Practical measurement of transfer functions using volume velocity sources

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Introduction

Measurement of transfer functions is required for many 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). For applications where the acoustic radiation from a complicated sound source is modelled, a series of sound pressure/volume velocity (p/Q) FRF's are usually measured and combined with operating acoustic source strengths as part of a method to find the airborne contributions from partial sound sources or the whole sound source. If structure-borne noise is the main concern, operating forces on the 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. Reciprocal measurement of p/Q and p/F transfer functions in a vehicle environment is shown in Figure 1.

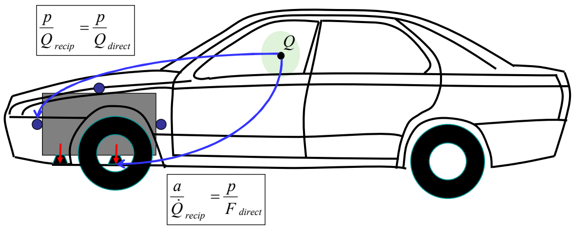

Figure 1: Reciprocal measurement of transfer functions in vehicle.

The acoustic source for this purpose must be powerful especially when measuring through a vehicle body. A further requirement is that the sound source is omni-directional and the source strength must be estimated either measured directly or calculated indirectly. 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 later use when the source is used in the real environment. For sound sources based on a driver attached to a hose and where the sound radiates from the orifice of an open duct end, the two-microphone method [1] 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 actual output volume velocity in any acoustic environment. See Figure 2 for a drawing of this principle.

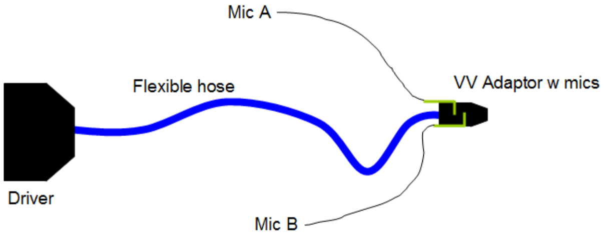

Figure 2: Volume velocity source based on driver and hose principle. Microphones in the adaptor estimate the volume velocity output.

Besides 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. In this paper we will describe and investigate two hose-based sources both based upon the two-microphone principle.

Sound sources

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) used for estimating 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. The output spectrum is estimated at the actual orifice of the adaptor.

In Figure 3 the source itself is shown with the adaptor positioned inside an anechoic room for verification measurements. The useful frequency range of the driving loudspeaker is 50 Hz-6 kHz, so in this range the output will be sufficient, however the radiation from the orifice of the adaptor becomes more directive, i.e. less omni-directional above 2-3 kHz. Later we call this the low-mid frequency sound source.

Figure 3: Low-mid frequency volume velocity source without hose in anechoic chamber.

Another newly developed sound source covering mainly mid-high frequencies and based on a similar principle has been considered as well for comparison. The construction of the mid-high frequency sound source is made out of powerful compression driver and a long hose consisting of steel reinforced PVC. The inner diameter of the hose is 10mm and a similar set of microphones is used close to the opening for estimating the true volume velocity output. Figure 4 shows a prototype version of this sound source for in-vehicle measurements of transfer functions.

Figure 4: Mid-high frequency volume velocity source based on horn driver and flexible hose for measuring in-vehicle transfer function.

Numerical simulation of sound sources

For the low-mid frequency source a series of verification measurements was carried out to understand its behaviour in different environments. Also a simulation experiment was done to determine the effect of having microphones and spacers occupying part of the space inside the volume velocity adaptor. The outcome of these investigations were reported in [3].

In this section we will verify the radiation characteristics of the mid-high frequency sound source using numerical simulation tools. These tools can provide initial information about the performance of a certain design. In the current mid-high frequency source a new adaptor was designed for accommodating the two microphones which are necessary for the volume velocity estimation principle. The new adaptor tends to have dimension which are larger than the hose outer diameter, therefore it was decided to simulate the directivity of the sound source to understand if the behaviour is still monopole-like (omni-directional) at high frequencies. A CAD drawing of the adaptor was used initially to perform a finite element simulation of the sound field outside the adaptor when only the orifice vibrates as a piston, see Figure 5 for the SPL distribution on the adaptor at 8 kHz.

