# Microflown Technologies

Charting sound fields

# Technical Note
# PP and PU Intensity measurements

19 June 2007

## *Introduction*

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.

## *Instrument set up NLR*

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 Figure.1.

## Measuring room

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].

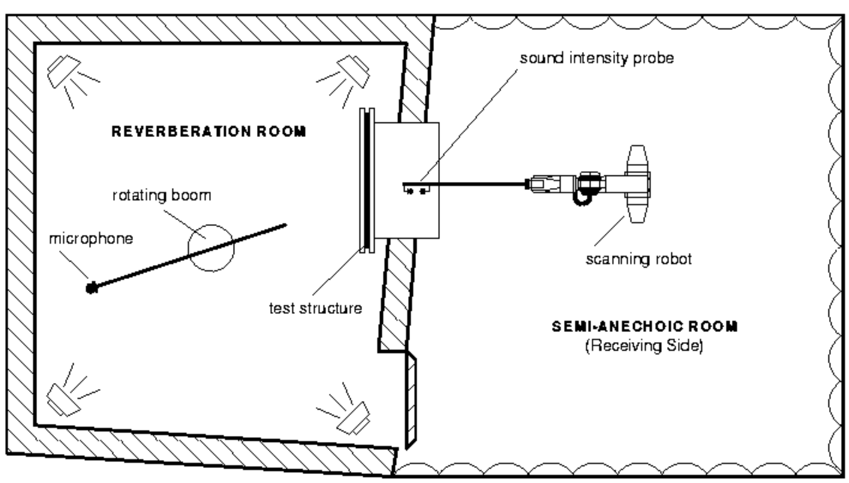


*Figure.1: NLR instrument set up for transmission loss measurements*

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

## Test specimen

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 Figure.2). 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.

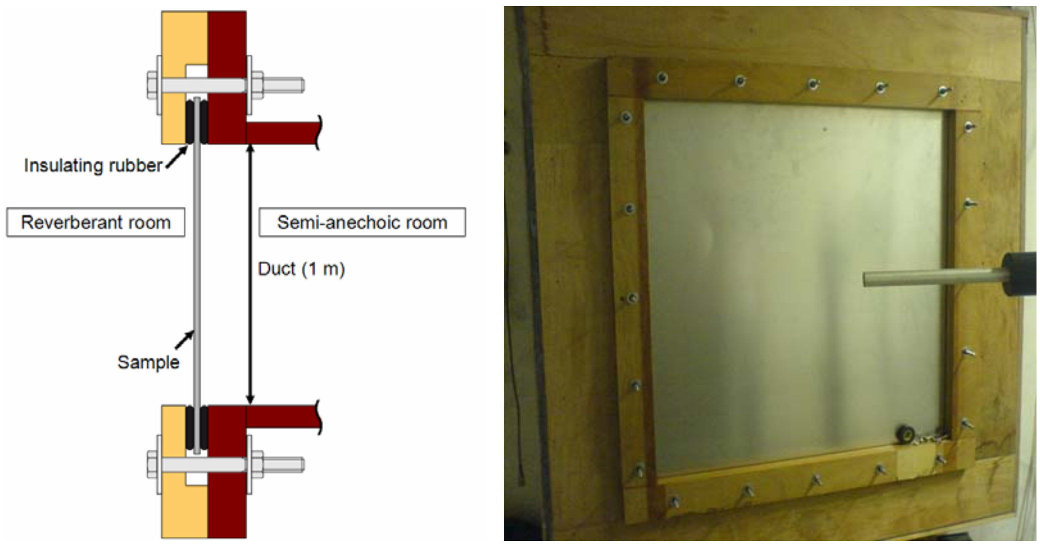


*Figure.2 Left: schematic view of the test sample set up; right: picture of an aluminum sample taken from inside the reverberant room.*

## 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 Figure.3). 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.

