Investigation of volume velocity source based on two-microphone method for measuring vibro-acoustic transfer functions

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Abstract
Measurement of transfer functions is required for most applications dealing with source-path-contribution techniques often called transfer path analysis. Here the transfer function, typically measured as Frequency Response Function (FRF), takes the role of connecting an input (e.g., source position) with an output (e.g., receiver position). In this paper we will further investigate a previously described low-mid frequency volume velocity source based on the two-microphone method for in situ measurement of volume velocity source strength. This investigation includes the effects of the acoustical environment when measuring transfer functions. The two strategies, direct and reciprocal measurement, will also be compared to investigate their validity for a typical acoustical setup. Finally we will compare the described volume velocity source with a mid-high frequency sound source based on the same two-microphone method.

1 Introduction

For applications where the acoustic radiation from a complicated sound source is modelled, normally a series of sound pressure/volume velocity (p/Q) FRF’s are measured and combined with operating acoustic source strengths as part of a method to find the airborne contribution of this sound source. If structure-borne noise is the main concern, the operating forces on a receiving structure are estimated and the noise contribution at a receiver position can then be estimated from these operating forces and a set of measured sound pressure/force (p/F) FRF’s. Both the p/Q and the p/F transfer function can be measured using acoustic excitation while there are no other operating sources.

To measure vibro-acoustic p/F FRF’s in a vehicle we normally take advantage of the reciprocity principle by placing a sound source inside the cabin at the receiver and mounting an accelerometer at the input force location. Acoustic p/Q FRF’s on the other hand can be measured using either a direct or reciprocal approach with a microphone measuring the sound pressure at either the receiver location or at an assumed acoustic source position for example on the engine surface, see also Figure 1. However, for practical reasons the type of transfer functions from engine room source to cabin receiver are usually measured reciprocally due to the limitation of space in engine rooms even if the source is based on a driver with a long hose mounted.

A volume velocity source has to meet some specific requirements [1]:

- The source should produce a sufficiently high sound level
- The frequency range covered should be appropriate
- The source should behave as a monopole in the frequency range of interest
- The output volume velocity should be measurable even when the acoustic environment changes
The acoustic source for this purpose must be powerful and omni-directional and a signal related to the source strength must be available – if the source strength is not available directly. Furthermore the frequency range covered should be as broad as possible. Most volume velocity sound sources use one microphone as a reference assuming there is a fixed linear relationship between volume velocity output and reference sound pressure at the microphone. To find this relationship the sound source is operated in an anechoic room and the volume velocity output can be estimated from a microphone measurement at some known distance from the source. A transfer function between volume velocity and reference sound pressure can then be calculated and stored for use when the source is used in the real environment. The influence of a changing environment on this fixed linear relationship will be investigated later in this paper by some real measurements. For sound sources based on driver and hose where the sound radiates from the orifice of an open duct, the two-microphone method can be used to estimate the volume velocity output without first estimating a sound pressure to source strength relationship in anechoic room. A further benefit of this approach is the ability to determine the output volume velocity in any acoustic environment.

A part from these technical requirements one may want to add some practical requirements for instance that the source should be small enough to be used in confined spaces for example inside a tightly packed engine room. For airborne contribution analysis a volume velocity source is used initially to provide acoustic transfer functions between source positions close to the surface of the actual noise source and some near-field microphones located around the noise source. Therefore to measure transfer function easily it must be possible to attach the sound source on any surface or to position it in the near-field if a reciprocal approach is used. This speaks in favour of using a sound source based on some sort of driver attached to a long flexible hose where the sound is radiated from the duct orifice. The duct end can then be attached onto a surface or be placed in air during transfer function measurements.

\[
\frac{p}{Q_{\text{meas}}} = \frac{p}{Q_{\text{direct}}}
\]

\[
\frac{a}{Q_{\text{meas}}} = \frac{p}{F_{\text{direct}}}
\]

Figure 1: Reciprocal measurement of acoustic (p/Q) and vibro-acoustic (p/F) transfer functions in vehicle.

