vector field is even more demanding. The visualization techniques used here are inspired by the work of prof. Weyna, see e.g. Error! Reference source not found.]. A number of plotting techniques are used here:

SPL value at each position

Before starting a detailed study it is important to know the sound pressure level at certain positions, like for instance the position of the passenger ears. Higher SPL levels are displayed as large (red) circles inside the car geometry while lower values are smaller and blue.

Isosurface A surface is fitted through all points that have a certain pressure, velocity or intensity value. This is another way to represent hotspots.

The intensity vector field is represented as a set of arrows at each position. This does not give too much information if the picture is static; if it is rotated it becomes clearer. The method is used because it displays the rough measured data points, without any interpolation or treatment.
The **sound intensity streamlines** represent the direction of the intensity field and the color of the line represents the source strength. The streamlines originate from a defined set of starting points and follow the direction of the intensity vectors. In this study all the boundaries of the measurement area were chosen as starting points.

**Streamslices** display the intensity level as a colormap and streamlines in certain cross-sections.

**Geometry Measurement**

The intensity measurements are plotted together with the geometry of the car. As there was no CAD data available of this car, the inner geometry was digitized with a new measuring unit, see *Error! Reference source not found.*. The rotation in each joint of this mechanical arm is determined with potentiometers, making the position of the measurement tip known. The measurement time is close to one hour.

![Image](image.png)

**Fig. 5.36:** The inner geometry is measured with a mechanical digitizing "Octopus" arm. The red dots are the measurement positions.

**Sound sources**

Several simple loudspeakers were placed inside the car and driven with a white noise signal. In three measurement sets different speakers were powered:

1. Two speakers in the front doors
2. Two speakers on the dashboard
3. One speaker in the trunk

**Measurement results**

In the figures below the sound pressure and the 3D intensity fields are visualized at 300Hz when there was signal on the two dashboard speakers.
It can be concluded that the intensity streamlines travel certainly not in a straight line. The same irregularities are measured when only a single source in the back of the truck is turned on. So the assumption of some far field methods that the sound travels directly from the source to the receiver cannot be valid. It can also be noted that the streamlines are different for each frequency.

Fig. 5.37 (left): SPL (dBV) at each position. 300 Hz, dashboard speakers. High values are red larger circles. Low values smaller, blue ones. Right: Isosurface of the pressure. 300Hz, two dashboard speakers.

Fig. 5.38 (left): Normalized intensity vectors, dashboard speakers. Right: Intensity streamlines, 300Hz, dashboard speakers.

Streamslices can provide even a better view as can be seen in the figures below. Intensity colormaps are shown in two planes at several frequencies. Even at low frequencies the streamlines do not follow a straight trajectory. For instance at 1650Hz and 3600Hz even vortexes are present in the vertical plane. These phenomena were also observed by S. Weyna.
Sound intensity measurements

Fig. 5.39 (Left): Intensity streamlines, 1000Hz, speaker in the trunk. Right: Intensity streamlines at 1000Hz. Two speakers in front doors.

Fig. 5.40 (Left): Intensity streamlines at 1200Hz. Two speakers in front doors. Right: Intensity streamlines at 1300Hz. Two speakers in front doors.

Fig. 5.41 (Left): Front speakers. Streamslice at 200Hz. Right: Front speakers. Streamslice at 500Hz.

Also in the vertical plane can be seen the streamlines tend to bend mostly around the front seat, but at 500Hz and 1650Hz more streamlines go through the seat. There could be several reasons. There could be real transmission though the seat. It could also be that there is a too complex interaction at the surface, and more measurement points should be taken close around the seat. Also the intensity streamlines are calculated with a certain threshold. This threshold could be too large and streamlines could continue and span the thickness of the seat.
Several sound sources are placed inside a car and the pressure and 3D pressure/velocity/intensity field has been measured on a high number of measurement points. A combination of several plotting techniques can give a good insight of the sound field inside car. The streamline plots in particular show that even with a single source the sound does not travel in a straight path from the source to the receiver, suggesting that far field techniques do not point towards the sound source. Curved paths and even vortexes are present. In some cases the intensity streamlines go around the seat while at other frequencies the lines go directly through the seat. This could be the result of actual transmission through the material, but might also be a bias result of the measurement method or the calculation technique and has to be studied in more detail. Even though a large number of points was measured the measurement time were done in one day. This can be considered to be reasonable fast as compared to many existing techniques. The inner geometry of the car was measured in one hour and shows the position of the intensity values relative to the vehicle. Different sound source positions will be measured in the future and the behavior of the seat will be studied in more depth. The ultimate goal is to measure the sources created by the car itself on a roller bench, maybe using an automated unmanned procedure.
5.16 A pp and pu intensity measurement of an engine

At Ricardo England the sound power of an engine was measured with a pp probe and a pu probe, see Fig. 5.44.

