11 Monopole sound sources

11.1 Introduction

Monopole sound sources are required for reciprocal measurements [5], [6], [7], [8], [9], [10], [11]. These reciprocal measurements are found in e.g. NVH applications for the reason of the very different space requirements of sound sources and sensors; measurements of acoustic transfer functions are often much easier done reciprocally, i.e. when source and sensor are interchanged.

A typical application is the measurement of acoustic transfer paths of sound radiated from a vehicle’s engine to the driver’s ear. The engine compartments of today’s cars are almost completely filled with the engine itself and its various subsystems. Therefore, a microphone can be installed much easier than a loudspeaker, whereas in the cabin there should be enough space for a sound source.

When measuring reciprocally, e.g. with a sound source inside the cabin, all transfer paths are excited - and thus can be measured - simultaneously. This means a significant reduction in time requirements compared with the direct method, where each transfer function of interest has to be measured one after another.

The quality of a monopole sound source is very important because the reciprocal measurement is the base of many measurements. If the source performs otherwise than expected, the result of the complete procedure may become useless.
A monopole sound source has a volume velocity output in cubic meters per second and an omni directional directivity. Volume velocity is equal to the particle velocity (in meters per second) times the surface of the sound source.

Practical monopoles are created when the diameter of the source is much smaller than the wavelength of the emitted sound field that it emits. The sound that leaves the output is omni directional if the wavelength of the highest frequency of interest is much longer than the diameter of the source output. ‘Much longer’ is rather vague. A save rule of thumb to create omni directionality is a wavelength more than six times larger than the diameter.

### 11.2 Theory

The simplest source to describe mathematically is a pulsating sphere with radius \( a \), that expands and contracts harmonically with spherical symmetry, see Fig. 11.2. If the radius (\( a \)) of the sphere is much smaller than the wavelength (\( ka << 1 \)), the source becomes a monopole or in other words a point source. Such sources are difficult to create in practice but the monopole sound source is a central concept in theoretical acoustics.

A point source is also called an omni directional sound source of constant volume velocity. In practice such sources are used for e.g. reciprocal measurements.

![Fig. 11.2: A pulsating sphere can be regarded as a monopole if the radius of the sphere is small compared to the wavelength.](image)

A monopole sound source has a sound field with point symmetry. The sound pressure field is depending on the distance to the source (and not on the angle) and is given by:

\[
p(r) = iρck \left( \frac{Q}{4πr} \right) e^{-ikr} = iρc \left( \frac{2πf}{4πr} \right) \frac{Q}{e^{-ikr}} = iρf \frac{Q}{2r} e^{-ikr}
\]

With \( Q \) the source strength in \([m^3 s^{-1}]\), and \( r \) the distance from the source. The acoustic impedance of a monopole is given by:
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\[ Z = \frac{p}{u} = \rho c \frac{ikr}{ikr + 1} \]  \hspace{1cm} (11.2)

The particle velocity field can be derived by combining Eq. (11.1) and Eq. (11.2) and results in:

\[ u(r) = \frac{Q}{4\pi} \frac{ikr + 1}{r^2} e^{-ikr} \]  \hspace{1cm} (11.3)

As can be seen, relative close to the source \((kr < 1)\), the particle velocity field is decreasing with the square of the distance and in the far field \((kr > 1)\) the particle velocity field is, just as the sound pressure, decreasing proportional with distance.

Close to the source \((kr < 1)\) the particle velocity is in phase with the source \(Q\) and the sound pressure is 90 degrees out of phase.

The sound power \(P [W]\) of an omni directional monopole is given by:

\[ P = \frac{\rho ck^2 |Q|^2}{8\pi} \]  \hspace{1cm} (11.4)

The sound power is proportional to the square of the frequency, indicating that a small pulsating sphere is not an efficient radiator at low frequencies.