2 Two-microphone method for volume velocity measurement

In an earlier paper, the principle behind a particular volume velocity sound source was described in terms of how it was designed [2]. An omni-directional sound source (B&K Type 4295) already used for room acoustics applications was chosen as driver together with a special adaptor (B&K Type 4299) that
measures the volume velocity output. A pair of phase-matched microphones is used inside the adaptor to estimate the calibrated volume velocity output spectrum in situ. Figure 2 shows the source itself with the adaptor mounted inside an anechoic room and the other picture shows a practical measurement setup where a hose (flexible duct) is mounted between driver and adaptor for ease-of-use during measurements. The useful frequency range of the driving loudspeaker is 50Hz-6kHz, so in this range the output will be sufficient, however the radiation from the orifice of the adaptor becomes more directive, i.e. less omnidirectional, above 2-3kHz. Later we call this the low-mid frequency sound source.

![Figure 2: Low-mid frequency sound source without and with extension hose.](image)

In the following section we will review some of the basic concepts behind the two-microphone method which has been widely used to measure acoustic properties in ducts [3]. We assume that only plane waves are measured at two microphone locations A and B inside a cylindrical duct, see Figure 3.

![Figure 3: Two-microphone measurement configuration for volume velocity output estimation.](image)

The sound pressure $p(x)$ in a cross-section of the duct can then be expressed:

$$p(x) = p_+e^{-jks} + p_-e^{jks}$$  \hspace{1cm} (1)
Where \( p_1 \) and \( p_2 \) are the incident and reflected plane wave components respectively and \( k \) is the wavenumber. By measuring the sound pressure inside the duct at the two different microphone locations we can determine the unknown incident and reflected plane wave components. Usually this is done by measuring the transfer function between the two microphones therefore the method is also referred to as the transfer function method.

The particle velocity evaluated in a cross-sectional area is given by:

\[
u(x) = \frac{1}{\rho c} \left( p_1 e^{-j k x} - p_2 e^{j k x} \right)
\]

Where \( \rho c \) is the characteristic impedance of air.

At the duct opening, \( x = 0 \), we have:

\[
u(0) = \frac{1}{\rho c} (p_1 - p_2)
\]

This expression leads to volume velocity estimation if we multiply with the cross-sectional area of the duct. We can further express the volume velocity output as an auto-spectrum based upon auto-spectra of microphone A and B and the cross-spectrum from microphone A to B [2].

Furthermore since the purpose is to use this source for measuring transfer functions we can express the transfer from volume velocity output at the source to sound pressure at a receiver microphone as a frequency response function:

\[
H_{0p} = \frac{C_{op}}{C_{00}}
\]

Here \( C_{op} \) is the auto-spectrum of the estimated volume velocity signal and \( C_{op} \) is the cross-spectrum from source volume velocity to receiver sound pressure. Both spectra can be expressed in terms of auto- and cross-spectra among signals from microphone A and B plus the receiver. Additionally we need the dimensional parameters \( l \) and \( \Delta \), where \( l \) is the distance from the duct opening to the nearest microphone (microphone B) and \( \Delta \) is the microphone spacing.

In [4] a study of the two-microphone was presented investigating the influence of different error sources on the estimated result of acoustic properties with emphasis on measuring reflection coefficients and acoustic impedance of materials.

### 3 Finite element modeling of sound field inside duct

In order to verify some of the aspects related to sound fields in ducts it is very useful to perform simulation studies for optimizing the design parameters. Some studies have been carried out investigating the influence of the surroundings on the duct output and also the interference effect of placing microphones inside the duct for measuring the sound pressure. The finite element method was used to do these simulations based on the standard Helmholtz equation.

In the two-microphone method we need to measure the sound pressure in two cross-sections of the duct in order to estimate the volume velocity output. The effect of placing the two microphones inside the duct may change the sound field locally around the microphones which can result in large errors in the calculated volume velocity spectrum. This will be evident when dealing with narrow ducts.

We will model the setup from the low-mid frequency sound source having the microphones placed inside the duct together with a spacer. The two microphones measure the sound pressure on the duct axis in order not to capture the first higher order mode. The spacer ensures that the sound pressure is measured on the actual center axis of the duct.

