4A Standard Calibration Techniques

4A.1 Summary

In the previous chapter various methods to calibrate the Microflown are presented in general; in this chapter the standard methods are explained. The goal of this chapter is to explain the standard methods step by step.

A **piston in a sphere calibration method** used the known sound field in front of a loudspeaker in a spherical housing. The usable bandwidth is 80Hz-20kHz. If the reference pressure microphone is put inside the sphere, the Microflown can be calibrated in a 20Hz-200Hz bandwidth. So this calibrator covers the entire frequency range in two steps.

The **short standing wave tube method** is an improvement of the log standing wave tube method that is not used anymore. The sound field just before the end of the tube is used to calibrate. The method is usable in a 20Hz-3.5kHz bandwidth.

4A.2 Sphere calibration

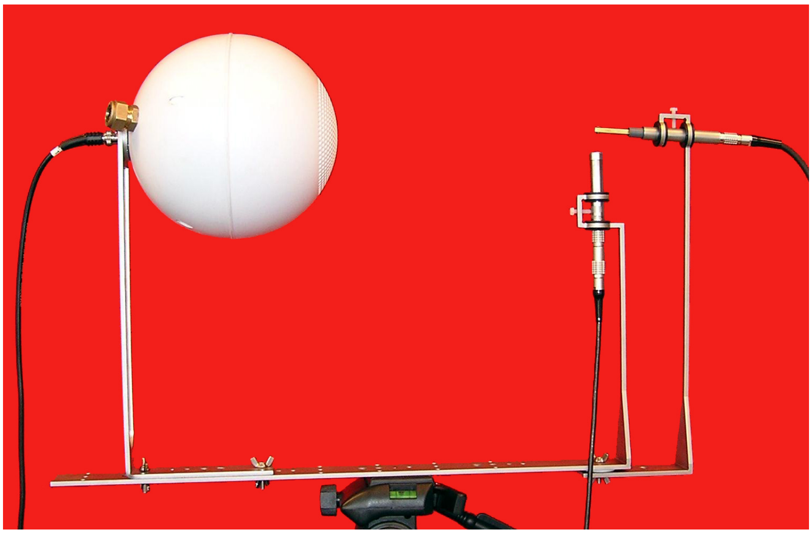
Recently it is shown that it is possible to calibrate a sound pressure and particle velocity sensor in free field conditions at higher frequencies. This is done by using the known acoustic impedance at a certain distance of a spherical loudspeaker. When the sound pressure is measured with a calibrated reference microphone the particle velocity can be calculated from the known impedance and the measured pressure. At lower frequencies this approach gives unreliable results.

The method is extended to lower frequencies by measuring the acoustic pressure inside the spherical source. At lower frequencies the sound pressure inside the sphere is proportional to the movement of the loudspeaker membrane. If the movement is known, the particle velocity in front of the loudspeaker can be derived.

This low frequency approach is combined with the high frequency approach giving a full bandwidth calibration procedure which can be used in free field conditions using a single calibration setup.

4A.3 High frequency calibration

For the calibration of a pressure-velocity probe a special loudspeaker is designed that has a known acoustic impedance, see Fig. 4A.1. The pressure velocity probe and a reference pressure microphone with a known sensitivity (in the present case a G.R.A.S. 40AC with G.R.A.S. 26AF preamplifier is used) will be positioned at certain distance in front of the speaker. The microphone and the pressure-velocity probe are positioned at nearly the same position, see Fig. 4A.1. With the measured pressure with the reference microphone and the known impedance at the measurement location the pressure-velocity probe can be characterized.



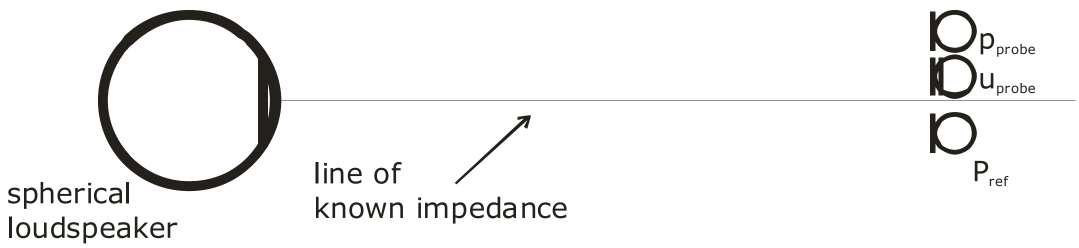


Fig. 4A.1: The piston in a sphere set up. The sound pressure probe is calibrated in the full acoustic bandwidth; the particle velocity probe is calibrated in a 100Hz-20kHz bandwidth.

The loudspeaker consists of a hard plastic sphere in which a loudspeaker is placed. This spherical loudspeaker can be modeled as a sphere with radius *a* and a moving piston with radius *b*. The relation between sound pressure and particle velocity (the acoustic impedance) on the axis of the piston is given by:

$$Z_{sphere}(r) = -i\rho c \frac{\sum_{m=0}^{\infty}\left(P_{m-1}(\cos\alpha) - P_{m+1}(\cos\alpha)\right)\frac{h_m(kr)}{h'_m(ka)}}{\sum_{m=0}^{\infty}\left(P_{m-1}(\cos\alpha) - P_{m+1}(\cos\alpha)\right)\frac{h'_m(kr)}{h'_m(ka)}} \qquad (4A.1)$$

Where r is the distance form the centre of the sphere, α=arcsin(b/a), a is the radius of the sphere, b is the radius of the loudspeaker and P_m is the Legendre function of the order m, h_m is the spherical Hankel function of the second kind and order m, and h'_m is its derivative, ρ is the density of the air and c is the speed of sound in air. Because the exact values of the density ρ and the speed of sound in air c are not known, but the exact pressure is measured by the reference microphone, the calibration results are normalized with the specific impedance ρc. The sensitivity of the particle velocity sensor will therefore by given in mV/Pa*. Where 1 Pa* corresponds to 1Pa/ρc ≈ 2.4 mm/s. The exact value of the specific impedance depends on environmental conditions, like temperature, atmospheric pressure and relative humidity. By normalizing with the specific impedance the calibration becomes independent of the environmental conditions.

Although the (normalized) impedance on the axis of the spherical source is described by the complex expression (4A.1), the resulting impedance is quite similar to the acoustic impedance of a monopole source, given by:

$$Z(r) = \rho c \frac{ikr}{1+ikr} \tag{4A.2}$$

The ratio of the impedance of the piston (diameter piston 6.5cm) in a sphere (diameter 20.5cm), described by Eq. (4A.1) and the acoustic impedance of a monopole source, Eq. (4A.2), is given in Fig. 4A.2 for varying distance from the front of the sphere. As can be expected, the difference between both impedance descriptions is largest at short distance from the source and for low frequencies.