The sound intensity at a certain position is given by the sound power divided by the area:

\[ I = \frac{\rho ck^2 |Q|^2}{32\pi^2 r^2} \]  \hspace{1cm} (11.5)

This equals to the square of the effective sound pressure divided by \(\rho c\) at that position, see Eq. (11.1)

\[ \left| \frac{p(r)}{2\rho c} \right|^2 = \left| \frac{1}{2\rho c} i\rho ck \frac{Q}{4\pi r} e^{-ikr} \right|^2 = \frac{\rho ck^2 |Q|^2}{32\pi^2 r^2} \]  \hspace{1cm} (11.6)

**Theory on practical monopoles**

A point source can be constructed using a high impedance loudspeaker (e.g. a horn driver) connected to a socket by a flexible tube, see e.g. Fig. 11.5. In a frequency range where only plane waves can propagate in the tube \((f < c/1.7d)\), an omni directional behavior of the acoustic radiated field from an open-ended tube is obtained for wavelengths much higher than the tube radius [3]. In water this effect can be observed if waves pass a small opening, see Fig. 11.3. In case of monopole sound sources, the tube diameter, \(d = 2a\), must be much (in the order of 2 to 3 times) smaller than a third of the wavelength of the sound wave:
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\[ ka = \frac{2\pi f}{c} a = \frac{2\pi}{\lambda} a \approx 1 \Rightarrow a \ll \frac{\lambda}{6} \text{ or } d \ll \frac{\lambda}{3} \text{ or } f \ll \frac{c}{3d} \quad (11.7) \]

In practice this means that to get an omni directional response (±1dB) up to \( f = 4 \text{kHz} \) a tube diameter of \( d = 2a = 1 \text{cm} \) is required (in this case \( ka = 0.35 \ll 1 \), with \( a \) the tube radius).

In practice the upper frequency for a monopole with diameter \( d \) is given by:

\[ f_{\text{max}} < \frac{40}{d} \quad (11.8) \]

It is not possible to use the loudspeaker signal as reference because the standing wave pattern in the tube is (a.o.) temperature dependent. And although it is possible to calculate where the maximums and minimums in the transfer function are, it is hard to calculate how high or low they exactly are: the damping in the tube is difficult to model exactly. (It is also reported that the driving current of the loudspeaker and the measured sound level is not linear related). It is therefore required to have a reference sensor at the end of the tube.

The volume velocity at the tube opening has to be known to determine the source strength. There are three choices as reference sensor: a pressure microphone, a pair of closely spaced microphones and a Microflown. These three options are discussed in more detail below.

Fig. 11.3: Plane waves through a small opening will alter in spherical waves.
A microphone as reference sensor

In a traditional approach a microphone is used as reference sensor due to a lack of particle velocity sensitive microphones in the past. A source with a microphone reference sensor is commercially available (e.g. LMS, ISVR) and was developed in a European project [2]. The acoustic impedance of an open ended tube is used to convert the sound pressure in a volume velocity.

If the termination of the tube is rigid, it can be considered that the specific acoustic impedance is infinite and the incident wave is totally reflected. For an open-ended tube the common simplification of null impedance at the termination is not correct since the tube radiates sound into the surrounding medium.

The impedance for the open-ended tube for $ka \ll 1$ is given by [4]:

$$Z_{\text{end}} = \rho_0 c \left[ \frac{(ka)^2}{4} + i 0.6 ka \right]$$  \hspace{1cm} (11.9)

With $a$ the radius of the tube.

For a radius of 0.5cm the impedance as described in Eq. (11.9) is depicted in Fig. 11.4. The upper frequency where Eq. (11.9) is valid is given by: $f < c / 2\pi a \approx 11\text{kHz}$. The source is omni directional up to approximately 4kHz.

![Graph showing impedance characteristics](image)

Fig. 11.4: The impedance of an open-ended tube for a 0.5cm radius.

As can be seen, the impedance is very low at lower frequencies indicating that almost all sound is reflected at the end of the tube and at higher frequencies the normalized impedance approaches unity meaning that much energy is radiated from the tube.

One of the major concerns related to the one microphone approach is the required independence of the surrounding impedance. In [2] some critical
situations were tested (i.e., the actuator was put close to a hard wall) and this requirement was fulfilled if the source is relative far away from the obstacles. Another concern is that the impedance, and therefore also volume velocity estimation, is (a.o.) temperature dependent at the open end. Furthermore, the sound pressure and particle velocity are only linear related at lower sound levels (below 135dB) so one can question if Eq. (11.9) is valid at the higher sound levels that are commonly seen at the source output.

A standing wave pattern exists in the tube and at the end of the tube the sound pressure has a minimum. The amplitude of the pressure field is (especially at higher frequencies) strongly dependent on the place due to this. The positioning of the microphone is therefore critical. Furthermore the (large) volume velocity is determined from a small value. This may also introduce some errors.

