12 Source path contribution breakdown of a sound pressure based compliance test

12.1 Introduction

Many electromechanical components are tested acoustically. A standard way to do this is to measure the sound pressure level at a specified distance in an anechoic room.

The product is approved when the pressure spectrum is below a certain threshold level and rejected when the pressure spectrum is above the threshold.

The sound pressure compliance test is used as a reference so that it can be checked if a product meets the specifications. The test cannot be done in the production line because it requires an anechoic room. Such compliance tests are time consuming and it is not possible to have a 100% test of products.

Another issue is that the test will only tell if a product is ‘good’ or ‘bad’ and it gives no clue on what part of the product causes problems.

In this paper method is presented that shows all the sound sources of the product how they contribute to the sound pressure of the compliance test. The method gives the anechoic sound pressure level but an anechoic room is not required: the measurement can be done ‘on the table’. If only a few sources cause the acoustic emission (and this is in general the case), the method can even be used in the production line. This allows a 100% test of products.
12.2 Theory

The sound pressure compliance test can be depicted in a general way as shown in Fig. 12.2 (left). A product is placed and operated in an anechoic room and the sound pressure is measured at a specified distance. When the sound pressure level is below a certain sound pressure spectrum level, the product is approved, see Fig. 12.2 (right).

![Fig. 12.2: Schematic representation of the sound pressure compliance test.](image)

The sound pressure that is measured can be calculated by the Helmholtz integral equation [8].

![Fig. 12.3: Nomenclature in the exterior acoustic problem.](image)

The Helmholtz Integral Equation relates the acoustic pressure and normal velocity on the closed boundary surface \( S \) of a vibrating object to the radiated pressure field in the fluid domain:

\[
p(\bar{x}) = \oint_S \left[ \frac{\partial G(r)}{\partial n_y} p(\bar{y}) + i\omega \rho G(r) v_{ny}(\bar{y}) \right] dS
\]  

(1)

In a field point \( \bar{x} \), the \( p(\bar{x}) \) can be calculated. The unit normal to the surface at source point \( \bar{y} \), denoted as \( n_y \), is pointed into the fluid domain.
Distance $r$ is the length of vector $\vec{r}$ that is directed from the source point $\vec{y}$ to the field point $\vec{x}$: $r = \|\vec{x} - \vec{y}\|$. In an unbounded fluid domain without reflecting objects (free space), $G(r)$ is the Green’s function.

Physically, $G(r)$ represents the effect observed at point $\vec{x}$ created by a unit source located at point $\vec{y}$.

We now identify the Green’s function and gradient of the Green’s function with the reciprocally measured airborne noise transfer functions between pressure, particle velocity and volume velocity (i.e. the monopole sound source) [12]:

$$G(r) = \frac{i \cdot p_r}{\omega \rho_0 Q_r} ; \quad \frac{\partial G(r)}{\partial n_y} = \frac{v_r}{Q_r}$$

(2)

With $p_r/Q_r$ is the reciprocally obtained transfer function between a monopole sound source that replaces the pressure microphone shown in Fig. 12.2 (left) to the surface pressure measured at the product under test.

And with $v_r/Q_r$ is the reciprocally obtained transfer function between a monopole sound source that replaces the pressure microphone shown in Fig. 12.2 (left) to the surface velocity measured at the product under test.

Eq. (1) now alters in:

$$p(\vec{x}) = \oint_S \left\{ \frac{v_r}{Q_r} p(\vec{y}) + \frac{p_r}{Q_r} v_{n_r}(\vec{y}) \right\} dS$$

(3)

The first step in the source path contribution (SPC) breakdown is the measurement of the transfer functions $v_r/Q_r$ and $p_r/Q_r$. This is done by replacing the pressure microphone shown in Fig. 12.2 (left), with a monopole sound source and measuring the surface pressure and the normal surface velocity with a pu probe. The measurement can be done with one PU probe, by hand.