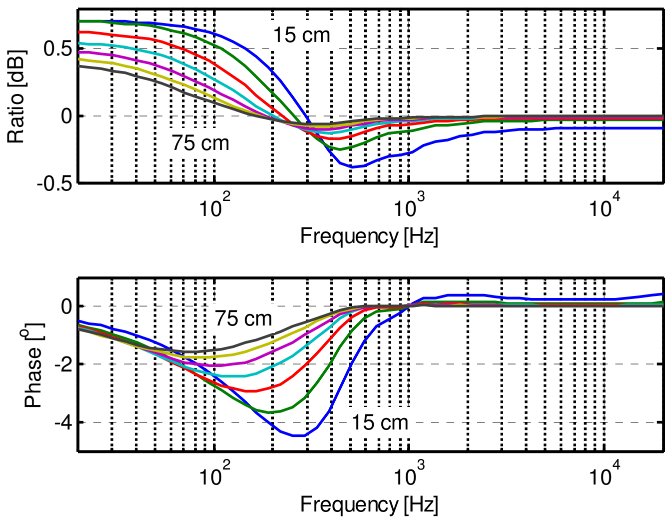


Fig. 4A.2: The ratio between the impedance of a piston in a sphere and the impedance of a monopole (Diameter piston 6.5 cm, diameter sphere 20.5 cm). The distance from the front of the sphere is increased from 15 to 75 cm in steps of 10 cm.

The 'piston in a sphere' model becomes more similar to a monopole source model when the dimensions of the sphere become smaller. The ratio between the piston in a sphere and the monopole source model for a small sphere (diameter 9.0cm with 4.5cm piston) and the large sphere (diameter 20.5cm with 6.5cm piston) is given in Fig. 4A.3. It is clear that when the dimensions become smaller the source characteristics approach that of a monopole source.

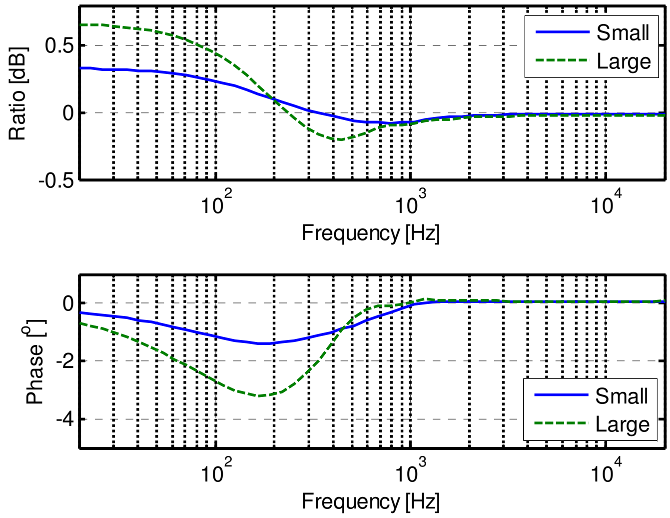


Fig. 4A.3: The ratio between the impedance of a piston in a sphere and a monopole (Small sphere: Diameter piston 4.5 cm, diameter sphere 9.0 cm, Large sphere: Diameter piston 6.0 cm, diameter sphere 20.5 cm). The distance from the front of the sphere is in both cases 31 cm.

Because a source based on the small sphere is more like a monopole source and is more practical to use, this small source is more favorable to apply as the calibration source in practical situations.

For the calibration procedure in the current paper the standard pressure-velocity probe is used. This probe has a packaging for protection and increases the sensitivity of the particle velocity sensor. However, this packaging makes that the PU probe can be used up to about 10kHz. Above these frequencies the packages has to much influence on the measured sound field.

4A.4 Low frequency calibration

At lower frequencies the calibration procedure described before has some drawbacks. At lower frequencies the background noise has higher pressure levels than the noise that is generated by the source. This is shown in Fig. 4A.4, where some measurement results are given in an ordinary room. The output of the microphone with the source on and the output when the source is switched off are given in the upper figure[1]. As can be seen, the background noise is dominant for frequencies below 50Hz. For the particle

[1] All measurements are done with a Siglab 20-42 signal analyzer

velocity this effect is not observed, see the lower figure. There the difference between background noise and the emitted signal from the loudspeaker is much higher. The main reason for this observation is that in the near field of a sound source the ratio between particle velocity and pressure increases. So for low frequencies, when the probe is in the near field of the source, the ratio between particle velocity and acoustic pressure is significant. For the background noise, for which the probe is in the far field, the ratio between pressure and particle velocity is similar as for high frequencies.

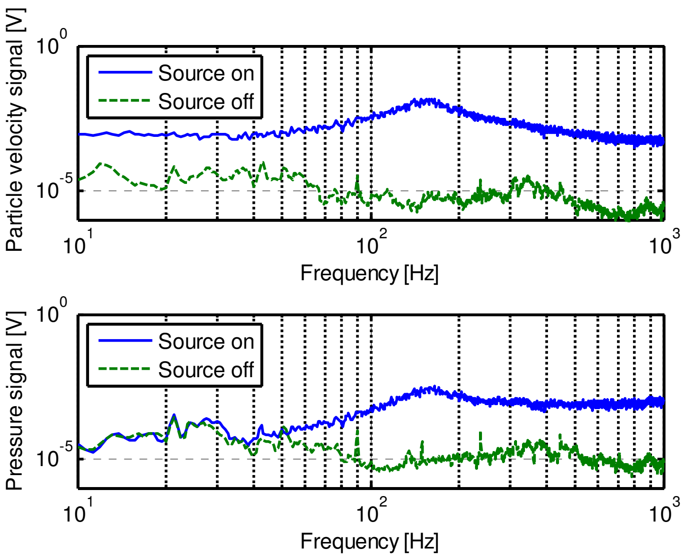
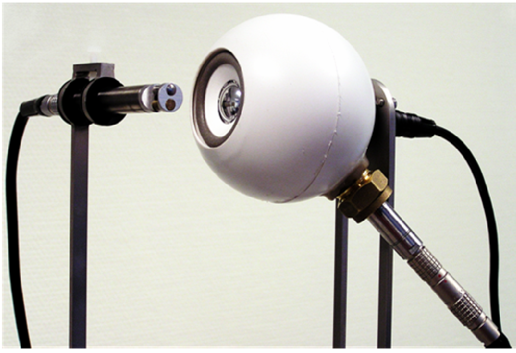


Fig. 4A.4: Autospectra of pressure and velocity signals with source switched on and off. At low frequencies the microphone signal is clearly more affected by background noise than the particle velocity signal.

Therefore, in an anechoic room with low background noise the method will work down to 50Hz. In an ordinary room the background noise is higher and the method starts to work properly from 100Hz to 200Hz. The sound pressure microphone however can be calibrated in the 20Hz-10kHz bandwidth, because its calibration is based on the comparison with the output of the reference microphone which is at the same position. Both sensors are omnidirectional and it doesn't matter if the output is caused by background noise or by the spherical loudspeaker. For the particle velocity sensor this doesn't hold, because its calibration is based on the known impedance due to the loudspeaker. When the background noise becomes dominant, Equation (4A.1) can not be applied anymore. Therefore, depending on the amount of background noise, the velocity sensor can be calibrated in the frequency range from several hundred Hz to 20kHz. For the low frequencies a different approach will be followed, see Fig. 4A.5.



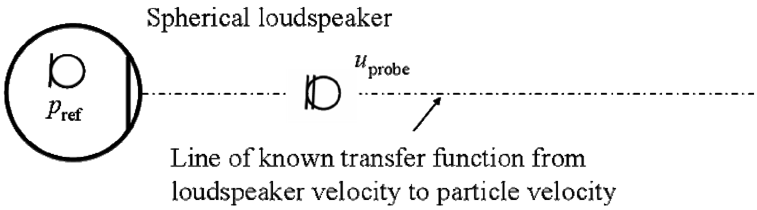


Fig. 4A.5: Measurement set up for the small sphere low frequency calibration. The pressure microphone is put inside the sphere.