A practical disadvantage of the pressure reference at the end of the tube is that the particle velocity (and thus the volume velocity) can only be calculated for an open tube, see Eq. (11.9). The source strength cannot be derived from the pressure measurement if the source is not used in an open space e.g. in an artificial head or close to a surface.

If the monopole source is used in a head shaped loudspeaker (see §11.4), a pressure microphone as reference is makes no sense: the specific acoustic impedance is not known at the end of the source and therefore the volume velocity cannot be calculated for the sound pressure. It is also not possible to derive the source strength from a pressure measurement in an anechoic chamber because Eq. (11.1) is only valid for a point source.

Fig. 11.5: A monopole source with a pressure microphone as reference.

(It might be possible to integrate the result from a three dimensional directional measurement but this is very time consuming and the accuracy is questionable. Another possibility is to use an extra true omni directional...
velocity source, measure the transfer function from the source to the pressure at the ear, and find the source velocity with a reciprocal way. A third possibility is to use a reverberant room method to determine the sound power of the source; the phase information however is lost in this method).

**Two closely spaced microphones as reference sensor**

To avoid some of the aforementioned problems it is also possible to use two closely spaced and matched microphones at the end of the tube. A two microphone solution is commercially available at e.g. B&K. With such arrangement it is possible to estimate the volume velocity from the pressure gradient (see also chapter 2):

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

Problems that are reported with this two microphone technique are similar to the problems that are reported with intensity probes [1]. The negative effect of phase errors and spacing problems: for lower frequencies the gradient becomes very small. The latter can be solved by adding a third pressure microphone with a larger spacing.

Furthermore, the sound pressure and particle velocity are only linear related at lower sound levels (below 135dB) so one can question if Eq. (11.10) is valid at the higher sound levels that are commonly seen at the source output.

**A Microflown as reference sensor**

The most obvious reference sensor is a particle velocity sensor at the end of the tube, since the volume velocity is defined from the particle velocity times the surface of the source output.

The advantage compared to a pressure microphone as reference is that the source strength is known, independent of the acoustic environment. This is a very important advantage.

The source output particle velocity level is relatively high at normal sound levels. If a SPL of 80dB (0.2Pa) at 1meter at 1kHz is required, the source strength can be derived by rewriting Eq. (11.1):

\[
Q = \frac{2r}{\rho_f} p(r) = \frac{2 \times 1}{1.2 \times 1000} \times 0.2 = 0.0003 [m^3/s]
\]

(11.11)

The particle velocity at the end of a 12mm in diameter tube can be calculated by:

\[
u = \frac{4}{\pi d^2} Q = 4 \frac{0.0003}{\pi 0.012^2} \approx 3 [m/s]
\]

(11.12)
A particle velocity of 3m/s is very high (156dB re. 50nm/s). The upper particle velocity limit of the standard Microflown element is in the order of 138dB so at these levels the Microflown will overload.

To avoid overloading, a high level Microflown is used. That is a Microflown built in a nozzle source approximately 90DEG rotated. Due to this, the sensitivity is reduced considerably, in the order of 20dB. If this trick is used, levels up to 160dB (5m/s) can be measured, see further chapter 14: 'a Microflown for high particle velocity levels'.

If the particle velocity becomes too high turbulences and wind induced noise may occur. The particle velocity at the output of the source is given by:

$$u_{output} = \frac{8r}{\rho f \pi d^2} p(r)$$  \hspace{1cm} (11.13)

The particle velocity at the source output is a function of frequency and the diameter squared. So to reach a certain sound pressure level at one meter, the particle velocity level or the source diameter has to be increased if the frequency decreases. To avoid too high velocity levels (and therefore turbulences and windnoise), the diameter has to be increased. Of course the diameter of the source has to be chosen so that the restrictions of Eq. (11.7) are respected:

$$d = \sqrt{\frac{8r}{\rho f \pi} \frac{p(r)}{u_{output}}} \ll \frac{c}{3f}$$  \hspace{1cm} (11.14)

The particle velocity of the sound source should be chosen smaller than 1m/s.

**11.3 The Microflown monopole source**

There are two approaches to realize a monopole sound source for source path contribution.

1) A simple flexible hose driven with a loudspeaker and with a reference sensor at the output. Such source is the reciprocal device of a pressure microphone.

2) A torso and an artificial head with monopole loudspeakers in the ears. This type of source is the reciprocal counterpart of a human.