Fig. 5.44: Measurement locations of a car engine (courtesy Ricardo UK).

Fig. 5.45: A pp and a pu measurement at a car engine (courtesy Ricardo UK).
The comparison of the sound power spectra obtained through the different methods shows good agreement. However, on the first glance, some deviation is obvious. Fig. 5.47 shows the sound power spectra from two pipes. The frequency behaviour is very similar. However, an offset is clearly visible.

The deviation seen above is caused by the different areas assumed by the different methods. It is very strong because of the cylindrical shape of the components. For planar or near-planar components, this influence is small, resulting in comparable area sizes and very good agreement.
### 5.17 A pp and pu intensity measurement

The traditional method for measuring intensity uses a pp probe (two pressure microphones) and determines particle velocity to acquire sound intensity. Using a pu probe (microphone and Microflown) enables measuring particle velocity instantly. In a student assignment the pp and pu probes are compared at the facility of the National Aerospace Laboratory (NLR) at the Noordoostpolder location.

The instrument set up at the NLR is used for measuring transmission loss (TL), using a certified measuring method. The NLR test set up is shown in Fig. 5.48.

The volume of the reverberation room is 33m$^3$, causing a diffuse sound field for frequencies of about 500Hz and higher. The whole room acts as one big speaker, of which all sound emitting properties are known. In order to reduce measuring errors below 500Hz due to insufficient diffusivity of the sound field, the TL has been determined from successive measurements for three different loudspeaker positions, according to the procedure, described in Annex C of ISO 140-3. There are eight speakers installed in the reverberation room to cause a sound level up to 130dB. In addition a spherical sound source is used to generate the lower frequencies (<500Hz) [5].

![Fig. 5.48: NLR instrument set up for transmission loss measurements](image)

To suppress the effect of reflections on the walls of the semi-anechoic receiving room, having a volume of about 205m$^3$, sound absorbing foam has been installed around the test opening.

The reverberant and semi-anechoic room are connected via a 1x1m hard reflecting duct (niche) with a depth of about 1m. At the reverberant room side of the duct an aluminum sample (a plate of 1.08x1.08mx0.001m) is clamped in front of the duct (see Fig. 5.49). The sample is tightened with bolts, washers and nuts. Insulating rubber assures no leakage of air between the reverberant and semi-anechoic room. The test sample used in
the measurement described in this paragraph is an aluminum plate with a thickness of 1.0mm. This sample is normally used by the NLR for reference measurements.

**pp and pu probes**

The measurement is performed using a pu probe attached to the pp probe, in order to acquire the same measurement data (see Fig. 5.50). The pp probe consists of two microphones separated by a space of 12mm normal to the measured surface. The distance between the two microphones is required to be able to calculate the particle velocity in the data post processing stage.

The acquired data is retrieved by scanning the sample surface twice; a vertical and horizontal scan. This is done in order to reach a higher accuracy in the measurement results.
Sound intensity measurements

Fig. 5.51: The vertical en horizontal scanning path.

Each scan is performed normal to the measured surface at a distance of 80cm and takes precisely 180 seconds.

**Data post processing**

All acquired data consists of five signals:

1. Pressure signal $P_1$ of the first pressure microphone of the pp probe; sensitivity = 84.0mV/Pa.
2. Pressure signal $P_2$ of the second pressure microphone of the pp probe; sensitivity = 80.6mV/Pa.
3. Pressure signal $P_3$ of the of the rotating pressure microphone in the reverberant room; sensitivity = 100.6mV/Pa.
4. Pressure signal $P_4$ of the microphone inside the pu probe; sensitivity set to 1 mV/Pa during the measurement.
5. Particle velocity signal $U_5$ of the Microflown inside the pu probe; sensitivity set to 1.0 mV/Pa during the measurement.

The data post processing is performed by the NLR computers, using the acquired signals, atmospheric conditions and microphone sensitivity as input. The sensitivity of the $P_1$, $P_2$ and $P_3$ microphones are constant over measured frequency interval [100 5000] Hz, in contrast to the pu probe’s signals $P_4$ and $U_5$. Because of the frequency dependent sensitivity of the pu probe, the input parameter is set to 1.0mV/Pa, in order to correct the retrieved values afterwards.