The air inside a piece of duct with inner diameter 3.8cm containing the two microphones and the two spacers was modeled using acoustic finite elements. The duct is excited in one end with a known constant
surface velocity and at the opening where the microphones are located an impedance boundary condition was imposed to simplify the setup of the simulation case. The impedance imposed on this boundary corresponds to the acoustic impedance seen from a piston in an infinite baffle [5]. Then the output from the simulation will be the particle velocity integrated over the opening of the duct which will be the simulated volume velocity also termed as exact. Further, we can take the simulated sound pressures integrated over the microphone diaphragm boundaries, process those data using the volume velocity estimation method described in section 2, and finally compare with the exact simulated volume velocity to investigate the interference effect of the microphones and spacers inside the duct. A simulation was carried out from 20Hz to 10kHz and as expected at high frequencies the influence of obstacles inside the duct will be quite significant. An example of a surface pressure distribution is given in Figure 4 for the frequency 8kHz. Locally around the position of the microphones the sound field changes and does not consist of plane waves.

![Figure 4: Setup of microphones inside duct and sound pressure distribution at duct end for a frequency of 8 kHz.](image)

A comparison of the direct simulated volume velocity output spectrum and the predicted one based on the simulated sound pressures inside the duct at the microphone diaphragms is shown below for the full frequency range considered in Figure 5. Moreover, the two spectra were subtracted to provide the error made by the two-microphone method as a function of frequency. Clearly, in the range where the actual low-mid frequency source is active, 50Hz-6kHz, the error is always less than 1.5dB and for most of the frequency range the error is actually less than 0.5dB.

![Figure 5: Comparison of simulated and predicted volume velocity output from duct with two microphones inside. Left: Volume velocity spectra. Right: Difference between spectra.](image)
4 Verification of volume velocity source

Verification measurements were done using the low-mid frequency sound source in order to explore some of the aspects explained earlier.

The basic parameters describing the sound source were already presented earlier [2], like max output power, directivity characteristics etc. Here we will present some other measurements verifying the concept of the volume velocity sound source. One of the ideas behind using the two-microphone for volume velocity estimation is that this quantity can change if the sound source is used in very different acoustical environments. Here the two-microphone principle should always provide a good estimate of the actual volume velocity. A couple of measurements were done with the hose and adaptor placed in different environments. Pictures of the different setups are shown below in Figure 6.

![Sound source placed in different environments. Inside room away from walls, close to floor, radiating into box and inside engine room.](image)

The sound source was driven by a band-pass filtered (bandwidth 6.4kHz) white noise signal with sufficiently high amplitude, narrowband auto- and cross-spectra between the two microphones were measured using FFT and averaging. For each of the four setups in Figure 6 the volume velocity spectrum was calculated based on the two measured microphone signals. Calculated volume velocity spectra are shown in Figure 7 left, where three of the calculated spectra are shown relative to the measurement where the source was placed free in the room away from walls. Below a certain frequency around 1.5 kHz the different outputs from the source are all within a few dB’s, but at higher frequencies the deviations from the free space measurement become more evident especially for the more confined spaces. The change in the output volume velocity spectrum due to change in the acoustical environment would require a reference signal which also changed accordingly.
Some volume velocity sources available are based on a single reference microphone for calibrating the volume velocity output from the source. The idea of such a principle is to estimate the volume velocity under anechoic conditions using a far-field microphone and then relate the calculated volume velocity output to a fixed reference signal in this case a microphone sitting close to the opening of the sound source. This results in a calibration spectrum. When using the sound source in a real application we measure the sound pressure at the reference microphone which then can be translated into volume velocity spectrum using the calibration curve. However the question is what influence the acoustic environment will have on the volume velocity estimations we get, since the actual measurement environment may be very confined, eg inside an engine room. In our test cases we will use the signal from the microphone closest to the opening as a reference to examine this ratio for our four setups. Figure 7 right plot, shows the individual curves and we see less variations in the ratio compared to the volume velocity spectrum. However we see that some errors are introduced if the environment becomes more confined, and especially at high frequencies there are quite large differences. At the same time we should remember that the source itself is only omni-directional up to 3kHz so the largest errors will occur outside this frequency range. Nevertheless, we have seen that the acoustical environment will have an effect on the output volume velocity spectrum and that we should measure the actual output in situ to minimize errors on volume velocity estimation, transfer functions etc.