Fig. 12.4: The transfer function from point source Q and surface sound pressure (and normal surface velocity) is measured in an anechoic room.
Normally the surface of an object is of high acoustic impedance (acoustically reflecting). This can be measured by taking the ratio of the transfer functions $p_{ff}/v_{ff}$ and $p_s/v_s$:

$$Z_s = \frac{p_s}{u_s} \frac{u_{ff}}{p_{ff}}$$  \hspace{1cm} (4)

Eq (4) is only an estimation of the surface impedance in where the $p_{ff}/v_{ff}$ is the non calibrated free field impedance and $p_s/v_s$ is the measured non calibrated surface impedance. In [13] a more accurate method is presented to determine the surface impedance. The particle velocity level of a sound radiating object usually is much larger than the sound pressure level. Therefore, if the normalized surface impedance is much larger than one ($Z_s >> 1$), Eq. (3) simplifies in to:

$$p(\bar{x}) = \frac{P_r}{Q_r} v_s (\bar{y}) dS$$  \hspace{1cm} (5)

Practically this means that if the surface of the product under test is acoustically reflecting, the sound pressure at a certain location in the anechoic room is determined by the surface velocity and the measured transfer function $p_r/Q_r$.

If the surface of the surface of the product under test is acoustically absorbing, then a measurement of the surface pressure is also required, see also [14]. In this investigation it is assumed that the surface impedance of the product under test is high so that the measurement of the surface pressure is not required.

The measurement of the transfer function $p_r/Q_r$ should in principle be done in the anechoic room. For this only the shape of the product under test is required, it has not to be operational. This is important to know because the transfer function has only to be measured once, so if the product under test is modified in a way that the shape is not altered much, the transfer function will not alter.

It is also possible to perform the anechoic transfer function in a normal room. There should not be any reflective surfaces nearby (so walls, floor and ceiling should be much further away than the source-product distance). In such case the room reflections will be influencing the transfer function (in frequency domain) in a random way. The transfer function will have a 'noisy' character. This 'noise' is removed with a moving average smoothing algorithm.

The surface velocity does not have to be measured in the anechoic room if the surface impedance is high. This is because the surface velocity is not affected by background noise or reflections of the environment [11]. This is also important to realize because this means that the product under test can be measured at the location where modifications are made. This saves considerably in measurement (preparation) time and infrastructure cost.
Furthermore, when a certain part of the product under test is altered, it is usually sufficient to only measure the altered part. This again reduces the required measurement time considerably.

In practice Eq. (5) is rewritten in the discrete form if the surface $S$ divided in small sub surfaces $\Delta S$ so that in each sub surface the normal velocity and the Neumann Green function can be considered constant:

$$p(\bar{x}) = \sum \frac{P_r}{Q_r} v_n \Delta S$$

(6)

**Properties of the path**

The method consists on two steps. The path measurement and the measurement of the sound field of the product in operation. The path measurement gives information on the acoustic environment. The sound field of the product in operation gives information of the product.

The path measurement, that is the transfer function of the monopole sound source to the pressure and the normal surface velocity at the surface of the product under test, will provide important information on the following measurement steps. The measurement can be done with a point by point measurement with only one pu-probe.

1) As explained above, if the surface impedance is high, only the surface velocity (and not the surface pressure) has to be measured in the second phase of the procedure. This surface impedance is measured at the same time as the path is measured. In practice this takes only a few minutes.

2) It is possible to measure the intensity sound field of the product under test. This can be done when the radiation field of the product under test behaves as a set of uncorrelated noise sources in relation to the pressure microphone. If noise sources are uncorrelated, the phase of the velocity signals does not influence the sound pressure at the measurement position. If the phase has no influence, it has not to be measured and this simplifies the measurement.

If the environment is highly reflective (causing the emitted sound field to be uncorrelated at the position of the reference sound pressure microphone), the intensity field (or the absolute velocity field) can be used in further analysis [2], [3], [4], [5], [6], [7], [9], [10]. Because the object of this measurement is a synthesis of the sound pressure level in an anechoic room and it cannot be assumed that sources are uncorrelated, this intensity method is not applied here.

**Noise properties of the product under test**

After the transfer paths are measured the sound field of the product under test is determined. The way the sound is measured is depending on the source properties.
Of an acoustically reflecting source only the particle velocity at the surface is required. If the source has an absorbing boundary, the sound pressure has to be measured too (and also the path measurement \( u/Q \) has to be obtained).

**Coherent and stationary sound fields** can be measured with two probes. One acts as a reference and the other is measuring the complex sound field (so amplitude and phase). These sound fields may be expected if one actuator is causing the noise. It is also possible that multiple actuators are present but these can be analyzed separately. A practical case of this type of source is dealt with in paragraph 12.3.