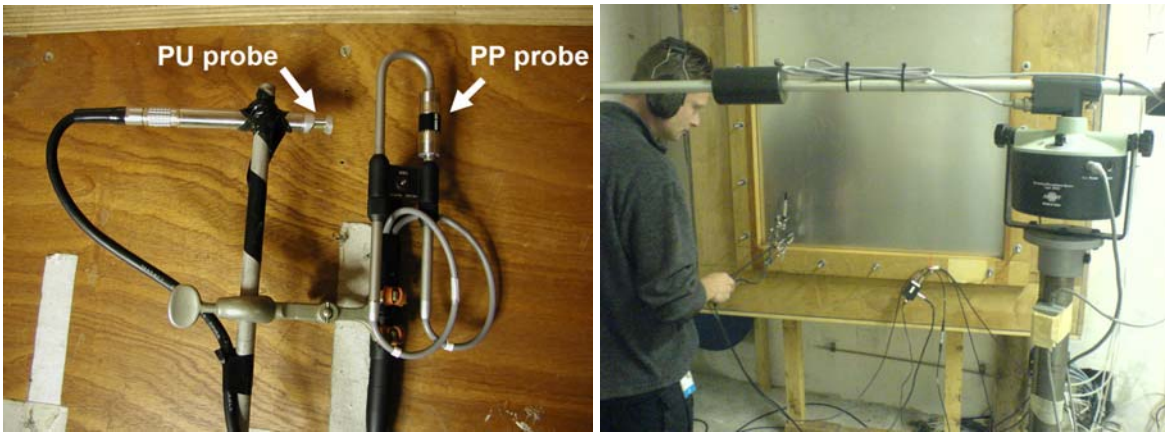


*Figure.3: Left: the PU probe is attached to the PP probe; right: the hand scanning method (in this picture shown on the reverberant side).*

The acquired data is retrieved by scanning the sample surface twice; a vertical and horizontal scan (see Figure.4). This is done in order to reach a higher accuracy in the measurement results.

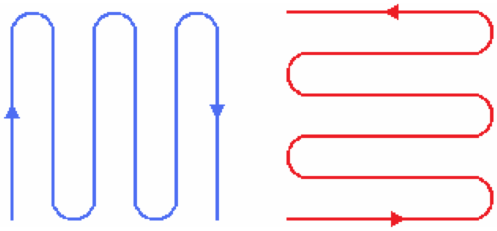

*Figure.4: The vertical en horizontal scanning path.*

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 (Figure.5).