Both realisations can be defended. The simple hose is a source that is always the same and the reciprocal results can be checked with a pressure microphone. However the sound in a car is not ‘heard’ with a pressure microphone but with a human ear. The result is different and therefore one can say that the torso loudspeaker gives more realistic results. Apart from the improved transfer function one can also claim that there must be a certain mass in the driver seat to simulate a human body in a more realistic way.
11.4 A head-shaped loudspeaker

A point source can be used to for the reciprocal determination of the sound pressure at a certain point in space. This of course has a great value but it is also important what a human would perceive. For such reciprocal measurements a head shaped loudspeaker is required.

A point source is not an efficient radiator at low frequencies as can be seen in Eq. (11.4). Therefore the head shaped loudspeaker consists of two separate loudspeakers.

A 68mm in diameter tube is used for lower frequencies. Since for lower frequencies the head is no obstacle, the output of the tube is simply put on top of the head shaped loudspeaker, see Fig. 11.6.

A reference particle velocity sensor is placed in a small (12mm in diameter) tube that can be put in a holder at the output source output. This reference sensor can be calibrated with an extension tube that creates a standing wave calibration tube, see §11.5.

The 68mm diameter tube is omnidirectional for frequencies below 750Hz.

For higher frequencies the wavelength reduces and the head becomes an obstacle. Now the exact location of the source is of relevance. Therefore two small sources are constructed at the ear’s position.

Fig. 11.6: First prototype of a head shaped monopole source. The low frequency source output (up to 750Hz) is seen at the top of the head, one of the high frequency sources (up to 7kHz) is seen in the ear.
The reference sensor that is built in a small nozzle is put in the ear and all the sound goes through the nozzle. The calibration is done similar with a small extension tube and a pressure microphone at the end of the tube see §11.5.

The 12mm sources can be used in a bandwidth of 350Hz up to approximately 6kHz.

**Anechoic measurements**

The properties of the monopole sound source are derived in the anechoic room at TNO, the Netherlands. For that the sound pressure at 2 meter distance, the reference particle velocity (at the output of the source) and the current through the loudspeaker was measured.

The sound pressure is measured at two meters distance. The large distance is chosen to reduce positioning errors in the directivity measurement. The sound pressure at one meter can be derived from these measurements. If the sound source is omnidirectional the sound pressure increases 6dB if the distance is reduced from two meters to one meter. See Eq. (11.1). The sensitivity of the monopole is given by the sound pressure level measured at 1 meter divided by the input current. In Fig. 11.7 sensitivity of the two loudspeakers is given.

![Graph showing sensitivity of the head shaped loudspeaker](image)

Fig. 11.7: Sensitivity of the head shaped loudspeaker (sensitivity is given in Pascal at 1 meter distance per ampere).

The directionality of the source is measured by rotating the source and the measurement of the sound pressure at 2 meters distance in an anechoic room. Four series of measurements are done: the rotation over two axes for the two loudspeakers (the low frequency source on top of the head and one of the high frequency sources from the ears, see Fig. 11.6). The measurement results are averaged in third octave bands.
The first two measurement series are done when the source is in the vertical position (positioned as shown in Fig. 11.1). The directivity of the low frequency source is given in Fig. 11.8 (direction nose is zero degrees). The directivity of the high frequency source (the ear) is given in Fig. 11.9 (direction of the sound emitting ear is zero degrees).

Fig. 11.8: The directivity of the low frequency source in the vertical position (as shown in Fig. 11.1).
The second two measurement series are done when the source is in the vertical position (on the ‘belly’ see Fig. 11.1). The directivity of the low frequency source is given in Fig. 11.10 (the low frequency source opening is zero degrees). The directivity of the high frequency source (the ear) is given in Fig. 11.11 (the low frequency source opening is zero degrees).
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As can be seen in Fig. 11.8, the vertical directivity of the low frequency source is negligible. This makes sense because the low frequency source is line symmetrical in this orientation. The horizontal directivity shows some directivity indicating that the torso has some influence, see Fig. 11.10.

For the high frequency source (the ears), the directivity is somewhat higher.

11.5 Calibrating the source

The aim of calibration the sound source is to find out how much sound (power or volume velocity) the source produces. First the source is calibrated in an anechoic room to find out the source strength $Q$ per ampere input. Then the reference sensor is calibrated and used to measure the source strength $Q$.