**Multicoherent and stationary sound fields** are sound fields that have multiple coherent sources. To tackle this problem multiple references may be required. A method for this is presented in [16].

**Incoherent and stationary sound fields** can be measured with only one probe. Such sound fields may be expected if the sources can be seen as uncorrelated sound emitting monopoles. This can be expected when sources are small compared to the wavelength and relatively far from each other.

**Instationary sound fields** have to be measured with an array of probes. Such sound fields can be expected when actuators cause short events e.g. rattle or flaws.

The power fold is an actuator that is driven with one motor and no strange clicks, squeaks or rattles are present. Therefore in this case the sound field is treated as coherent and stationary. It is measured with two PU probes, see paragraph 12.3.

A HVAC is the system in a car that takes care of the heating, ventilation and air conditioning. If an internal valve motion causes noise, the motion causes the plastic of the HVAC to vibrate in a motion that is frequency dependent, time dependent and place dependent. Several modes of vibration can be expected in the plastic cover. The problem is therefore instationary. The measurement procedure of this HVAC is shown in paragraph 12.4: ‘Low sound level source path contribution on a HVAC’.

### 12.3 Coherent, stationary sound fields; a measurement

A power fold (that is an actuator that folds the mirrors of a car) is measured with the aforementioned method. The compliance test dictates that the power fold actuator shall not make more noise than a certain SPL (so measured with a sound pressure microphone) at 40cm distance from the actuator in an anechoic room.

**Step 1: Determination of the surface impedance**

The surface impedance of the device under test is measured in two steps. The method is similar to the measurements described in [13]. If the surface impedance is high there is no need to measure the sound pressure at the surface in step 4 of the procedure. And if the sound pressure is not
required, the path $u/Q$ is also not required in step 3 of the procedure. This saves measurement time.

First the sound pressure and particle velocity of the pu match probe are measured in a normal room with no obstacles nearby and the monopole is source switched on at 40cm distance from the probe. The ratio $Z_{ff} = p_{ff}/u_{ff}$ is measured without calibrating the source and both sound probes.

After this, the power fold is place close to the probe (without altering the setup) and the ratio $Z_s = p_s/u_s$ is measured at several locations.

The ratio $Z = Z_s/Z_{ff}$ is gives a good approximation of the normalized surface impedance (without calibration of probes and source required) and is shown in Fig. 22.6. A moving average algorithm is applied to remove room reflections.

![Fig. 12.5 left: The surface impedance is measured. In the back (sharp) the power fold and the pu match probe at the surface. On the foreground the monopole sound source is seen out of focus.](image)

![Fig. 22.6 (right): The measured surface impedance is high.](image)

As can be seen in Fig. 22.6 the normalized surface impedance shows to be much larger than one (i.e. larger than 0dB) and therefore the simplification of Eq. (3) in to eq. (5) is justified. In practice this means that in the source measurement only the surface velocity has to be measured at the surface and that the sound pressure at the surface is of no relevance.

Total measurement time (including set up) of this measurement step is a few minutes.

**Step 2: Calibration of the pressure and velocity element**

The pressure element of the pu-match probe needs to be calibrated in order to be able to calibrate the Microflown element. Once the sensitivity of the pressure element the sensitivity of the Microflown can be determined with the free field impedance.

In the same measurement run that the ratio $Z_{ff} = p_{ff}/u_{ff}$ is measured, a reference sound pressure microphone is used. The ratio of the sound pressure measured with the pu match and the reference microphone is used to calibrate the pressure element of the pu match probe.
The reference pressure microphone has a sensitivity of 14mV/Pa so the pressure element of the pu match has a sensitivity that is approx 10dB (approx. 3X) higher, see Fig. 12.7. The calibration of the pressure element takes a few minutes.

The Microflown has to be calibrated to get the true surface velocity value. Normal calibration procedures can of course be used for this but since a monopole sound source with a known radiation impedance is used for the path measurements and the pu-match was positioned at a known distance from the source in an environment with no reflecting obstacles nearby, the Microflown can also be calibrated in this set up. This saves setup time.