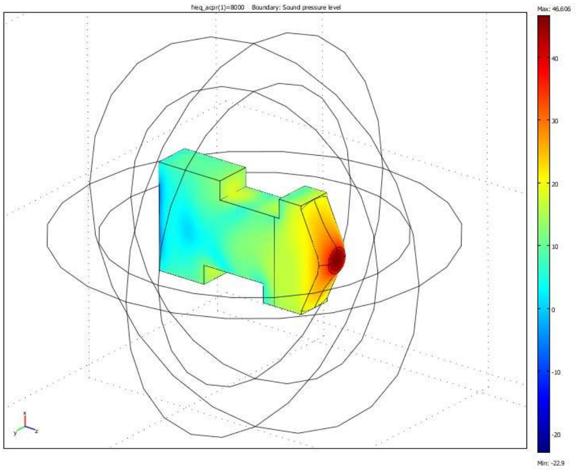

Figure 5: Sound pressure level distribution on adaptor at 8 kHz simulated using finite element modeling.

Furthermore we can simulate the sound pressure in the farfield and make a directivity plot to understand how the source radiates. Since the adaptor is not an axisymmetrical structure, the directivity in the vertical plane is different from the horizontal plane. See Figure 6 for source directivity.

The directivity plots for the adaptor design at this frequency 8 kHz reveal that the source will still be reasonably omnidirectional within ± few dB's. At this frequency there is only a sligth problem with radiation in the rear direction ±120/150 degrees. We also notice that the source behaves differently in the horizontal and vertical plane.

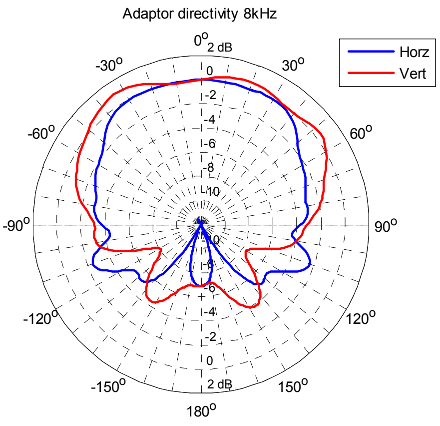

Figure 6: Simulated directivity plot based on mid-high freq adaptor geometry. Results shown are for 8 kHz provided for horizontal plane (blue line) and vertical plane (red line).

Experimental study of sound sources

A couple of measurements in a real vehicle environment were carried out with each of the investigated sound sources for the same source position on the top engine surface, see Figure 4. The receiver positions in the direct measurement consisted of microphones in the ears of a Head and Torso Simulator (HATS) placed in one of the front seats. The sources were controlled using a dedicated measurement template allowing to set up the individual source parameters like microphone spacing, hose inner diameter etc. During measurement the volume velocity spectrum is shown real-time, as well as the FRFs measured and their corresponding coherences.

Source directivity

When comparing transfer functions from the same position but different orientations, the directivity of a source can be examined with respect to omni-directionality. In Figure 7 we compare transfer functions measured with the mid-high frequency sound source for different orientations of the adaptor, i.e. pointing towards the rear, front, left and right side of the vehicle.

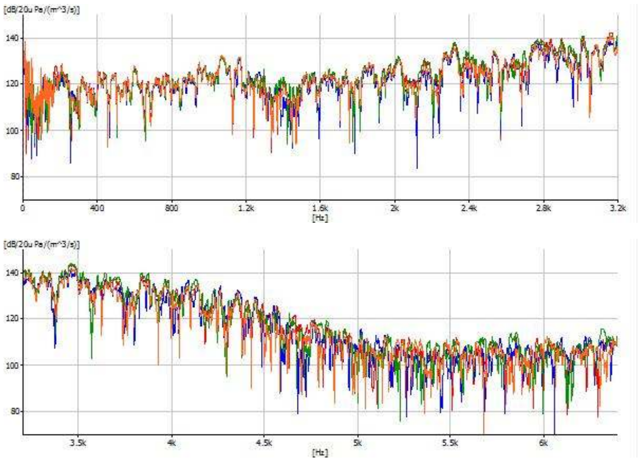

Figure 7: Acoustic transfer functions measured between top engine position and HATS right ear for different adaptor orientations using mid-high frequency sound source. Top: 0-1000 Hz. Bottom: 0-6400 Hz.

The measured transfer functions are valid down to 200 Hz where the output power from the horn driver itself starts to decrease significantly. We see similar transfer functions for all four orientations and the trend is the same even at the highest frequencies shown i.e. 6.4 kHz. From that frequency and upwards 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 7.