Now the reference microphone is put into a hole in the sphere and tightened with rubber rings. The reference microphone measures the interior pressure variations of the sphere and the relation between the interior pressure and the particle velocity at a distance in front of the sphere will be used for calibration. The advantage is that the pressure inside the sphere is sufficiently high down to lower frequencies and there is a simple relation between the interior pressure and the particle velocity at the probe position. For low frequencies (well below the first internal acoustic resonance of the sphere), the interior pressure is linear related to the velocity of the membrane of the loudspeaker. Due to the continuity condition the particle velocity just in front of the membrane is similar to the velocity of the membrane itself. Therefore, the relation between the sound pressure in the sphere and the particle velocity just in front of the sphere is given by:

$$u_{piston} = -\frac{i\omega V_0}{\gamma A_0 p_0} p_{ref} \tag{4A.3}$$

where ω is the angular frequency, V_0 is the interior volume of the sphere, A_0 the surface area of the moving piston, p_0 the ambient pressure and γ is the ratio of specific heats (1.4 for normal air). To apply this relation it is assumed that the compression and rarefaction of the air in the sphere is an adiabatic process.

To verify that this relation a simple experiment is performed, see Fig. 4A.6. Here the transfer function between the sound pressure in the sphere and the displacement of the membrane is given. The displacement is measured by integrating twice the output of an accelerometer which for this measurement is glued on the membrane of the loudspeaker. It is clear that the pressure is linearly related to the displacement from 10Hz up to about 200Hz. For higher frequencies the method fails because of internal acoustic modes in the sphere. If the wavelength is smaller than the dimensions of the sphere the sound pressure is not uniform in the sphere and the simple relation given by Equation (4A.3) is not valid anymore.

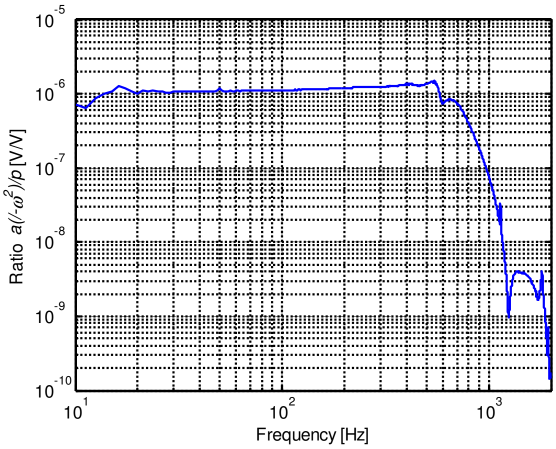


Fig. 4A.6: Measured transfer function between pressure in the sphere and the displacement of the membrane (large sphere).

Because the characteristics of an acoustic field around a sphere with a moving piston are known, also the particle velocity at a certain distance of the sphere can be derived when the particle velocity just in front of the piston is known. Therefore the particle velocity at the measurement position can be related to the interior pressure of the sphere.

The relation between the particle velocity just in front of the piston, which equals the normal velocity of this pistion (u_n) and the particle velocity at a distance r from the centre of the sphere is given by:

$$u(r) = -\frac{u_n}{2}\sum_{m=0}^{\infty}\left(P_{m-1}(\cos\alpha) - P_{m+1}(\cos\alpha)\right)\frac{h_m'(kr)}{h_m'(ka)} \quad (4A.4)$$

The ratio of the surface velocity of the loudspeaker (u_n) to the particle velocity $u(r)$ measured from 1-16cm in front of a piston (6.5cm) in a sphere (20.5 cm) calculated with Equation (4A.4) is given in Fig. 4A.7. It is clear that for lower frequencies (<200Hz) the amplitude is almost independent of the frequency and the phase shift is almost zero. This means that the phase shift of the reference pressure microphone can directly be related to the phase of the particle velocity sensor. The ratio has to be 90 degrees and can be used for calibration.

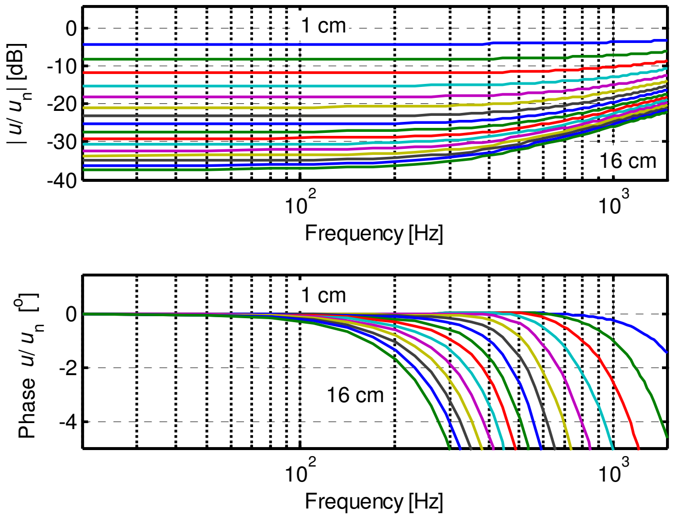


Fig. 4A.7: Transfer function between particle velocities at several distances from the moving piston and the particle velocity just in front of the piston as given by Equation (4A.4). The diameter of the sphere is 20.5cm and the piston diameter is 6.5cm.

For a small sphere, close to the moving piston these condition are valid up to even higher frequencies, see Fig. 4A.8. The phase between the particle velocity at 1 cm to the moving piston and the piston itself is just about 0.1° at 1 kHz. This means that the column of air in front of the speaker behaves as if it is incompressible.

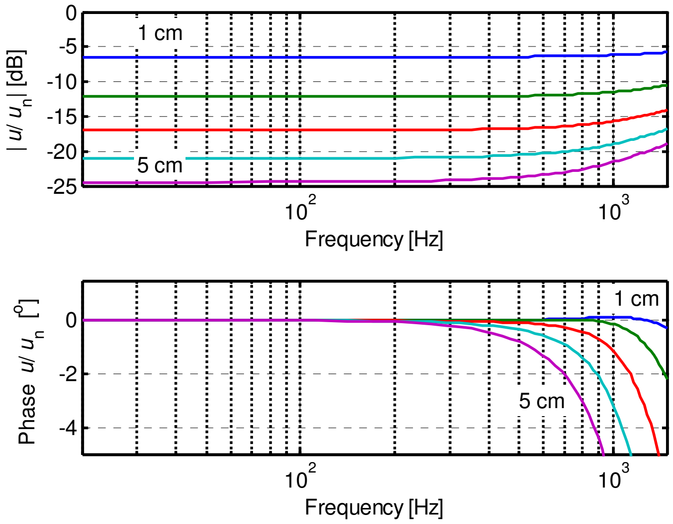


Fig. 4A.8: Transfer function between particle velocities at several distances from the moving piston and the particle velocity just in front of the piston as given by Equation (4A.4). The diameter of the sphere is 9cm and the piston diameter is 4.5cm.