The free field impedance is known from the previous measurements. The inverse of the non calibrated free field impedance is the relative sensitivity of the Microflown (that is the sensitivity with as reference the non calibrated pressure element of the pu-match). This relative sensitivity is not measured with a plane wave but with a spherical one so this should be corrected for. The radiation impedance of a monopole sound source is given by [15]:
The sensitivity of the Microflown is now given by:

\[ S_u = Z^{-1}_{free\ field} Z^{-1}_{monopole} S_p \]

The only unknown in Eq. (8) is the sensitivity of the pressure microphone of the pu-match. This is determined at the same time as the free field path measurement, see above.

**Step 3: Measurement of the paths**

First the transfer path \( p/Q \) is measured in a normal room (the path \( u/Q \) is not required because the surface impedance is high). The room reflections are cancelled with a standard moving average algorithm. Because the object is small (5cm) compared to the object source distance (40cm), only a few measurements are taken (at each side of the power fold one measurement).

In [14] it was shown that to make the representation of the path more understandable, it is better to show the relative path. The measurements of the path \( p/Q \) are normalized to the theoretic free field path measurement at one measurement point.

In this paper a method is used that makes measurement procedure even less time consuming. In [14] the monopole sound source had to be calibrated [15]. In this study it shows that the monopole does not have to be calibrated because the path is normalized to the measured free field path (and not theoretic free field path as in [14]).

First the uncalibrated monopole is set up in a normal room with no sound reflecting obstacles nearby. A miniature pu-match probe is positioned 40cm from the source and the transfer function \( p/Q \) is measured. After smoothing with a moving average algorithm this transfer function represents the non-calibrated free field path. (This measurement is done at the same time as the impedance is measured so it requires no setup time).

After these measurements, the power fold is positioned close to the pu-match. Now the transfer function \( p/Q \) is measured again. After smoothing with a moving average algorithm this transfer function represents the non-calibrated path. (This measurement is done at the same time as the impedance is measured so it requires no setup time).

The ratio of the non-calibrated path and the non-calibrated free field path is the relative path. A calibration of the pressure element and the source is not required because the ratio is taken, and this saves time.

The relative transfer functions are simply determined by measuring the non calibrated sound pressure at several points close to the surface (with the monopole source switched on) at 40cm from the power fold and divide this by the non-calibrated free field path.
As can be seen in Fig. 12.9 left, the influence of the object under test is minimal below 1kHz and considerable above 1kHz. Fig. 12.9 middle: deviation of the relative path is in the order of 2dB below 1kHz and somewhat more above 1kHz. Fig. 12.9 right: there phase shift is almost linear with frequency what is consistent with the phase shift that can be expected form a path length difference. At approximately 5kHz for example, the phase shift from front to back is 360DEG. The wave length at 5kHz is in the order of 6cm which is approximately the path length from front to back.

These relative path measurements take a few minutes.

Step 4: Measurement of the source

The sources (the particle velocity measured at the surface of the power fold) are likely to be coherent because they are excited by the operation of a single motor. If the environment is highly reverberant, coherent noise sources may have a non coherent relation at a certain measurement position. This means that the phase of the velocity signal of the source has no effect on the sound pressure at the measurement position.

Consequence of non-coherent sources (that is measurement points at the surface) is that the phase of the signal does not have to be taken into account. If this is the case, the measurement procedure simplifies: no (phase) reference has to taken.

It is possible to determine from the path measurements if the environment is so that coherent sources become incoherent, this is explained in [14]. However here the environment is anechoic and therefore this has not to be determined: coherent sources will stay coherent.

The source is considered to be coherent and of high impedance. Therefore close to the surface the particle velocity has to be measured (and not the sound pressure, due to the high surface impedance) and the phase of the particle velocity should be measure too (because the coherent sources).

The measurement procedure is the following. First two Microflownns are positioned close to each other at the position where the relative path is determined (the front). Then one of the probes is repositioned in a number of measurement roving the surface.
The transfer function between the roving Microflown and the reference Microflown determines the phase shift between the measurement point and the reference point.

To get an impression of the source levels and interesting frequencies the auto spectrum of the sound pressure at the assessment point and the particle velocity close to the surface is measured.

As can be seen in Fig. 12.10, the sound pressure level has distinct peaks at 250Hz and multiples. The measured particle velocity level at the surface is much higher than the sound pressure level at 40cm as can be expected.