Anechoic calibration

A monopole sound source can be calibrated in an anechoic room. If the sound pressure is measured at a certain known distance, the source strength can be calculated by (rewriting Eq. (11.1)):
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\[ Q = \frac{2r}{\rho f} p(r) \quad (11.15) \]

With \( Q \) [m\(^3\)/s] the source strength, \( f \) [Hz] the frequency, \( \rho \) [kg/m\(^3\)] the density and \( p(r) \) [Pa] the pressure measured in an anechoic room at some distance from the source.

Fig. 11.12: Source strength \( Q \) per ampere determined with a sound pressure measurement in an anechoic room.

Eq. (11.1) is only valid for an omni directional source. The head shaped source is not omni directional and therefore in the frequency range where the source is not omni directional, the values shown are only indicative. As can be seen in Fig. 11.8 and Fig. 11.10, the low frequency source has some directivity. In Fig. 11.12 the source strength per ampere is shown.

The source power is in direct relation with the source strength, see Eq. (11.4). In Fig. 11.13 the sound power per ampere is shown.

Fig. 11.13: Source power \( P \) per ampere determined with a sound pressure measurement in an anechoic room.
Calibration of the reference velocity sensor

The monopole sound source is simply a tube with a particle velocity reference sensor at the end. The calibration can be done when the source output is extended with a tube that is terminated rigidly. In the rigid termination a reference pressure microphone is placed. Now a standing wave calibration tube is created so that that the reference sensor can be calibrated with the standard standing wave tube calibration method as explained in chapter 4A: ‘standard calibration techniques’. Here theory will be explained briefly.

In a standing wave tube, a rigidly terminated tube with rigged side walls, the sound wave can only travel in one dimension and all the sound is reflected at the end of the tube. This is true up to a certain frequency; in a round tube the sound waves are plane below the cut-off frequency:

\[ f < \frac{c}{1.7d} \]  \hspace{1cm} (11.16)

with \( d \) the diameter of the tube and \( c \) the speed of sound. So the bandwidth is limited for high frequencies, the smaller the tube diameter, the higher the frequency where the tube can be used. This upper frequency limit is of no consequence because Eq. (11.7) shows that the upper frequency where the source is still omni directional is given by:

\[ d \ll \frac{\lambda}{3} = \frac{c}{3f} \implies f \ll \frac{c}{3d} = \frac{110}{d} \]  \hspace{1cm} (11.17)

At lower frequencies (\( f<100\text{Hz} \)) small leakages in the tube mountings influence the measurement. The reference sound pressure probe has to be sealed with e.g. a rubber ring to avoid this.

![Fig. 11.14: A standing wave tube that is rigidly terminated at \( x=l \) and in which the fluid is driven by a loudspeaker at \( x=0 \).](image)

For the low frequency source a tube with 68mm inner diameter is used and the tube length (\( l-x \)) is in the order of 7cm. For the high frequency source an extension tube of 12mm diameter and 2cm in length. The pressure microphone is used as the rigid termination.
Fig. 11.15: A standing wave tube with a reference pressure microphone mounted for calibration on the high frequency monopole.

A reference velocity is positioned at the end of the tube and this tube is extended a certain length \((l-x)\). The relation between the velocity microphone and the reference (pressure) microphone at the end of the tube is given by: \(\frac{u_{\text{probe}}}{p_{\text{ref}}} = \frac{i}{\rho c} \sin(k(l-x))\)

\[ (11.18) \]

The relation of the source reference particle velocity sensor and the reference sound pressure at the end of the tube turns out to be a simple sine function.

Fig. 11.16: Transfer function of the high frequency velocity signal (black line), and the low frequency velocity signal (grey line).

The transfer function \(S_{p_{\text{ref}}u}/S_{p_{\text{ref}}p_{\text{ref}}}\) is measured. The result is shown in Fig. 11.16.
The transfer function of the velocity signal ($\frac{Sp_{\text{ref}}u}{Sp_{\text{refP}}}$) of the low frequency source has a minimum at $f_u=1196\,\text{Hz}$; the high frequency transfer function has a minimum of $f_u=4527\,\text{Hz}$. Based on Eq. (3) the response of the velocity signal is corrected for the response of the tube by:

$$u_{\text{corrected}} = u_{\text{measured}} - 20\log\left|\sin\left(\frac{\pi}{f_u} f\right)\right|$$

(11.19)

The result of the correction is shown below.