As a check for this behaviour a measurement is performed with the large spherical loudspeaker. The transfer function is measured between the particle velocity 1cm in front of the piston and the particle velocity at 14cm, see Fig. 4A.9. As can be clearly seen, the phase shift at low frequencies (<200Hz) is almost zero, as is also predicted by the model, for which the results are also plotted in this figure. The measurement results are in very good agreement with the model.

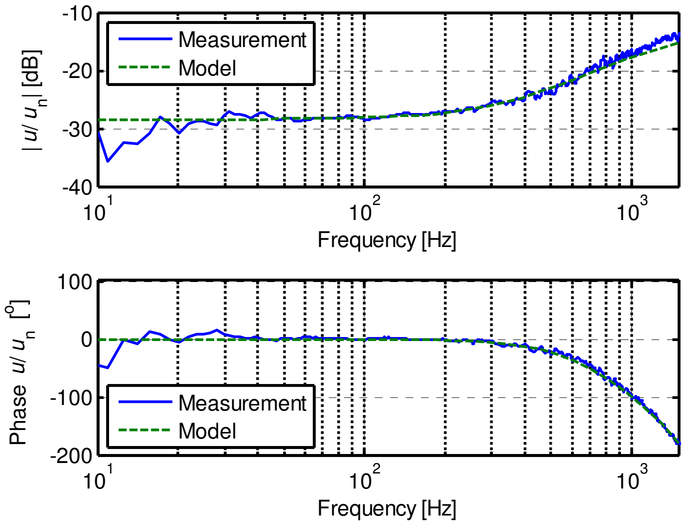


Fig. 4A.9: Measured and modeled transfer function of particle velocities measured at 1cm and at 14cm in front of the large spherical loudspeaker. Upper: modulus, Lower: phase.

Combining equations (4A.3) and (4A.4) gives a relation between the particle velocity at position r and the pressure in the piston. This means that when the interior acoustic pressure of the sphere is measured, the particle velocity at distance r is exactly known. This known particle velocity value is used for calibration. This can only be done for frequencies, well below the first internal resonance frequency of the sphere. For higher frequencies the pressure inside the sphere is not uniform anymore. With a correction, taking into the effect the first resonance frequency of the sphere, the low frequency approach can be applied up to higher frequencies.

4A.5 Combining the low and high frequency approach

Two steps to determine the full bandwidth sensitivity and phase characteristics of the pressure-velocity probe are described, one for the high frequency range and one for the low frequency range. These two results will be combined in the final step. It is assumed that the high frequency approach and low frequency approach should give similar results in the medium frequency range.

The complete procedure is now as follows. First a measurement is performed with the high frequency configuration. That means that the reference pressure sensor and the particle-velocity probe are held at a known position on the axis of the spherical source, while white noise is emitted. The transfer functions between all sensors are measured. The ratio of the reference microphone output (in Volts) and the output of the pressure sensor (in Volts) is directly used to determine the sensitivity S_p [mV/Pa] of the pressure sensor:

$$S_p\left[\frac{\mathrm{mV}}{\mathrm{Pa}}\right]=\frac{p}{p_{ref}}\left[\frac{\mathrm{V}}{\mathrm{V}}\right]\cdot S_{ref}\left[\frac{\mathrm{mV}}{\mathrm{Pa}}\right] \tag{4A.5}$$

where S_{ref} is the known sensitivity of the reference microphone (in this example 14mV/Pa), which is assumed to be independent of frequency in the frequency range of interest.

The particle velocity cannot directly linked to the reference sensor output. Here the model of the impedance of the piston in a sphere, Equation (4A.1), has to be used. The sensitivity of the particle velocity sensor S_u [mV/Pa*] is calculated by:

$$S_u\left[\frac{\mathrm{mV}}{\mathrm{Pa}^*}\right]=\frac{u}{p_{ref}}\left[\frac{\mathrm{V}}{\mathrm{V}}\right]\cdot Z_{sphere}\left[\frac{\mathrm{Pa}}{\mathrm{Pa}^*}\right]\cdot S_{ref}\left[\frac{\mathrm{mV}}{\mathrm{Pa}}\right] \tag{4A.6}$$

Now the sensitivity of the pressure sensor of the probe is known for the complete frequency range and the sensitivity of the particle velocity sensor only for the high frequency range.

Next, the reference pressure sensor is put in the hole of sphere and tightened with rubber rings so that the sphere is leakage free. Again all transfer functions are measured while white noise is emitted by the source. The particle velocity is now calculated based on equations (4A.3) and (4A.4):

$$S_u\left[\frac{\mathrm{mV}}{\mathrm{Pa}^*}\right]=\frac{u}{p_{ref}}\left[\frac{\mathrm{V}}{\mathrm{V}}\right]\cdot\frac{u_n}{u}\left[\frac{\mathrm{Pa}^*}{\mathrm{Pa}^*}\right]\cdot\frac{p_{ref}}{u_n}\left[\frac{\mathrm{Pa}}{\mathrm{Pa}^*}\right]\cdot S_{ref}\left[\frac{\mathrm{mV}}{\mathrm{Pa}}\right] \tag{4A.7}$$

Equation (4A.3) relates the pressure p_{ref} to the absolute normal velocity u_n [m/s] of the piston instead of the normalized velocity u [Pa*]. Besides, there are some parameters in that equation that are not known exactly, such as the volume of the interior of the sphere and the moving surface area of the piston. Therefore the relation is not known in absolute sense. However, by not knowing the exact scalar values only an amplitude error is made which is constant over the frequency range. The amplitude error can be resolved by shifting the low frequency calibration curve in vertical direction such that it coincides with the high frequency calibration curve. This is shown in Fig. 4A.10.

So in the next step the low and high frequency curves are connected. For the amplitude, see Fig. 4A.10 upper, the low frequency calibration curve (<350Hz) is shifted such that it connects with the high frequency curve. The phase is a continuous line over the frequency. Any irregularities are due to the correction term, for which the distance is the most important. Because for the low frequency approach around 350Hz the phase is exact, the correction for the high frequencies can be tuned, such that that the phase connects with the phase determined for low frequencies. In this way a full bandwidth calibration is performed.

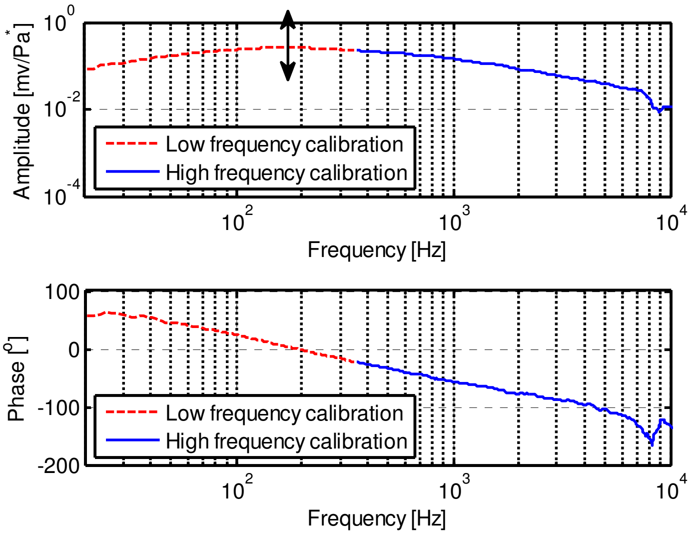


Fig. 4A.10: Low and high frequency calibration combined.