![Graph showing sound pressure and particle velocity levels](image)

Fig. 12.10: Measured sound levels. The particle velocity is measured at the surface and the sound pressure is measured 40cm from the power fold.

The surface velocity is shown for the first peak (approx. 250Hz and approx. 500Hz). As can be seen in Fig. 12.11, the red and blue parts are high levels but in anti phase.

The velocity profile at 250Hz shows that the front an the back are in anti phase, see Fig. 12.11. Physically this means that the complete device is vibrating.

Although the motor (shown at the left side in Fig. 12.11, left and at the right side in Fig. 12.11 right) is the actuator, most of the velocity is measured at the opposite side.

![Graph showing measured particle velocity levels at 250Hz](image)

Fig. 12.11: Measured particle velocity levels at 250Hz. The red and blue parts are high levels with opposite phase.
Step 5: Synthesis and verification of the sound pressure

The power spectrum of the sound pressure is measured at 40cm from the power fold. Because the emitted levels are low, the background noise level is disturbing the measurement but the peak at 250Hz can be assumed to be reasonable quality as they rise from the background noise considerably.

The pictures of Fig. 12.11 show the surface velocity profile. The velocity profiles in combination with the path look similar because the paths as are for all points almost the same (the variation is a few dB and a few degrees).

As can be seen in Fig. 12.11, at 250Hz the velocity profile in the front is in anti phase with the back. The side, see Fig. 12.11 middle, has a velocity profile that is divided in a positive and a negative part. This part therefore will almost not radiated sound. At 500Hz the same effect is observed (not shown).

The sound pressure that is generated is calculated with Eq. (6). Because in this case only four paths are measured (only the front, back and both sides) the problem is divided in four. The sum of the velocities multiplied with the area’s $\Delta S$ is calculated for each side. This is the source strength $\nu \Delta S = Q$ per side.

The source strength of the front side is of similar strength as the back side but as can be seen in the paths, the contribution to the sound pressure is different and this difference increases with frequency. This is an indication that the position of the measurement microphone (or the orientation of the product under test) is of influence in the anechoic measurement.

In the previous procedure only the relative paths are taken. Therefore these values have to be multiplied with the free field transfer function of a monopole. This is given by:

$$p(r) = \frac{\rho f}{2r} \nu \Delta S$$

(9)

The result of the calculated sound pressure (that is called the synthesized sound pressure) is shown in Fig. 12.12. As can be seen: the measured and the synthesized sound pressure are in good agreement. This indicates that the path and the surface velocity measurements are measured correctly.

The surface velocity measurements of the source in operation measurements are done in a normal room. The path measurements are done in a normal room taking care that all reflecting obstacles are far from the monopole source and power fold and the result is smoothed with a moving average algorithm removing possible reflections.

The result of this measurements done in a normal room is that the sources are visualized as they are perceived at the measurement position in an anechoic room.
Fig. 12.12: Synthesized sound pressure level (red) and measured sound pressure level (black).

The total measurement time (including set up time) for the path measurement was in the order of a half hour and for the source in operation was two hours (80 measurement points).

12.4 Low sound level source path contribution on a HVAC

To assess if the noise level of a HVAC is within limits a test is done by measuring its noise output with a pressure microphone at 20cm distance in an anechoic room. In this paragraph a method is presented that makes it possible to visualize all sources of the HVAC as a function of time and place. Although the pressure levels are low, the HVAC does not have to be measured in an anechoic room with this method.

Determination of a low pressure level in a noisy environment

Low level sources are difficult to measure with a pressure microphone in an environment with background noise. It is difficult to measure the sound pressure close to the surface and it is even more difficult to measure the sound pressure caused by the low emitting source 20cm away from the source.

A particle velocity measurement close to a surface is less affected by background noise compared to a sound pressure measurement. There are three reasons for that:

1. The sound pressure level and particle velocity level are of similar magnitude in the free field. If the sound wave reflects on a rigid surface, the sound pressure doubles and the particle velocity reduces to zero.

2. On the other hand, close to a vibrating (sound emitting) surface, the sound pressure level is reduced as compared to the particle velocity level that coincides with the surface velocity.