Another simple experiment was conducted investigating if the sound is radiated mainly from the opening of the tube as desired or if the driver and tube walls contribute significantly. A microphone was placed 30cm in front of the opening of the duct and a narrowband sound pressure spectrum was recorded for white noise excitation of the sound source. Then the orifice of the duct was blocked and another narrowband sound pressure spectrum was recorded. For normal operation with the duct open and when the opening was blocked by a thick layer of damping material inside the duct opening, the measured spectra in front of the opening are shown in Figure 8 and compared to the general background noise inside this normal room. The tests show that the sound is mainly radiated from the opening of the open duct, and even though the blocking of the orifice was not perfect the levels in that case are more than 20dB lower than the open duct case over the complete frequency range for that source. When the source was blocked some sound is transmitted through the damping at the duct opening, especially at lower frequencies, otherwise only some sound coming directly from the driver itself was identifiable. All together it is concluded that sound produced by the assembly of driver and hose is to a large extend radiated from the duct orifice which means it can be used as a monopole to measure vibro-acoustic transfer functions.

Figure 7: Left: Calculated volume velocity output spectrum relative to free space for three different environments. Right: Volume velocity to reference sound pressure ratio for all environments.
5 Application of volume velocity sources

The volume velocity source described so far has been used to measure acoustic transfer function between an assumed source position inside an engine room and receiver positions inside the vehicle. Direct transfer function measurements – from source at engine surface to microphones inside a vehicle – were compared to reciprocal measurements where the source, i.e. the duct orifice, was positioned at the receiver with a microphone measuring the sound pressure at the engine surface position. Since the receiver positions in the direct measurement consisted of microphones in the ears of a Head and Torso Simulator (HATS), the reciprocal measurement should ideally be made with a HATS having sound sources placed at the entrance of the closed ear canals. This was not practically using the current sound sources, so in this experiment the orifice of the adaptor was placed as close to the ear microphones as possible but still outside the pinna/concha. The effect of the head and torso will be included in the reciprocal transfer functions but not the full effect of the concha, but this measurement should give an indication if it is possible to measure binaural transfer functions related to an in-the-ear receiver using a reciprocal approach where the sound source is simply attached just outside the pinna. In that case a standard HATS with microphones in the ears can be used for measuring binaural transfer functions based on the reciprocal approach with one of the described sound sources attached to the pinna. The validity of this approach can be examined by comparing to binaural transfer functions using the direct approach which contain the effect of the concha since the microphones are placed at the entrance of each ear canal. At the same time we want to compare the low-mid frequency sound source to a mid-high frequency sound source based on the similar principle. The mid-high frequency sound source is constructed out of a powerful compression driver and a long hose made out of nylon reinforced PVC. The inner diameter of the hose is 10mm and a similar set of microphones is used at the opening to estimate the volume velocity.

The measurements were made with a vehicle standing in a normal room. Some level of background noise was expected during the measurements. One source position on the engine top was marked for use in all direct and reciprocal measurements. Additionally, a HATS with two microphones was placed in the passengers’ seat of this right-hand steering wheel car, see Figure 9.
Figure 9: Measurement of acoustic transfer function from top engine surface point to left and right ear using the mid-high frequency sound source. Left: hose at engine source position for direct transfer function measurement. Right: positioning of sound source at right ear for reciprocal transfer function measurements.

5.1 Source directivity

A couple of measurements where carried out with each of the investigated sound sources for the same source position on the top engine surface where the orientation of the adaptor or hose was changed. When comparing transfer functions from the same position but different orientations, the directivity of the source can be examined with respect to omni-directionality. In Figure 10 we compare a transfer function measured with the low-mid frequency sound source for different orientations of the adaptor, i.e. pointing towards the rear, front or left side of the vehicle. The measured transfer functions are valid down to 50Hz where the output power of loudspeaker starts to decrease significantly, and we see similar transfer functions for all three orientations up to 2-3kHz. From that frequency on the sound from the orifice of the adaptor becomes more directive as explained earlier and this can be seen from the lower plot in Figure 10.

Figure 10: Acoustic transfer function measured between top engine position and HATS left ear for different nozzle orientations using low-mid frequency sound source. Top: 0-2kHz. Bottom: 2-4kHz.
In all measurements a white noise signal band-limited to 6.4kHz was driving the sound source at a maximum level, FFT processing and averaging was used to calculate transfer functions as FRF’s with frequency resolution 1Hz.