Comparison of sources

Measuring the same direct transfer functions 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 6.4 kHz whereas the high-mid frequency sound source was driven by a similar white noise signal high-pass filtered with cutoff at 600 Hz 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 0-1000 Hz and 0-6400 Hz for the amplitude characteristics. Even though the input signal for the mid-high frequency sound source is high-pass filtered at 600 Hz, the transfer functions obtained by this source are valid down to 200 Hz since sufficient sound output is produced by the source compared to background noise levels. In Figure 8 it can be seen that the measured transfer functions using the two sound sources agree very well in amplitude from 200 Hz up to at least 3 kHz. The lower plot in Figure 8 shows the amplitude in the frequency range 0-6400 Hz, where deviations are seen in the range of 10 dB's at high frequencies. This is expected as the high frequency source is omni-directional to a much higher frequency than the low frequency source and also the dimensions of the sources plays a role at higher frequencies together with their different acoustic centers, thus introducing deviations.

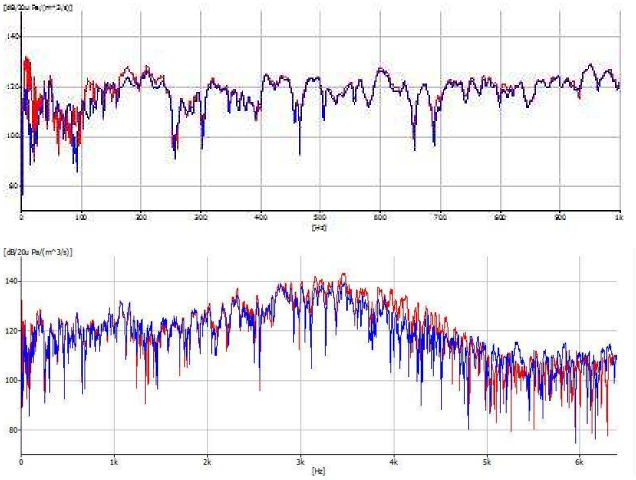

Figure 8: Comparison of acoustic transfer functions measured between engine top and right ear position. Low-mid freq source (blue) and mid-high freq source (red). Top: 0-1000 Hz. Bottom: 0-6400 Hz.

Direct vs reciprocal measurement

Further 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 adaptor just outside the concha part of the right pinna is shown in Figure 9.

Figure 9: Positioning the adaptor of mid-high frequency sound source at HATS right ear for reciprocal transfer function measurements.

For the reciprocal measurements a standard ½″ microphone 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 adaptor piece would be neccessary.

Comparison of direct and reciprocal measured transfer function is shown for the high frequency source in Figure 10.

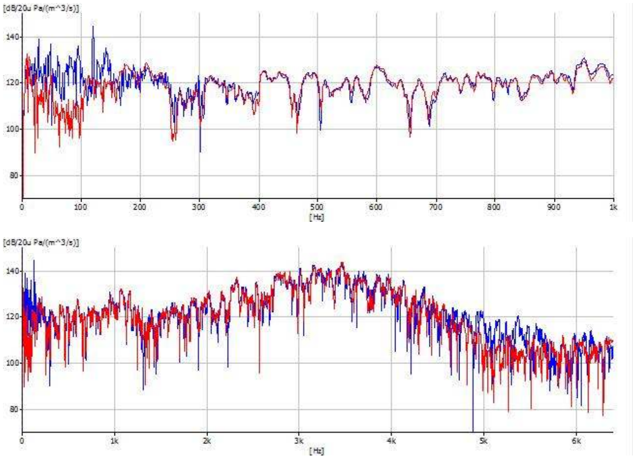

Figure 10: Direct (red curve) and reciprocal (blue curve) measurement of top engine surface to HATS left ear transfer function using mid-high frequency source. 0-1000 Hz (top) and 0-6400 Hz (bottom).

Some deviations are expected at lower frequencies where the output of the source is limited, i.e. below 200 Hz. Also the effect of having a poor signal-to-noise ratio for the microphone at the source position will have an impact and we see this as a more noisy reciprocal transfer function below 400 Hz. Otherwise we see good agreement between the two transfer function up to nearly 5 kHz, above that frequency other types of errors are introduced mainly due to incorrect positioning of the sound source for reciprocal measurement, i.e. the adaptor orifice is not placed at the entrance of the ear canal.

Conclusions

Sound sources for measuring different vibro-acoustic transfer functions have been investigated although the emphasis has been on the acoustic transfer functions. The type of sound source presented here was based on a powerful driver attached to a long hose equipped with two microphones close to the orifice for estimating the volume velocity source strength in situ. Transfer functions measured as FRF's can then easily be estimated. The principle was reviewed and two different sound sources were presented. In particular a sound source aimed for mid-high frequency measurements making use of the two-microphone method was investigated and compared to a current low-mid frequency sound source. Directivity aspects were discussed and simple measurements showed the sensitivity of the measured transfer functions with respect to adaptor orientation. 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. However one has to be aware that background noise will have a greater impact on the reciprocal measurements. 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.

References

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