3. A sound pressure microphone is omni-directional and thus measures the sound field in all directions. A Microflown measures the particle velocity in one direction. Therefore in a diffuse sound field a Microflown measures only one third of the sound field whereas a pressure microphone measures the total sound field.
Once the normal particle velocity is measured close to the HVAC, the sound pressure at each point in space can be determined. This is done with the path of the reciprocity method. This path links the normal velocity to a sound pressure at a listening position.

**Measurements**

First a simple measurement is done with the monopole sound source to verify the measurement chain. After this the transfer functions $p/Q$ en $u/Q$ from monopole source to the surface of the HVAC are measured in half an hour. These transfer functions must be known before the HVAC is measured to be able to know if apart from the surface velocity also the surface pressure must be measured. If the surface impedance is high (this can be derived from the transfer functions), only the velocity has to be measured.

After this the HVAC is operated and its sound emission is measured. This is measured with an array of PU probes. An array is required if the source is coherent and varying in place and time. A point for point measurement is practically impossible.

**The monopole source**

The sensitivity of the reference Microflown of the monopole is 0.5mV/Pa*. The output voltage of the probe is measured, converted with the sensitivity to m/s and multiplied with the output area of the source (15mm diameter). The result is the volume velocity $Q$ of the source measured in m$^3$/s. As a first check the sound pressure is measured 20cm from the source in a normal room. The measured result is compared with the theoretical result that is calculated with:

\[ p(r) = i \rho c k \frac{Q}{4 \pi r} e^{-ikr} \tag{10.10} \]

The measured and calculated response is depicted in Fig. 12.13. As can be seen, both measured and calculated sound pressure level match reasonable. Most probably the differences are caused by the influence of the room.

![Graphs showing measured and calculated results](image)

Fig. 12.13 Left: volume velocity of the monopole source, right: the sound pressure level that the source produces at 20cm distance. The red line is the calculated SPL, the black line is the measured SPL.
The ratio \( \frac{p}{Q} \) is an important quantity in a transfer path analysis; it is the path from source to the listener’s position. In this case the listener’s position is the test microphone. It is for an engineer not easy to ‘feel’ how large this quantity must be. From Eq. (10.10) the ratio \( \frac{p}{Q} \) can be derived theoretically:

\[
\frac{p(r)}{Q} = \frac{i \rho c k e^{-ikr}}{4\pi r} = i \frac{\rho f e^{-ikr}}{2r}
\]  

From the measurement \( \frac{p}{Q} \) the practical value of the path can be derived. The ratio of the practical value and the theoretical one gives more insight. Zero dB and zero degrees means an anechoic condition without any obstacles. In Fig. 12.14 (right) this ratio between the measured path and theoretical (anechoic) path is shown for the measurement. As can be seen, the value varies around zero dB. The deviations are most probably caused by reflections.

![Fig. 12.14: Left: measured path Q/p. Right the ration of the measured free field path and the theoretical free field path.](image)

**Measurement of the path from HVAC to test microphone**

The path from the monopole sound source to the surface is measured by placing the source at the position where originally the reference pressure microphone was placed, see Fig. 12.15. During the path measurement the HVAC is not operated so it is possible to measure it with a single PU probe. This is not a very difficult task, done by hand. Approximately 80 measurement positions are measured in half an hour (with two persons). The transfer functions \( \frac{p}{Q} \) and \( \frac{u}{Q} \) are measured.

In Fig. 12.16 the relative paths are displayed. The relative path is the measured path divided by the theoretical anechoic path of 20cm, see also Eq. (10.11). As can be seen in Fig. 12.16, the variation in paths is roughly 10dB. This is cased by the path length variations and the acoustic properties of the surface.

In Fig. 12.17 the relative path is visualized for a frequency of 500Hz. As can be seen, in the middle of the HVAC the amplitude response of the path is increased 6dB. The path is relative to the free field path. Due to the HVAC as an obstacle, the pressure signal increases approximately 6dB.
Fig. 12.15 Left: test microphone is placed 20cm in front of a HVAC. Right a monopole sound source is placed at that position to be able to measure the path.

At the edges of the HVAC the distance to the monopole roughly doubles (compared to the middle) so in first instance the amplitude response of the path should roughly reduce 6dB. However, due to the angle of incidence, the path reduces more. Local variations are caused by the local surface properties.