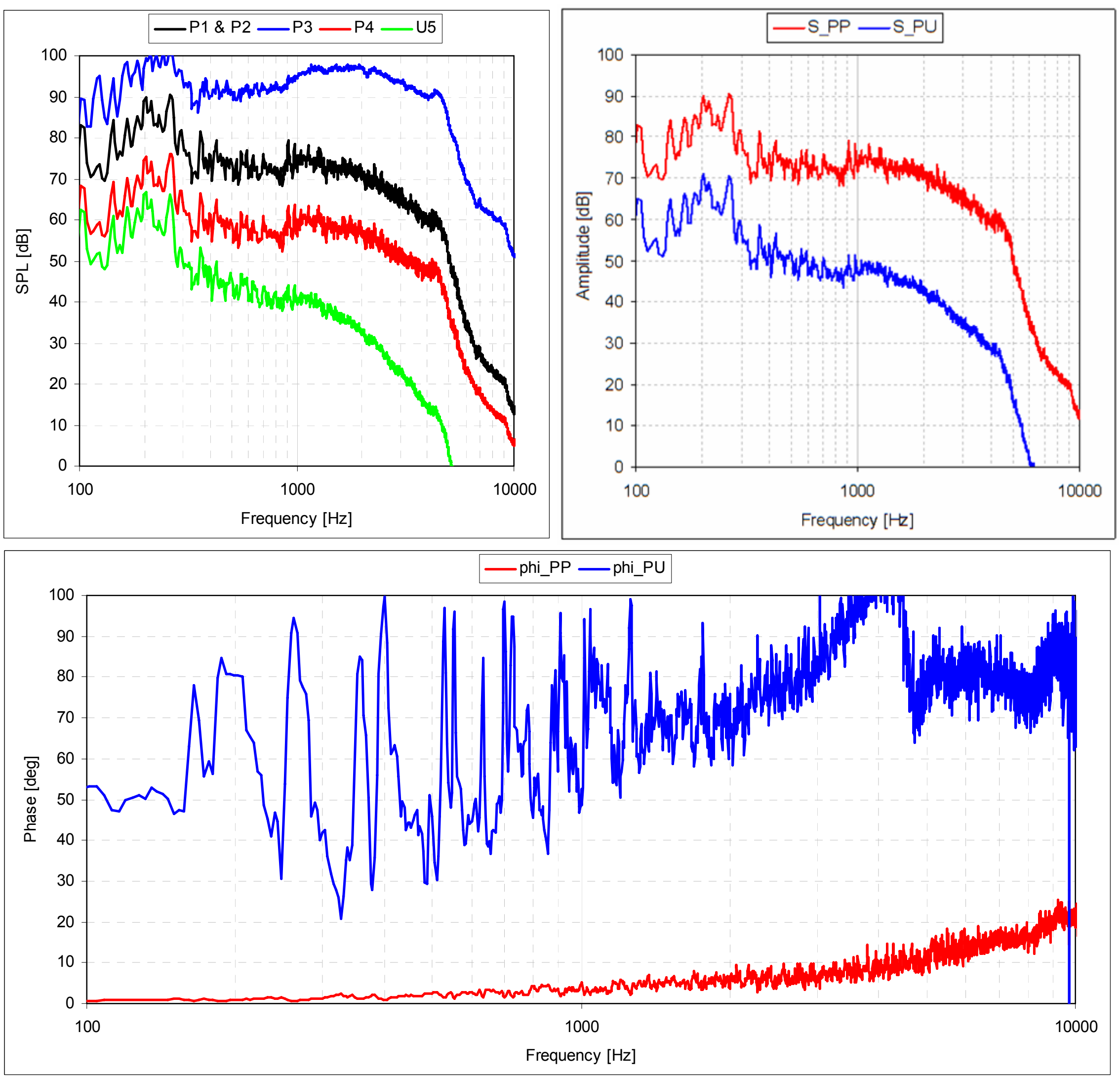


*Figure.5: All raw data from the NLR measurement.*

All values expressed in decibels of the above summation, including particle velocity, are calculated by using Equation 1.1:

$$X(f) = 20 \cdot \log\left(\frac{x(f)}{x_{ref}}\right) \qquad (1)$$

With $x_{ref}$ = 20 · $10^{-6}$ [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 of Equation 1.1 is used as a first step in the calculation sequence:

$$x(f) = 10^{\left(\frac{X(f)}{20}\right)} \cdot x_{ref} \qquad (2)$$

With $x_{ref}$ = 20 · $10^{-6}$ [Pa or mV]
The operation described in Equation 1.2 results in de following units per signal:

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

# $|P_4|$ 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:

$$|p_4|_{corrected} = \frac{|p_4|}{|S_p|} \qquad (3)$$

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

$$|u_5|_{corrected} = \frac{|u_5|}{|S_u|} \qquad (4)$$

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

$$1\text{Pa}^* = \frac{1.0 \quad [m/s]}{\rho_0\,[kg/m^3] \cdot c_0\,[m/s]} = 2.4 \quad [\text{mm/s}] \qquad (5)$$

The typical shape of the Microflown sensitivity is shown in Figure.6.

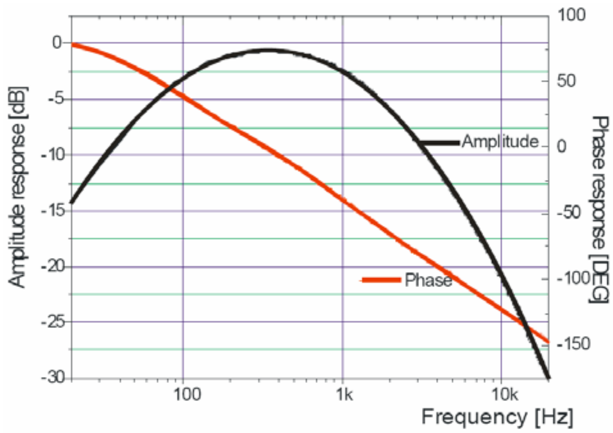


*Figure.6: The Microflown sensitivity ($S_{pu,cor}$).*

Using Equation 1.1 again, $|p_4|_{corrected}$ turns into $|P_4|_{corrected}$ and $|u_5|_{corrected}$ turns into $|U_5|_{corrected}$, expressed in decibels. (because the sensitivity of the Microflown is expressed in Pa*).