![Graph showing the calibration curve of the particle velocity reference sensor in both sources.](image)

Fig. 11.17: The calibration curve of the particle velocity reference sensor in both sources.

Once the sensitivity of the reference sensor is known, the particle velocity level inside the tube can be determined. The volume velocity of the source is given by the particle velocity level times the tube area.

If the calibration tube has to be designed, it is smart to choose the length so that the dip in the response (at $f_u$) is at the highest frequency that the source is still omni directional, see Eq. (11.17). The upper frequency for calibration is higher than that, see Eq. (11.16). So:

$$f_u = \frac{c}{3d} = \frac{c}{2(l-x)} \rightarrow (l-x) = 1.5d$$

(11.20)

If the length of the standing wave tube is chosen 1.5 times the diameter, the dip in the response (at $f_u$) will be below the upper frequency where the tube can be used for calibration and above the useable frequency where the source is still omni directional.

Optimal calibration distance for a 15mm inner diameter tube is 3cm.
Comparison of the methods

The source strength $Q$ is easily derived from the calibrated particle velocity reference sensor at the source output: the volume velocity $Q$ equals the measured particle velocity times the surface of the source:

$$Q = u_{\text{ref}} \frac{\pi d^2}{4}$$

(11.21)

Fig. 11.18: Low frequency source strength $Q$ per ampere determined with a sound pressure measurement in an anechoic room (black line, copy from Fig. 11.12), low frequency source strength $Q$ per ampere determined with a calibrated particle velocity reference sensor (grey line).

Fig. 11.19: High frequency source strength $Q$ per ampere determined with a sound pressure measurement in an anechoic room (grey line), high frequency source strength $Q$ per ampere determined with a calibrated particle velocity reference sensor (black line).
The source strength that is calculated from the particle velocity reference sensor is compared with the source strength that is derived from a pressure measurement in an anechoic room, see Fig. 11.18. The black line represents the source strength that is derived from a pressure measurement at two meters, see Eq. (11.15). The grey line represents the source strength derived from the velocity measurement at the end of the source, see Eq. (11.21).

The results coincide reasonable, especially when one keeps in mind that the source strength determination based on a pressure measurement is only valid when a source is omni directional and de directivity measurements (seen in Fig. 11.8 and Fig. 11.10) show some directionality.

11.6 A hose type loudspeaker

The practical realization of a monopole sound source is a loudspeaker driving a tube with a diameter that is small compared to the wavelength, see Eq. (11.7). A realization of such tube is shown in Fig. 11.20. A high sound level reference sensor is built in a small nozzle that can be mounted at the end of the tube.

Fig. 11.20: A hose type monopole source.

The inner diameter of the nozzle of the level reference sensor is 12mm. From Eq. (11.7) it can be found that the upper frequency for monopole
behavior is ‘much lower’ than 9kHz. In a study of the directionality [2] it is found that the source becomes less omni directional for frequencies higher than 3kHz. (deviation 3kHz: 2dB, deviation 4kHz: 3dB, deviation 5kHz: 4dB).

Fig. 11.21: A prototype hose type monopole source is calibrated in an anechoic room with a sound pressure measurement at a known distance.

Fig. 11.22: Source strength per ampere determined with a sound pressure measurement in an anechoic room (grey line), source strength per ampere determined with a calibrated particle velocity reference sensor (black line). The measurement set up of this measurement is shown in Fig. 11.21.
The hose type of monopole is calibrated in an anechoic room. The source strength $Q$ is calculated from a sound pressure measurement at one meter by using Eq. (11.15). And the source strength $Q$ is calculated from the reference velocity signal by Eq. (11.21). The source strength as function of the input current determined with both methods is shown in Fig. 11.22. As can be seen, the source strength determined with the two methods coincides within one dB.

**Source strength of the high frequency monopole**

The source is driven with white noise. The sound pressure level is measured in a normal room at 25cm distance. The particle velocity is measured at the source with the reference velocity sensor. The sound pressure at 25cm is calculated with Eq. (11.1). As can be seen, both results are in good agreement up to approximately 3kHz. At higher frequencies the source becomes less omni directional. This may cause the sound pressure to increase in front of the source.