![Graph showing sound pressure breakdown](image)

Fig. 12.16: Relative paths from source to measurement locations

![Visualisation of relative path](image)

Fig. 12.17: Visualization of the relative path p/Q at 500Hz.
The phase is zero in the middle and shifts to -100 degrees to the edges. This is explained by the extra path length. At 500Hz the wavelength is 68cm so an extra 20cm path length would cause 105 degrees phase lag. Local variations are caused by the local surface properties.

**Measurement of the surface impedance of the HVAC**

The transfer function \( p/Q \) is measured and displayed in the previous paragraph. At the same time the transfer function \( u/Q \) is measured. However the surface velocity level is expected to be (much) lower than the surface pressure level. The ratio \( p/u \) at the surface is much easier to measure than the path \( u/Q \). From the surface impedance and the path \( p/Q \), the transfer function \( u/Q \) can be derived (if required): \( Z_s = p/u = (p/Q)/(u/Q) \).

![Graph showing surface impedance](image)

If \( (p/Q)/(u/Q) = Z_s << \rho c \), the last term of the Helmholz integral is negligible and only the measurement of the surface velocity is required. The surface impedance measurement is therefore very important.

**Background noise reduction**

The ratio of the radiation impedance \( Z_r \) and the surface impedance \( Z_s \) determines the reduction of background noise that a Microflown has compared to a pressure microphone close to the surface [11]. The surface impedance \( Z_s \) shows how much the sound pressure is larger than the particle velocity if a sound wave hits the surface of the HVAC. The radiation impedance shows how much smaller the sound pressure level is compared to the particle velocity level if the sources of HVAC emits.

In Fig. 12.19 left, the surface impedance at a point of the HVAC is shown. The value is in the order of 20dB indicating that the surface pressure is 20dB higher than the surface velocity. This is caused by the reflection of the sound wave on the HVAC. Due to this the pressure goes up and the velocity goes down [11].

Generally speaking, close to an emitting source the sound pressure level is lower than the particle velocity level [1], [11]. For each type of source this is different. The ratio of sound pressure and particle velocity \( 1/Z_r = u/p \) shows how much higher the velocity level is compared to the pressure level. In Fig. 12.19 right this is shown for the HVAC in operation.
The sum (in dB) of surface impedance $Z_s$ and the inverse of the radiation impedance $1/Z_r$ indicates how much the influence of the background noise is reduced due to the use of a velocity probe close by instead of a pressure microphone.

It shows also how much smaller the second term is in Eq. (3) is compared to the first term. In this case the second term is about 30 dB smaller and can therefore be left out.

![Graphs showing surface impedance and radiation impedance.](image)

Fig. 12.19: Left: surface impedance (p/u), right the inverse of the radiation impedance (u/p). The sum of estimates how much dB the second term in Eq. (3) is smaller than the first term. It is also an estimation of the rejection of background noise.

**Measurement of the normal surface velocity of the HVAC in operation**

As second step the sources of the HVAC in operation are measured. Because the surface impedance is high, only the surface velocity is measured. At the following page the surface velocity distribution is shown in 0.2 second steps. The red parts indicate the maximal surface velocity (in the order of 0.3 mm/s), the blue parts are also the maximal surface velocity but in opposite phase. From these pictures a movie is made.

**Pressure reconstruction**

The particle velocity distributions (as function of time) are multiplied with the path. The velocity probes are spaced 5 cm. The equivalent volume velocity sources are determined by multiplying each velocity value with $0.05 \times 0.05 \text{m}^2$. Those values are multiplied with the path. The phases of the velocity signals are summed with the phase of the path and visualized below.

The pictures that are shown are the distribution of the sources that contribute to a sound pressure at 20 cm in front of the HVAC.

The red sources and blue sources are sources that are out of phase. They might cancel each other. So simply remove one source might even increase the sound pressure level at the test microphone.

![Graphs showing velocity distribution and reconstructed pressure distribution.](image)

Fig. 12.20: (next page) velocity distribution as function of time at 500 Hz. The surface velocity distribution is shown in 0.5 second steps.

Fig. 12.21: (second next page) velocity distribution multiplied with the path result in a reconstructed pressure distribution as function of time at 500 Hz. The reconstructed sound pressure distribution is shown in 0.5 second steps.
References

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Sound pressure breakdown