Before connecting the low and high frequency calibration curve, the complex sensitivities for the high frequency approach are smoothed. Because of the reflections in the ordinary room, the determined sensitivities seem rather noisy. This is avoided by smoothing the results by a moving average filter. Another technique to smooth the curves is a time selective technique. In this way room reflections can be removed by canceling the reflected signals in the impulse response. However this method is not accurate for low frequencies.

4A.6 New calibration setup

The small (9cm) sphere has only advantages. The low frequency set up works up to higher frequencies and the model of the impedance of the high frequency set up resembles almost the model of a point source. This simplifies the understanding of the raw calibration measurement data. A last advantage is that a smaller source is easier to handle.

The new set up is modified so that the probe under test can easily be shifted from the high frequency measurement position (relative far from the source) to the low frequency measurement position (relative close to the source). See Fig. 4A.11.

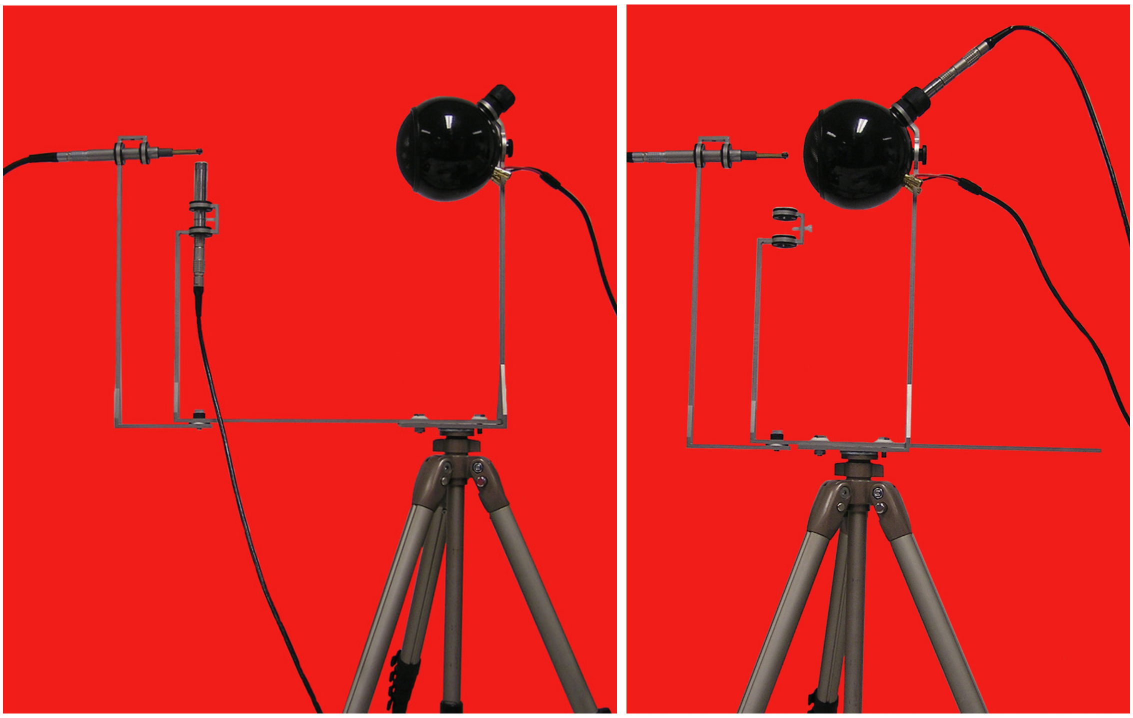


Fig. 4A.11: The new small sphere calibration set up.

4A.7 Model approximation

For most sensors, the sensitivity is independent of frequency in the range of interest. The sensitivity of particle velocity sensors, however, is frequency dependent as is clearly visible in Fig. 4A.10. For practical applications it is not convenient to use a measured calibration curve to calculate the particle velocity sensor from the measured voltage. Therefore, the calibration curve is approximated by a simple analytic model containing some parameters. The amplitude of the particle velocity sensitivity *S*(*f*) is approximated by:

$$\left|S(f)\right| = \frac{LFS}{\sqrt{\left(1+\left(\frac{f_{c1u}}{f}\right)^2\right)\left(1+\left(\frac{f}{f_{c2u}}\right)^2\right)\left(1+\left(\frac{f}{f_{c3u}}\right)^2\right)}} \tag{4A.8}$$

Where *LFS* [mV/Pa*] is the low frequency sensitivity and f_{c1u}, f_{c2u}, f_{c3u} are some characteristic frequencies which describe the corner frequencies of the calibration curve in Fig. 4A.10.

The phase is modelled by:

$$phase(S(f)) = \arctan\left(\frac{C_1}{f}\right) - \arctan\left(\frac{f}{C_2}\right) - \arctan\left(\frac{f}{C_3}\right) \tag{4A.9}$$

Where C_1, C_2 and C_3 are three characteristic frequencies which can be different from those of the amplitude approximation curve.

After calibration, the model is fit on the measured calibration curve given in Fig. 4A.10. The values of the current probe are *LFS*=240.1 mV/Pa*, f_{c1}=72Hz, f_{c2}= 750Hz, f_{c3}=21.910Hz, C_1=44Hz, C_2=560Hz and C_3=11000Hz. Both measured and model are given in Fig. 4A.12. Both the amplitude and phase are well approximated, although for some frequencies the differences can be significant.

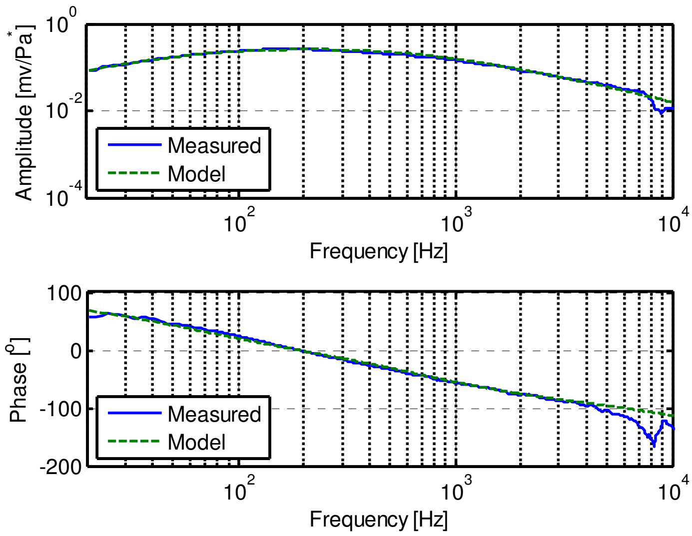


Fig. 4A.12: The measured calibration curve is approximated by a model.

4A.8 Introduction standing wave tubes

The sound field in a tube is used to calibrate. In contrast to an anechoic room where in theory all sound is absorbed at the walls, in the tube all sound is reflected. The standing wave tube calibration methods have proven themselves many years now.

There are two types of standing wave tube calibration techniques, a long tube technique where the probe is positioned more than one quarter wavelength away from the end of the tube. And a short tube technique where the probe is positioned closer than one quarter wavelength to the end of the tube. The long tube calibration technique is not used anymore. Of course 'long' and 'short' are relative to the wavelength. The methods will be discussed below; first a summary of general tube theory is given. The extended theory is given in chapter 4: 'Calibration'.