The output of the data post processing is a spreadsheet with the following frequency dependent values ordered in columns:

- $f$, the values of frequency data points [Hz]
- $|P_1|$, the amplitude of the power spectrum of $P_1$ [dB]
- $|P_2|$, the amplitude of the power spectrum of $P_2$ [dB]
- $|P_3|$, the amplitude of the power spectrum of $P_3$ [dB]
- $|P_4|$, the amplitude of the power spectrum of $P_4$ [dB]
- $|U_5|$, the amplitude of the power spectrum of $U_5$ [dB]
- $|S_{pp}|$, the amplitude of the cross spectrum of $P_1$ and $P_2$ [dB]
- $\varphi_{pp,measured}$, the phase of the cross spectrum from $P_1$ and $P_2$ [°]
- $|S_{pu}|$, the amplitude of the cross spectrum of $P_4$ and $U_5$ [dB]
- $\varphi_{pu,measured}$, the phase of the cross spectrum of $P_4$ and $U_5$ [°]

Note: all dB values have a reference of 20µPa
The data that is summoned above (the NLR output) is shown in the next three diagrams (Fig. 5.52).

![Graphs showing sound intensity measurements](image)

Fig. 5.52: All raw data from the NLR measurement

All values expressed in decibels of the above summation, including particle velocity, are calculated by using:

\[ X(f) = 20 \cdot \log \left( \frac{x(f)}{x_{ref}} \right) \]  \hspace{1cm} (5.12)

With \( x_{ref} = 20 \cdot 10^{-6} \) [Pa] for \( P_1 \), \( P_2 \), and \( P_3 \) or [V] for \( P_4 \) and \( U_5 \)

As all signals are expressed in dB, it is not possible to process or correct their values. This is why the inverse is used as a first step in the calculation sequence:

\[ x(f) = 10^{\left( \frac{X(f)}{20} \right)} \cdot x_{ref} \]  \hspace{1cm} (5.13)

With \( x_{ref} = 20 \cdot 10^{-6} \) [Pa or mV]

The operation described results in the following units per signal:
Sound intensity measurements

- $|P_1| \rightarrow |p_1| \ [\text{Pa}]$
- $|P_2| \rightarrow |p_2| \ [\text{Pa}]$
- $|P_3| \rightarrow |p_3| \ [\text{Pa}]$
- $|P_4| \rightarrow |p_4| \ [\text{mV}]$
- $|U_5| \rightarrow |u_5| \ [\text{mV}]$
- $|S_{pp}| \rightarrow |S_{pp}| \ [\text{Pa}^2]$
- $|S_{pu}| \rightarrow |S_{pu}| \ [V^2]$

**|P_4| en |U_5| correction**

Now that the $p$ and $u$ signals of the pu probe are expressed in mV, the calibration file of this probe can be used to correct the current values. Because the correction values for pressure and particle velocity in the calibration file are expressed in mV/Pa and mV/Pa* the current values can be divided by their correction values per frequency:

$$|p_{4\text{corrected}}| = \frac{|p_4|}{|S_p|} \tag{5.14}$$

With $S_p$ is the sensitivity of the microphone per frequency:

$$|u_{5\text{corrected}}| = \frac{|u_5|}{|S_u|} \tag{5.15}$$

With $S_u$ is the sensitivity of the Microflown per frequency in Pa*:

$$1 \text{Pa*} = \frac{1.0 \ [m/s]}{\rho_0 [kg/m^3] \cdot c_0 [m/s]} = 2.4 \ [\text{mm/s}] \tag{5.16}$$

In order to calibrate the cross spectrum of $p$ and $u$ of the pu probe, the complex values for $S_{pu,\text{comp}}$ have to be composed from the amplitude, $|S_{pu}|$, and phase, $\varphi_{pu}$:

$$S_{pu,\text{comp}} = |S_{pu}| \cdot \cos(\varphi_{pu}) + i \cdot |S_{pu}| \cdot \sin(\varphi_{pu}) = |S_{pu}| \cdot e^{i\varphi_{pu}} \tag{5.17}$$

Now the measured data can be corrected using:

$$S_{pu,\text{cor}} = \frac{S_{pu,\text{comp}}}{S_p \cdot S_u} \cdot \left(\cos(\varphi_{pu,\text{cal}}) - i \cdot \sin(\varphi_{pu,\text{cal}})\right) = \frac{S_{pu,\text{comp}}}{S_p \cdot S_u} e^{-i\varphi_{pu,\text{cal}}} \tag{5.18}$$

With:

- $S_p$ = the sensitivity of the microphone per frequency [mV/Pa]
- $S_u$ = the sensitivity of the Microflown per frequency [mV/Pa*]
- $\varphi_{pu,\text{cal}}$ = the phase correction in the calibration file of $p$ and $u$ [°]

The argument of $S_{pu,\text{cor}}$ is the corrected phase shift [°] between the $p$ and $u$ signal of the pu probe.
\[ \varphi_{pu,cor} = \text{arg} \left( S_{pu,cor} \right) \] (5.19)

**Calculate** \( P_{pp} \), \( U_{pp} \) and \( \varphi_{pu,pp} \)

The intensity is given by the local pressure times the local particle velocity times the cosine of the local phase between sound pressure and particle velocity.

The local particle velocity and the local phase between sound pressure and particle velocity measured with the pp probe is calculated here.

To compare the sound pressure levels \(|P_1|\) and \(|P_2|\) with \( |P_4| \text{corrected} \), the average of both signals (in Pa) is taken using:

\[ |P_{pp}| = \frac{|P_1| + |P_2|}{2} \] (5.20)

When a pp probe is used to acquire sound intensity, impedance or the cross spectrum of \( p \) and \( u \), the particle velocity needs to be calculated using:

\[ |U_{pp}| = \left| \frac{P_2 - P_1 \cdot e^{i\varphi_{pp}}}{\rho \Delta \omega} \right| \] (5.21)

With:

\( \rho \) = the air density [kg/m\(^2\)]
\( \Delta \) = the distance between the microphones of the pp probe (=12mm)
\( \omega \) = the angular velocity [rad s\(^{-1}\)] = \( 2 \pi f \)

Now phase shift between \( U_{pp} \) and \( P_{pp} \) needs to be calculated via the following equations:

\[ \varphi_{p,pp} = \text{arg} \left( i \cdot \left( |P_2| - \left( |P_1| \cdot e^{i\varphi_{pp}} \right) \right) \right) \]
\[ \varphi_{u,pp} = \text{arg} \left( |P_2| + \left( |P_1| \cdot e^{i\varphi_{pp}} \right) \right) \]
\[ \varphi_{pu,pp} = \varphi_{u,pp} - \varphi_{p,pp} \] (5.22)

With:

\( \varphi_{p,pp} \) = the phase of pressure of the pp probe [°]
\( \varphi_{u,pp} \) = the calculated phase of particle velocity of the pp probe [°]
\( \varphi_{pu,pp} \) = the phase shift between \( \varphi_{p,pp} \) and \( \varphi_{u,pp} \) of the pp probe [°]

**Pressure signals of the pp and pu probe**

As shown in Fig. 5.53, the sound pressure levels \((P_{ref} = 20 \cdot 10^{-6} \text{ [Pa]}\)) of both probes are compared. The blue line is the averaged value of both pressure signals from the pp probe. They represent the results from the NLR computations which are supplied in the raw data. The microphone sensitivity in this result is already taken into account.
Sound intensity measurements

In addition, the graph shows the plot of the raw pressure signal from the pu probe, indicated by the green line. The result indicated with the red plot after correction of the microphone sensitivity.

![Graph showing pressure amplitude response](image1)

Fig. 5.53: A comparison of the pressure amplitude response of the pp and pu probe (both pressure microphones).

**Particle velocity signals of the pp and pu probe**

Fig. 5.54 shows the amplitudes ($x_{\text{ref}} = 20 \cdot 10^{-6}$ mV) of the particle velocity of the pp and pu probe. In addition the measured values (green line) and corrected values (red line) from the particle velocity signal from the pu probe are shown.

![Graph showing particle velocity amplitudes](image2)

Fig. 5.54: A comparison of the particle velocity amplitudes for the measured and corrected $U_5$ and the estimated $U_{pp}$.

**Phase shift of pressure and velocity of the pp and pu probe**

The graph in Fig. 5.55 shows phase between pressure and velocity determined with he pp and pu probe. The raw measured data of the pu probe is shown in green, the corrected values are shown in red, the phase response determined with the pp probe is shown in blue.
Comparing pp en pu intensities

When all (corrected) values of \( p, u \) and \( \phi \) of both probes are known, the sound intensities can be calculated and compared.

\[
I_{pp} = p_{pp} \cdot u_{pp} \cdot \cos(\phi_{pu,pp}) \tag{5.23}
\]

\[
I_{pu} = p_{pu} \cdot u_{pu} \cdot \cos(\phi_{pu,pu}) \tag{5.24}
\]

With:

- \( I_{pp} \) = Sound intensity level derived from the pp probe [dB]
- \( p_{pp} \) = Pressure derived from the pp probe [Pa]
- \( u_{pp} \) = Particle velocity derived from the pp probe [m/s]
- \( I_{pu} \) = Sound intensity level derived from the pu probe [dB]
- \( p_{pu} \) = Pressure derived from the pu probe [Pa]
- \( u_{pu} \) = Particle velocity derived from the pu probe [m/s]

Intensity signals of the pp and pu probe

The calculated intensities are shown in Fig. 5.56 and as expected \( I_{pu} \) and \( I_{pp} \) are nearly the same.
At lower frequencies an approximate 3dB difference between both intensities is remarked. A reason for this is the fundamental difference between the pu probe and pp probe design. The pp probe error is explained below.

The pp probe uses a spacer between the two microphone sensors (in this case 0.012m) resulting into a phase mismatch error $\varphi_{pe}$. It can be shown that a small phase mismatch error $\varphi_{pe}$ gives rise to a bias error that can be approximated by the following expression:

$$\hat{I}_r \approx I_r - \frac{\varphi_{pe}}{k\Delta r} \frac{p_{\text{rms}}^2}{\rho c} = I_r \left(1 - \frac{\varphi_{pe}}{k\Delta r} \frac{p_{\text{rms}}^2}{\rho c} \right)$$

(5.25)

With:

- $I_r$ = True intensity, unaffected by the phase error
- $p_{\text{rms}}$ = The root mean square value of sound pressure
- $\Delta r$ = spacer distance = 0.012m
- $c$ = speed of sound through air \([\text{m/s}]\)
- $k = 2 \cdot \pi \cdot f / c_0$; the wave number \([-\text{]}\)
- $f$ = frequency \([\text{Hz}]\)

This expression shows that the effect of a given phase error is inversely proportional to the frequency and the microphone separation distance and is proportional to the ratio of the root mean square sound pressure to the sound intensity. If this ratio is large then even the small phase errors will give rise to significant bias errors. Because of phase mismatch it will rarely be possible to make reliable measurements at low frequencies using a pp probe, unless a longer spacer than the usual 12 mm spacer is used.

**Reactivity**

To describe a sound field both the active and reactive intensity have to be known. The reactive intensity ($J_r$) is the non-propagating part of the energy that is merely flowing back- and forwards. The reactive intensity is the imaginary part of the cross spectrum:

$$J_r = \text{Im}\left\{S_{pu}e^{j\varphi_{pu}}\right\} = p \cdot u \cdot \sin (\varphi_{pu})$$

(5.26)

The active intensity ($I_r$), the real part of the cross spectrum, indicates the net flow of sound energy:

$$I_r = \text{Re}\left\{S_{pu}e^{j\varphi_{pu}}\right\} = p \cdot u \cdot \cos (\varphi_{pu})$$

(5.27)

The reactive intensity ($J$) is needed together with the active intensity ($I$) as a sound field indicator, called reactivity. It defines the quality of the results. Reactivity is the ratio of $J/I$:

$$\text{Reactivity} = 10 \cdot \log_{10} \left( \frac{p \cdot u \cdot \sin (\varphi_{pu})}{p \cdot u \cdot \cos (\varphi_{pu})} \right) = 10 \cdot \log_{10} \left( \tan (\varphi_{pu}) \right) \ [\text{dB}]$$

(5.28)
When the ratio J/I becomes large the sound field is called reactive. This happens close to a sound source where the phase between p and u is almost 90 degrees. As a result the active intensity is not accurate, and the results are not representative. When the ratio J/I becomes small the sound field is called reactive. This happens far from the source where sound waves become plane and the phase between in p and u is almost zero.

The phase shift of a sound field is not difficult to measure. The relation between reactivity and the phase shift of the sound field is depicted in Fig. 5.7. As can be seen, a reactivity of 5dB equals a phase shift of 70 degrees; a reactivity of 25dB equals a phase shift of almost 90 degrees.

As a consequence the reactivity from any measurement needs to be below 10dB at all times for an accurate data validation.

**Measured reactivity**

The result for the reactivity for the pp probe is shown in Fig. 5.57. An extra line is added which contains the average reactivity data. The graph stays below the border of 10dB, which means that the measured data is valid.

![Fig. 5.57: Reactivity of the measured sound field.](image)

### 5.18 References


Sound intensity measurements

[5] Finn Jacobsen et al., Intensity-based sound power determination under adverse sound field conditions: pu probes versus pp probes, ISCV12 Lisbon, 11-14 juli, 2005