In order to calibrate the cross spectrum of p and u of the PU probe, the complex values for $S_{pu,comp}$ have to be composed from the amplitude, $|S_{PU}|$, and phase, $\varphi_{PU}$, using Equation 1.6:

$$S_{pu,comp} = |S_{PU}| \cdot \cos(\varphi_{PU}) + i \cdot |S_{PU}| \cdot \sin(\varphi_{PU}) = |S_{PU}| \cdot e^{i \cdot \varphi_{PU}} \qquad (6)$$

Now the measured data can be corrected using Equation 1.7:

$$S_{pu,cor} = \frac{S_{pu,comp}}{S_p \cdot S_u} \cdot \left(\cos\left(\varphi_{pu,cal}\right) - i \cdot \sin\left(\varphi_{pu,cal}\right)\right) = \frac{S_{pu,comp}}{S_p \cdot S_u} e^{-i\varphi_{pu,cal}} \qquad (7)$$

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

The argument of $S_{pu,cor}$ is the corrected phase shift [°] between the p and u signal of the PU probe (see Equation 1.8).

$$\varphi_{pu,cor} = \arg\left(S_{pu,cor}\right) \qquad (8)$$

## 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 $|P_4|_{corrected}$, the average of both signals (in Pa) is taken using Equation 1.9.

$$|p_{PP}| = \frac{|p_1| + |p_2|}{2} \qquad (9)$$

Then $|P_{PP}|$ is generated via Equation 1.1.

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 Equation 1.10.

$$|u_{PP}| = \left| \frac{|p_2| - |p_1| \cdot e^{i \cdot \varphi_{PP}}}{\rho \Delta \omega} \right| \qquad (10)$$

With:
ρ = the air density [$kg/m^2$]
Δ = the distance between the microphones of the PP probe [m] = 0.012m
ω = the angular velocity [$rad \cdot s^{-1}$] = 2·π·f

Now phase shift between $U_{PP}$ and $P_{PP}$ needs to be calculated via the following equations:

$$\varphi_{p,PP} = \arg\left(i \cdot \left(|p_2| - \left(|p_1| \cdot e^{i \cdot \varphi_{PP}}\right)\right)\right)$$
$$\varphi_{u,PP} = \arg\left(|p_2| + \left(|p_1| \cdot e^{i\varphi_{PP}}\right)\right) \qquad (11)$$
$$\varphi_{pu,PP} = \varphi_{u_{PP}} - \varphi_{p_{PP}}$$

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 Figure.7, the sound pressure levels ($x_{ref}$ = 20 · $10^{-6}$ [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.

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.

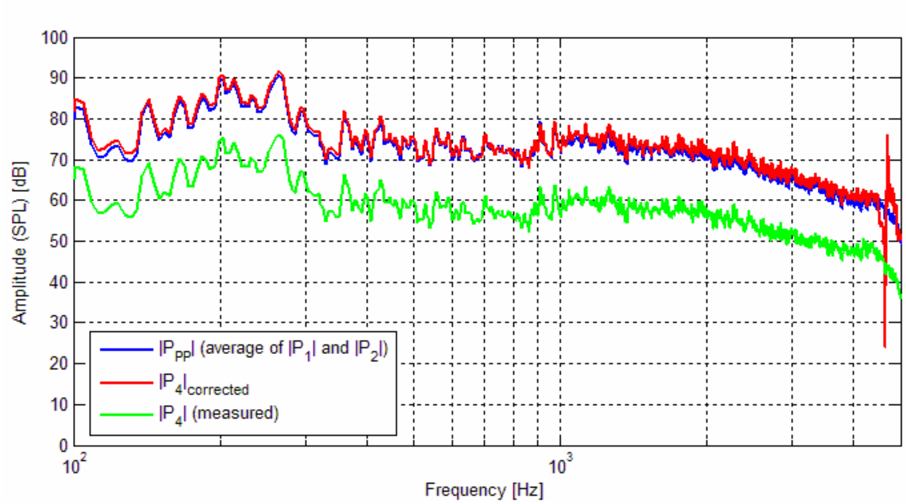


*Figure.7: A comparison of the pressure amplitude response of the PP and PU probe (both pressure microphones).*

## Particle velocity signals of the PP and PU probe

Figure.8 shows the amplitudes ($x_{ref}$ = 20 · $10^{-6}$ 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.