A rigidly terminated tube with rigged side walls with a diameter small compared to the wavelength is called a standing wave tube. The sound wave can only travel in one dimension and all the sound is reflected at the end of the tube. In these realizations this is true up to 3.5kHz.

At lower frequencies (f<100Hz) small leakages in the probe mountings influence the measurements. To avoid these influences, the probes have to be sealed with e.g. a rubber ring. The short calibration tube has these rings.

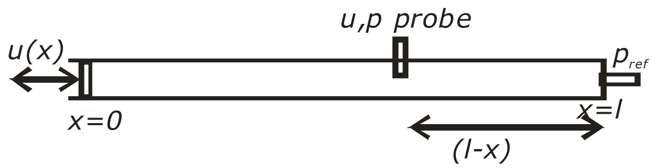


Fig. 4A.13: A standing wave tube that is rigidly terminated at x=l and in which the fluid is driven by a loudspeaker at x=0.

The lower frequency limit of the tube is caused by the length of the tube, the sound probe fittings (the probes should be mounted airtight) and in some extend to the tube diameter. With a 32cm length and a 5cm diameter tube, a lower frequency limit of 20Hz can be achieved when the probe mountings are airtight. The long standing wave tube does not have fittings and can therefore be used for frequencies higher than 100Hz.

Apart from the tube, one needs a ½" calibrated pressure microphone for the (absolute) amplitude response calibration.

If a pu-probe is put at a certain position *x* in the tube the relation between the pressure microphone of the pu-probe and the reference (pressure) microphone at the end of the tube is given by: ($p_{probe}=p_{probe}(x)$).

$$\frac{p_{probe}}{p_{ref.}}=\cos(k(l-x)) \qquad (4A.10)$$

The relation turns out to be a simple cosine function. The distance (l-x) can easily be obtained by measuring a minimum of the cosine function.

Analogously, almost the same applies for the particle velocity ($u_{probe}=u(x)$):

$$\frac{u_{probe}}{p_{ref.}}=\frac{i}{\rho c}\sin(k(l-x)) \qquad (4A.11)$$

The relation of the particle velocity and the reference sound pressure at the end of the tube turns out to be a simple sine function. The phase shift between them equals plus or minus 90 degrees.

It shows that for phase calibration of the pu-probe most of the time only the phase mismatch (φ_p-φ_u) should be determined and individual phase mismatch of both probes does not have to be determined.

The pu-probe phase mismatch (φ_p-φ_u) can be determined by measuring the ratio of the particle velocity and the sound pressure in the tube. The equation of the ratio is given by:

$$\frac{u_{probe}}{p_{probe}}=\frac{i}{\rho c}tg(k(l-x)) \qquad (4A.12)$$

This relation shows that in a standing wave tube particle velocity and sound pressure are 90 degrees out of phase. In this way the pu-probe can be phase calibrated in the arrangement as it is used. For a phase calibration the reference microphone is not used.

A calibrated reference microphone is used to determine the amplitude response and not needed to determine the relative phase response (φ_p-φ_u); the phase of the sound field is 90 degrees.

4A.9 Short standing wave tube calibration method

The short standing wave tube calibration technique requires that the probe under test (it can be a particle velocity and/or pressure probe) is positioned in the tube at a distance *(l-x)=55mm* to the end of the rigid end, see Fig. 4A.14.

The method for calibration the Microflown and microphone element is based on Eq. (4A.10) and Eq. (4A.11). The response u/p_{ref} is measured and compensated with the values given by Eq. (4A.11) and the response p/p_{ref} compensated with the values given by Eq. (4A.10).

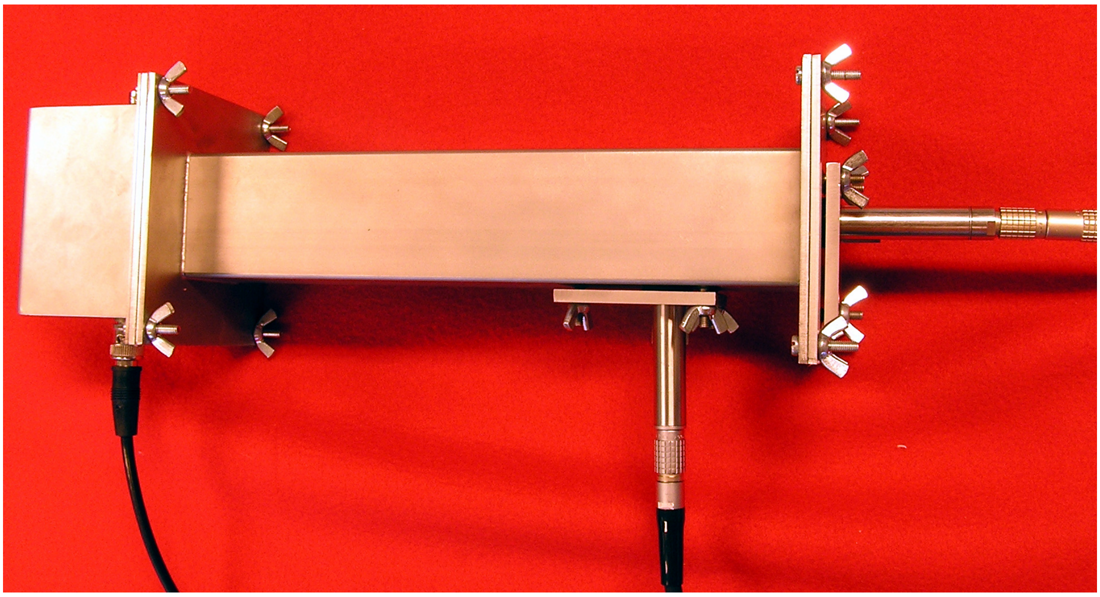


Fig. 4A.14: The small standing wave tube as it is sold by Microflown Technologies.

An example will make things more clear.

A half inch reference pressure microphone is placed with a sensitivity of 14mV/Pa at the end of the tube. A half inch PU probe is positioned in the tube. The transfer functions $Sp_{ref}u/Sp_{ref}p_{ref}$ and $Sp_{ref}p/Sp_{ref}p_{ref}$ are measured at 5.5cm before the end of the tube. The result is shown in Fig. 4A.15. The red line is the velocity transfer function; the black line is the pressure transfer function. For frequencies higher than 3.5kHz in theory the tube is not valid anymore.