5.2 Comparison of sound sources

Measuring the same direct transfer function from top engine surface position to HATS ears is now investigated using the two sound sources. The low-mid frequency sound source was driven by a white noise signal band-limited to 6.4kHz whereas the mid-high frequency sound source was driven by a similar white noise signal high-pass filtered with cutoff at 800Hz in order not to overload the driver at low frequencies. Transfer functions measured with the orifice pointing towards the vehicle rear were measured and are compared below in the frequency ranges 0-2kHz and 2kHz-6kHz for both amplitude and phase characteristics. Even though the signal for the mid-high frequency sound source is high-pass filtered at 800Hz, the transfer functions obtained by this source are valid down to 400Hz since sufficient sound output is produced by the source compared to background noise levels. From Figure 11 it can be seen that the measured transfer functions using the two sound sources agree very well in both amplitude and phase from 400Hz up to at least 2kHz. Figure 12 shows similar amplitude and phase plots but now in the high-frequency range 2kHz-6kHz, where deviations are in the range of 10dB’s. This is expected as the mid-high frequency source is omni-directional to a much higher frequency than the low-mid frequency source and also the dimensions of the sources plays a role at higher frequencies together with their different acoustic centers.

![Figure 11: Amplitude and phase of acoustic transfer function from top engine surface to HATS left ear measured using low-mid frequency source (red curve) and mid-high frequency source (blue curve). 0–2kHz.](image-url)
Figure 12: Amplitude and phase of acoustic transfer function from top engine surface to HATS left ear measured using low-mid frequency source (red curve) and mid-high frequency source (blue curve). 2kHz–6kHz.

5.3 Direct vs reciprocal measurements

Finally we compare transfer functions measured in the direct sense to reciprocal transfer functions. In case of reciprocal measurements the HATS was still in place inside the vehicle but now the sound source is placed as close as possible to one of the microphones inside the ears. An example of locating the orifice of the hose just outside the concha part of the pinna was shown in Figure 9. A small ¼” microphone normally used for array applications was placed at the top engine surface position for measuring the blocked surface pressure. Ideally the effect of hose and adaptor on the sound field locally around the engine surface position should be included by having those in place during reciprocal measurement, but this effect will be neglected since it will not be practical and in case we wanted to include this effect another piece of hose with blocked orifice would be neccessary.

Comparison of direct and reciprocal measured transfer function is shown for the low-mid frequency source in Figure 13. At low frequencies there is very good agreement as expected from low frequencies and even up 3-4kHz the tendency remains the same for both curves. Above 4kHz the deviations become more pronounced. At these higher frequencies the sound source is first of all no longer acting as a monopole but also the effect of the concha in the reciprocal transfer function is missing.
Figure 13: Direct (red curve) and reciprocal (blue curve) measurement of top engine surface to HATS left ear transfer function using low-mid frequency source. Top: 0-2kHz. Bottom: 2kHz-6kHz.

Comparison of direct and reciprocal measured transfer function is shown for the mid-high frequency source in Figure 14. Some deviations are expected at lower frequencies where the output of the source is limited, this is due to less sensitive array microphone for the reciprocal measurement and also because of poor signal-to-noise ratio for that microphone. Otherwise we see good agreement between the two transfer function up to nearly 5 kHz, above that frequencies other types of errors are introduced mainly due to incorrect position of the sound source for reciprocal measurement.

Figure 14: Direct (red curve) and reciprocal (blue curve) measurement of top engine surface to HATS left ear transfer function using mid-high frequency source. 0-6kHz.
Conclusions

Sound sources for measuring vibro-acoustic transfer functions have been investigated although the emphasis has been on the acoustic transfer functions. The type of source presented here was based on a powerful driver attached to a long hose equipped with two microphones close to the orifice for measuring the volume velocity source strength in situ. Transfer functions measured as FRF’s can then easily be estimated. The principle was reviewed and some error analysis related to the current sources was made. Acoustic transfer functions were measured in a vehicle environment proving that it is possible to measure reciprocally with some confidence, the binaural transfer functions, by placing the orifice close to the entrance of the outer ear. In that case a standard HATS and the volume velocity source can be used to do all operating and transfer function measurements related to source-path-contribution analysis including binaural effects. Also, a sound source aimed for mid-to-high frequency measurements making use of the two-microphone method was investigated and compared to the current low-to-mid frequency sound source.

References