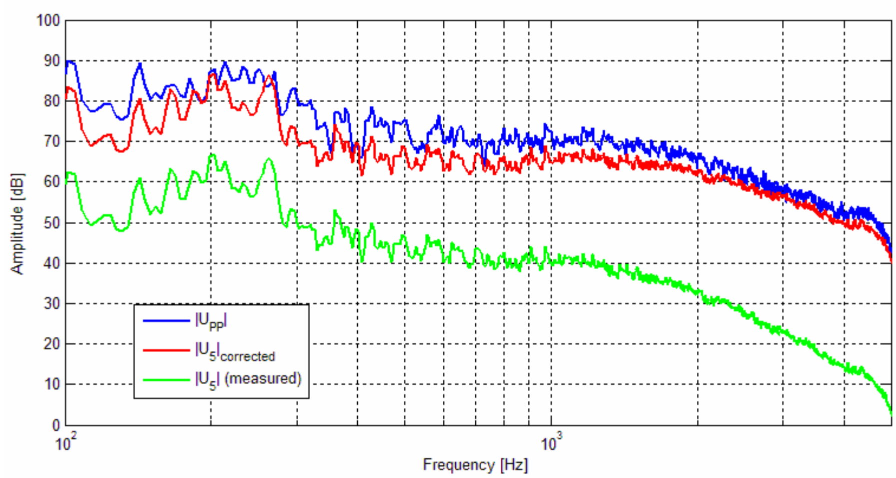


*Figure.8: A comparison of the particle velocity amplitudes for the measured and corrected $U_5$ and the estimated $U_{PP}$.*

## Phase shift between pressure and velocity of the PP and PU probe

The graph in Figure.9 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.

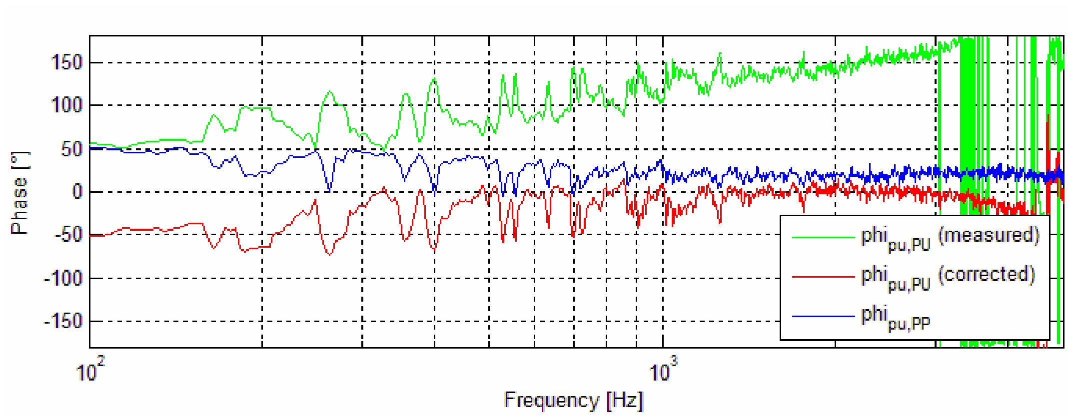


*Figure.9: A comparison between the phase responses.*

## Compare intensities

When all (corrected) values of p, u and φ of both probes are known, the sound intensities can be calculated and compared via the Equation 1.12 and 1.13.

$$I_{PP} = p_{PP} \cdot u_{PP} \cdot \cos\left(\varphi_{pu,PP}\right) \quad (12)$$

$$I_{PU} = p_{PU} \cdot u_{PU} \cdot \cos\left(\varphi_{pu,PU}\right) \quad (13)$$

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 Figure.10 and as expected $I_{PU}$ and $I_{PP}$ are nearly the same.

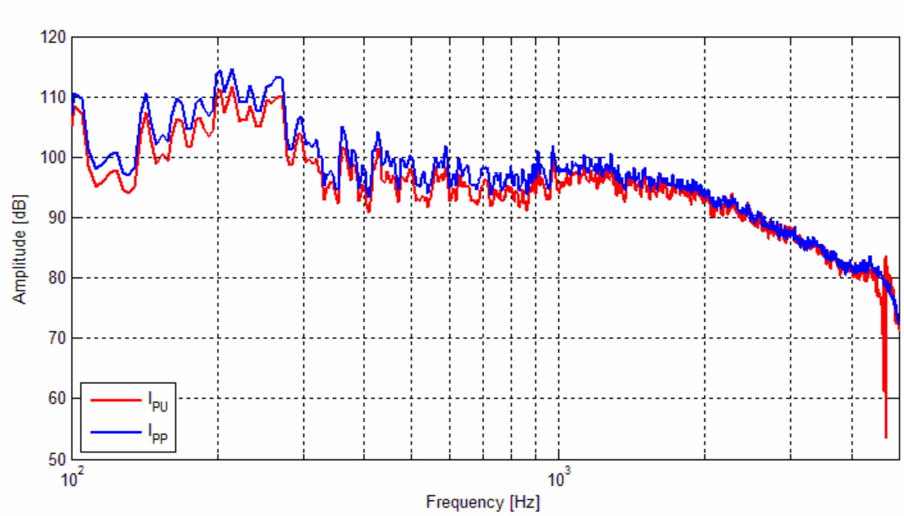


*Figure.10: The determined intensities using a PP and PU probe.*

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:

$$\hat{I}_r \cong I_r - \frac{\varphi_{pe}}{k\Delta r}\frac{p_{rms}^2}{\rho c} = I_r\left(1-\frac{\varphi_{pe}}{k\Delta r}\frac{p_{rms}^2/\rho c}{I_r}\right) \tag{14}$$

With:

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

$$J_r = \text{Im}\left\{S_{pu}e^{i\cdot\varphi_{pu}}\right\} = p\cdot u\cdot\sin\left(\varphi_{pu}\right) \tag{15}$$

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

$$I_r = \text{Re}\left\{S_{pu}e^{i\cdot\varphi_{pu}}\right\} = p\cdot u\cdot\cos\left(\varphi_{pu}\right) \tag{16}$$

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:

$$\text{Reactivity} = 10\cdot\log_{10}\left(\frac{p\cdot u\cdot\sin\left(\varphi_{pu}\right)}{p\cdot u\cdot\cos\left(\varphi_{pu}\right)}\right) = 10\cdot\log_{10}\left(\tan\left(\left|\varphi_{pu}\right|\right)\right)\quad[dB] \tag{17}$$

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 Figure.11. 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.

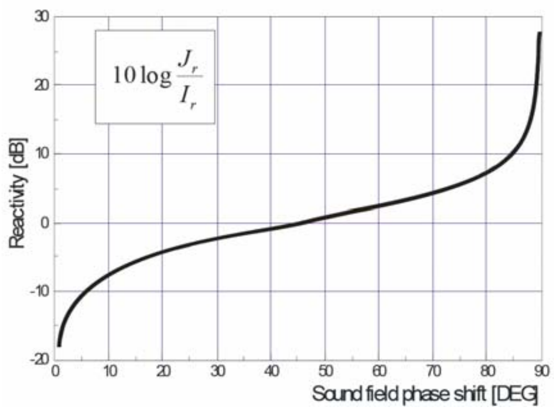


*Figure.11: Reactivity as function of the phase shift of sound pressure and particle velocity*

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 Figure 12. 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.

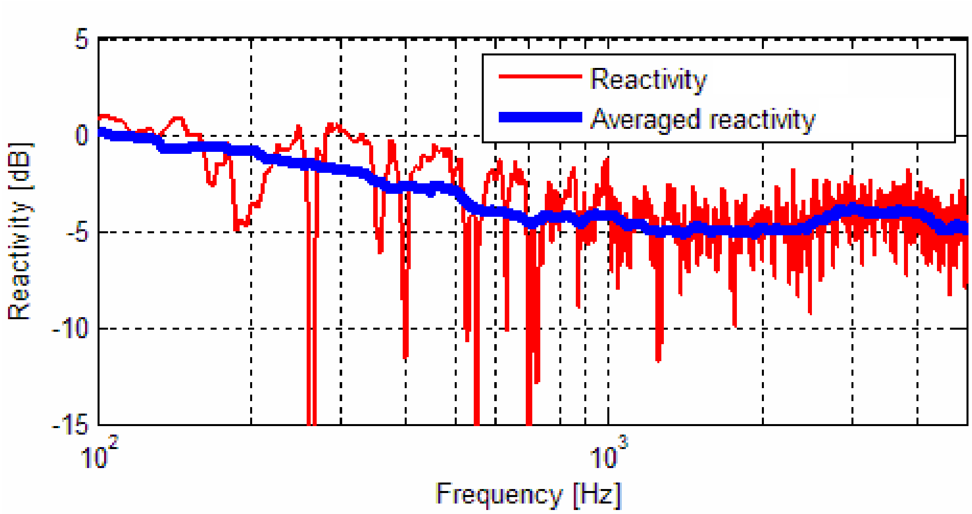


*Figure 12: Reactivity of the sound field.*