The transfer function of the velocity signal ($Sp_{ref}u/Sp_{ref}p_{ref}$) has a minimum at f_u=3185Hz. Based on Eq. (4A.11) the response of the velocity signal is corrected for the response of the tube by:

$$u_{corrected} = u_{measured} - 20Log\left|\sin\left(\frac{\pi}{f_u}f\right)\right| \quad (4A.13)$$

The transfer function of the pressure signal ($Sp_{ref}p/Sp_{ref}p_{ref}$) has a minimum at f_p=1565Hz. Based on Eq. (4A.10) the response of the pressure signal is corrected for the response by:

$$p_{corrected} = p_{measured} - 20Log\left|\cos\left(\frac{\pi}{2f_p}f\right)\right| \quad (4A.14)$$

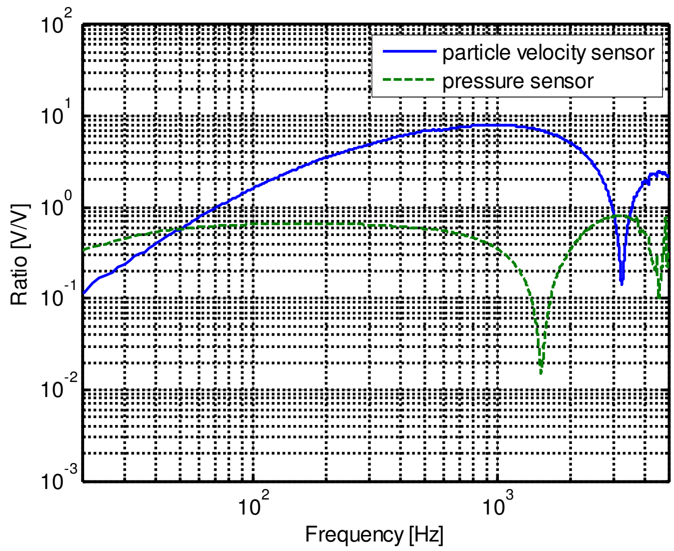


Fig. 4A.15: Transfer function of the velocity signal (red line), pressure signal (black line) for a 5.5cm distance to the end of the tube.

The result of the correction is shown below. With these responses the absolute sensitivity of the microphone and Microflown is derived. Is these responses are multiplied with the sensitivity of the reference pressure microphone, the absolute sensitivity is given in mV/Pa for the pressure microphone and in mV/Pa* for the Microflown.

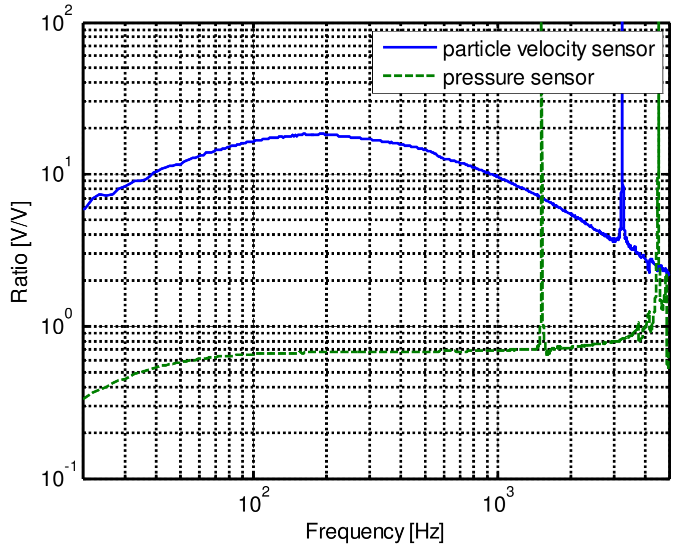


Fig. 4A.16: Corrected transfer function of the velocity signal (red line), pressure signal (black line) for a 5.5cm distance to the end of the tube.

The phase response

The phase between sound pressure and particle velocity at the same position in the tube is ±90 degrees. Because the phase of the sound field is known, the reference microphone is not needed. In this example the reference is used to be able to show the individual absolute phase response of the Microflown and the microphone, see Fig. 4A.17.

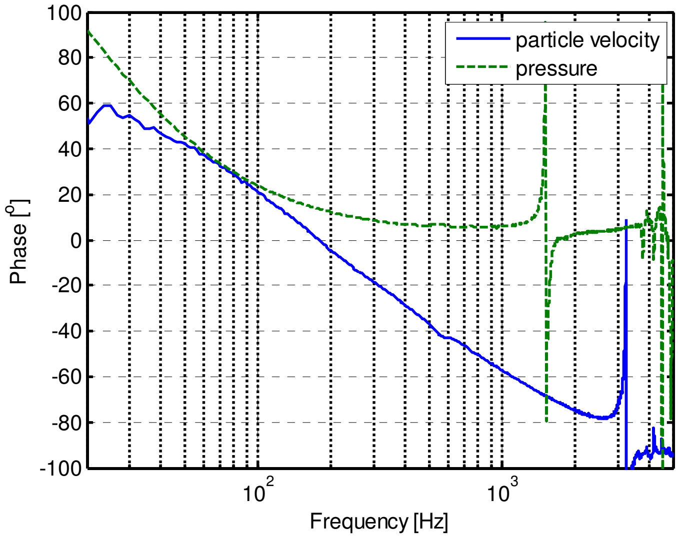


Fig. 4A.17: Absolute phase response of the velocity signal and the pressure signal of the PU probe in a standing wave tube for r=5.5cm.

In the tube the phase shift is ±90 degrees. The phase flips at the frequency where the pressure response has a minimum and where the velocity response has a minimum. The response is corrected for the tube's response by simply adding or subtracting 90 degrees. The result is shown in Fig. 4A.18. In this figure the phase shift between the sound pressure microphone and the Microflown is measured; this is the relative phase response.

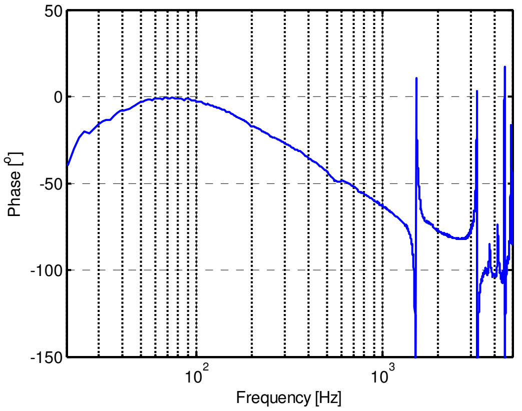


Fig. 4A.18: Corrected relative phase response of the velocity signal and the pressure signal of the PU probe in a standing wave tube for r=5.5cm.

The calibration results of the particle velocity sensor measured with the sphere setup and standing wave tube setup are compared in Fig. 4A.19. Both the absolute amplitude and phase responses are given. The results agree within 0.5 dB and the phase within 2.5 degrees. The deviations are probably caused by experimental inaccuracies.

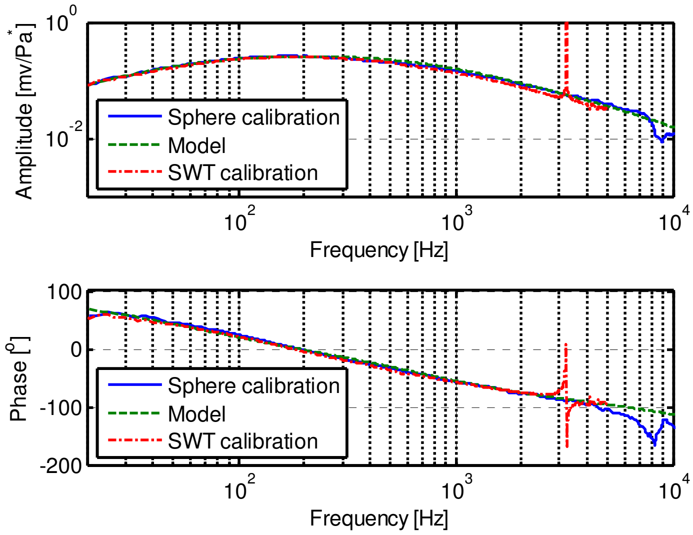


Fig. 4A.19: Results of calibration of the particle velocity probe. The curves for the sphere calibration, the model and the standing wave tube results are given. Upper: amplitude, lower: phase.