11.7 The low frequency monopole source

A point source is not an effective radiator at low frequencies, so the generated sound pressure level is low at low frequencies. A very high volume velocity is required to reach a proper sound pressure level. One can increase the particle velocity to reach an acceptable sound pressure level but this will result in turbulences or 'wind noise' at the end of the tube.

To keep the particle velocity within limits, the diameter of the tube is increased. In this case a diameter of $d=15$cm is chosen; the upper frequency that the speaker is radiating omni directional is below 260Hz, see Eq. (11.8).
Fig. 11.24: Photo LF source.

The source is build as a 32cm in diameter and 27cm high cylinder that is closed at one side and at the other side a 15cm in diameter and 22cm in length tube is mounted. A 27cm and 200Wrms bass loudspeaker is mounted just before the tube. A 28cm long standing wave tube used for calibration.

Fig. 11.25: Left grey line: raw calibration data of the reference sensor of the low frequency source. Left black line: corrected for the standing wave tube response ($f_0=540\text{Hz}$). Right: the sensitivity of the reference particle velocity sensor at the end of the tube.

The reference Microflown at the end of the source exhaust is calibrated by putting a 28cm closed tube with a reference microphone in the closed end.
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The ratio of the Microflown signal and the reference pressure microphone signal at the end of the tube (sensitivity is 14mV/Pa) is given as a calibration result in Fig. 11.25 grey line. The raw data of the calibration is corrected for the standing wave tube behavior, see Fig. 11.25 black line.

The source is driven with white noise and the signal of the reference probe is used to calculate the sound pressure level at 50cm. This is shown in Fig. 11.26 red line. The sound pressure is also measured 50cm in front of the loudspeaker in a normal room. As can be seen, the calculated and the measured sound pressure level are in reasonable agreement up to 250Hz. At higher frequencies the measured sound pressure level is higher than the calculated one. The source becomes directional at these higher frequencies. This is most probably the cause of the higher measured levels.

![Fig. 11.26: Red line: calculated sound pressure level at 50cm from the source. Black line measured sound pressure level 50cm in front of the source.](image)

![Fig. 11.27: Red line: maximal PVL at the opening of the LF source; green line maximal volume velocity at the opening and black line maximal SPL at 1meter from the source. Diameter source opening is 16cm.](image)
The output voltage of the reference sensor is measured and divided by the sensitivity of the sensor. To increase the driving power the speaker was driven with a pure tone signal. The measured velocity at the source exit is shown in Fig. 11.28. (This measured velocity should be multiplied with the area of the tube to get the volume velocity).

If the source is driven at 50Hz and the output is 1m/s there is a DC wind going outwards the tube’s exit. The wind can be noticed by hand ½ meters away. This effect is cause due to that the tube sucks air from all directions and blows in only one.

The volume velocity is derived from the particle velocity and the area of the tube. It is possible to express the volume velocity in a level. The reference then is 50nm$^3$/s. The output level $Q$ is expressed in dB re $50$nm$^3$/s and shown in Fig. 11.28.

![Graphs](image)

**Fig. 11.28:** The output of the source. Left upper: source velocity in m/s; right upper: calculated sound pressure level in dB re 20µPa at 1 meter distance from the source; left lower: volume velocity in m$^3$/s; right lower: volume velocity in dB.

### 11.8 Acoustic centre

A monopole sound source is an omni directional source. The acoustic centre is found just above the output of the tube. An example of a measurement that shows the acoustic centre is shown in Fig. 11.29.
Monopole sound sources

A Microflown is moved in a line over the monopole sound source. At each position the Microflown is rotated so that the sound source can not be measured. That position is photographed and the probe is moved again. A series of photographs is overlaid so that the probe positions and orientations can be seen. A line trough the two circles at the top of the Microflown shows the line of zero sensitivity. The crossing point of all lines shows the acoustic centre of the monopole sound sources.

Fig. 11.29: A series of measurements with a Microflown shows the acoustic centre of the monopole sound source. Left the low frequency source and right the high frequency source.

11.9 Velocity distribution at the output

The volume velocity of the source can only be determined by the particle velocity times the surface of the output if the velocity profile is rather constant at the output of the source. The velocity profile is measured with a scanning probe for a 35mm diameter hose.

A d=35mm realization of a monopole is omni directional up to about 1kHz. As can be seen in Fig. 11.30, the velocity profile is almost constant.

Fig. 11.30: velocity profile of a 35mm hose type loudspeaker.
11.10 References