4A.10Calibration of USP's in the short calibration tube

A USP has three orthogonal Microflowns so at first sight it impossible to calibrate all three Microflowns with the small standing wave tube. The long standing wave tube had a 45 degree probe entry that could be used. For the small standing wave tube another method is developed.

First the two perpendicular Microflowns and the pressure element are calibrated in the standard way (as shown in the previous paragraph).

For the calibration of red Microflown the calibrated pressure element is used. For this specific probe the sensitivity of the pressure element is shown in Fig. 4A.20.

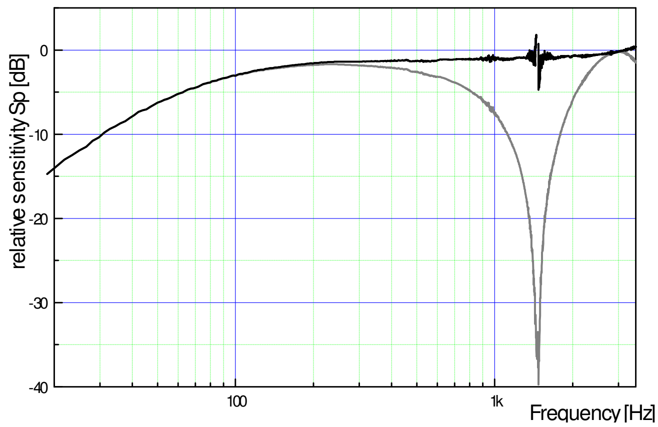


Fig. 4A.20: Sensitivity of the pressure element of a USP relative to the reference microphone (14mV/Pa). Grey line: the uncorrected response; black line: the corrected response.

Now the USP is put in at the end of the tube, at the position where the reference pressure microphone is normally placed. The regular probe mounting is closed.

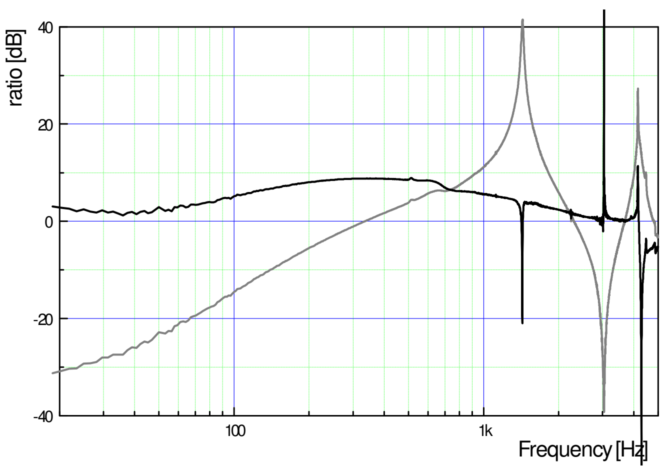


Fig. 4A.21: Transfer function of the velocity to the pressure element of a USP put in the end of a small standing wave tube.

The transfer function of the red Microflown to the pressure element (of the USP) is measured. The result is given in Fig. 4A.21 (grey line). The response has a maximum of f_p=1548Hz and the minimum is found at f_u=3371Hz. The response is corrected in a similar way as in §4A.9 explained:

$$\left|\frac{u_{corrected}}{p_{corrected}}\right| = \left|\frac{u_{measured}}{p_{measured}}\right| - 20Log\left|\frac{\sin(\frac{\pi}{f_u}f)}{\cos(\frac{\pi}{2f_p}f)}\right| \quad (4A.15)$$

The corrected response is also shown in Fig. 4A.21 (black line).

The black line in Fig. 4A.21 is the relative sensitivity (u_{probe}/p_{probe}) and this is the data that is used for the reduced calibration.

The corrected response, u_{red}/p (Fig. 4A.21, black line) should be multiplied with the response of the pressure element (relative to the reference pressure microphone) in order to retrieve the sensitivity of the red velocity element.

4A.11 Sensitivity of sound pressure versus particle velocity

By tradition pressure microphones are the standard in acoustics and their sensitivity is given in millivolts per Pascal [mV/Pa].

The Microflown is not sensitive for sound pressure but for particle velocity and the unit of particle velocity is meter per second. One Pascal sound pressure corresponds to quite amount of sound (a sound level of 94dB) but one meter per second particle velocity corresponds to an enormous amount of sound (a sound level of 146dB).

In order to be compatible to acoustic standards and to be able to compare the sensitivity of Microflowns and microphones, a reference level of 1Pa* is defined. 1Pa* is the amount of particle velocity that corresponds with 1Pa sound pressure in a plane wave without reflections. So 1Pa* equals 1Pa/ρc≈2.4mm/s.

The regular calibration methods are based on a known specific acoustic impedance and a reference pressure microphone. To be more precise: the methods are based on the *normalised* specific acoustic impedance, i.e. the specific acoustic impedance divided by ρc. So in the methods the exact value of ρc is not known. It is therefore more appropriate to use Pa* in stead of m/s as a reference.

In the "vibrations world" it is common to think in meters per second so the sensitivity is also given in meters per second. For example a sensitivity of 10mV/Pa* equals to 4.55V/(m/s) or 4.55mV/(mm/s).

4A.12The calibration file

The goal of calibration is to find the frequency dependent amplitude and phase response of a sound probe. There are two options to communicate this data. A model of the general behaviour of the Microflown and pressure element of a sound probe is provided. The specific response of a probe is defined by a set of constants. For the amplitude and phase response of the Microflown seven constants are required and for the amplitude and phase response of the pressure microphone three constants are required. For the equations see below in this text and also chapter 3: 'the Microflown' and chapter 4: 'calibration'.

The model gives a reasonable good approximation of the true response.

A more accurate way of communicating the amplitude and phase response of the Microflown and microphone of a PU sound probe is the so-called calibration file.

The calibration file is a common text file that contains columns and rows with data.

The frequency depended response of a sound probe is given in columns.

The first column contains frequency points.

The second column contains the frequency dependent sensitivity of the pressure microphone (in mV/Pa) for the frequency points that are given in the first column. This information is used in most measurements (intensity, source path contribution, acoustic camera, etc.).

The third column contains the frequency dependent absolute phase response of the pressure microphone (in degrees) for the frequency points that are given in the first column. This information is not used often.

The fourth column contains the frequency dependent sensitivity of the Microflown (in mV/Pa*) for the frequency points that are given in the first column. This information is used in most velocity based measurements (intensity, contactless vibration measurement, acoustic camera, etc.).

The fifth column contains the frequency dependent absolute phase response of the Microflown (in degrees) for the frequency points that are given in the first column. This value is used in array measurements (e.g. velocity based source path contribution, acoustic camera, etc.).

The sixth column contains the modulus of the sensitivity of the microphone (in mV/Pa) divided by the Microflown (in mV/Pa*) for the frequency points that are given in the first column. No reference microphone is required to obtain this data. This modulus of the relative calibration is required for e.g. impedance measurements.

The seventh column contains the relative phase response of the sound probe (so the phase response of the microphone subtracted by the phase response of the Microflown). No reference microphone is required to obtain this data. This relative phase calibration is used in most acoustic measurements (e.g. impedance, intensity, source path contribution, etc.).