Techniques for Measuring the Vibro-Acoustic Transfer Function

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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 (for example, source position) with an output (receiver position). In this article, we 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 compare the described volume velocity source with a mid-high-frequency sound source based on the same two-microphone method.

For applications where the acoustic radiation from a complicated sound source is modeled, a series of sound pressure/volume velocity (p/Q) FRFs are normally 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) FRFs. Both the p/Q and the p/F transfer functions can be measured using acoustic excitation while there are no other operating sources.

To measure vibro-acoustic p/F FRFs 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 FRFs 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 (on the engine surface; for example, see Figure 1). For practical reasons, however, transfer functions from engine room source to cabin receiver are usually measured reciprocally due to the limitation of space in engine compartments, even if the source is based on a driver (loudspeaker) with a long hose attached.

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

- Source should produce a sufficiently high sound level.
- Frequency range covered should be appropriate.
- Source should behave as a monopole in the frequency range of interest.
- Output volume velocity should be measurable even when the acoustic environment changes.

The acoustic source for this purpose must be powerful and omnidirectional, and a signal related to the source strength must be available if the source strength is not available directly. Also 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 is covered later in this article 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 the anechoic room. A further benefit of this approach is the ability to determine the output volume velocity in any acoustic environment.

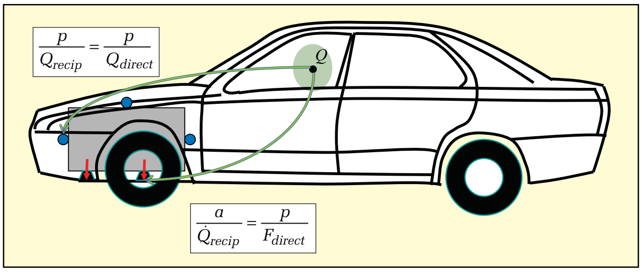

Figure 1. Reciprocal measurement of acoustic (p/Q) and vibro-acoustic (p/F) transfer functions in a vehicle.

Apart from these technical requirements, one might 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 compartment. 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 to any surface or to position it in the near field if a reciprocal approach is used. This supports the use of 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 to a surface or be positioned in free space during transfer function measurements.

Two-Microphone Measurement Method

The principle behind a particular volume velocity sound source was described in terms of how it was designed in a paper from 2004.[2] An omnidirectional sound source (B&K Type 4295) already used for room acoustics applications, was chosen as the 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 2a shows the source itself with the adaptor mounted inside an anechoic room and Figure 2b shows a practical measurement setup where a hose (flexible duct) is mounted between driver and adapter for ease of use during measurements. As the useful frequency range of the driving loudspeaker is 50-6000 Hz, the output will be sufficient. However, the radiation from the orifice of the adaptor becomes more directive; that is, less omnidirectional, above 2-3 kHz. Later we will call this the low-mid-frequency sound source.

We will now review some of the basic concepts behind the two-microphone method that 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).

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

$$p(x) = p_+ e^{-jkx} + p_- e^{jkx} \tag{1}$$

where p_+ and p_- are the incident and reflected plane wave com-

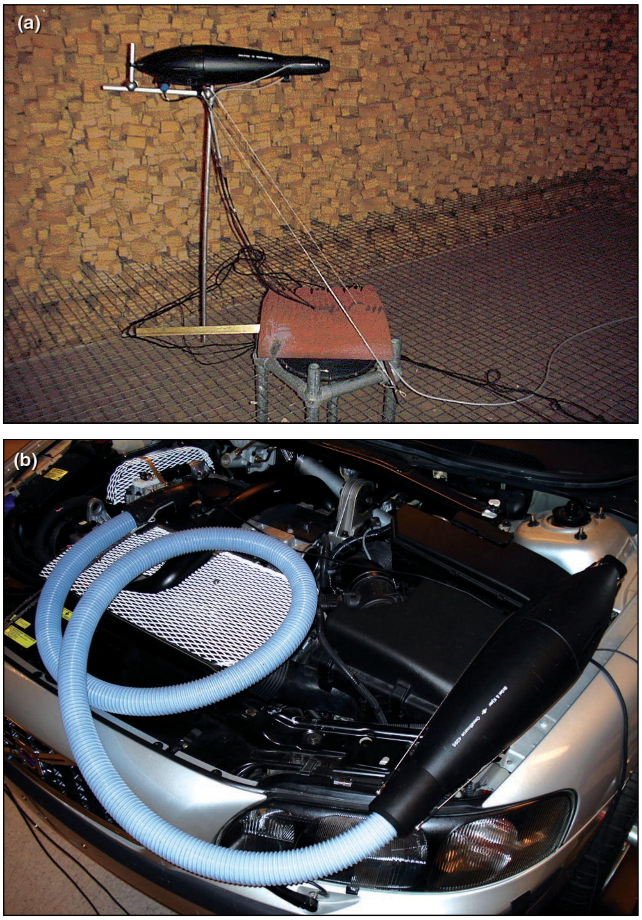

Figure 2. Low-mid frequency sound source (a) without and (b) with extension hose.

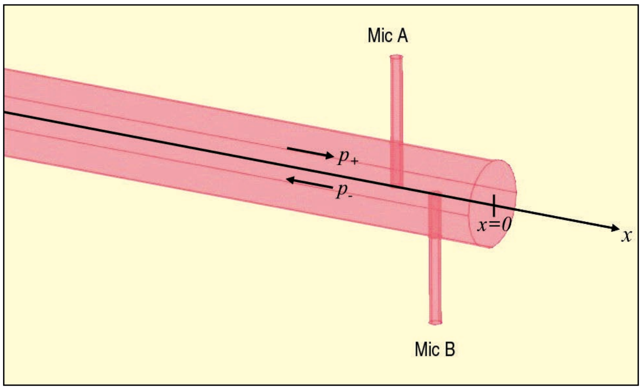

Figure 3. Two-microphone measurement configuration for volume velocity output estimation.

ponents respectively, and k is the wave number. 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:

$$u(x) = \frac{1}{\rho c}\left(p_+ e^{-jkx} - p_- e^{jkx}\right) \tag{2}$$

where ρc is the characteristic impedance of air.

At the duct opening, $x = 0$, we have:

$$u(0) = \frac{1}{\rho c}\left(p_+ - p_-\right) \tag{3}$$

This expression leads to volume velocity estimation if we multiply by the cross-sectional area of the duct. We can further express the volume velocity output as an autospectrum based upon the autospectra of Microphones 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:

$$H_{Qp} = \frac{C_{Qp}}{C_{QQ}} \tag{4}$$

Here C_{QQ} is the autospectrum of the estimated volume velocity signal, and C_{Qp} 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 Microphones A and B plus the receiver. Additionally, we need the dimensional parameters l and Δ, where l is the distance from the duct opening to the nearest microphone (Microphone B) and Δ is the microphone spacing.

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

Finite-Element Modelling Inside Duct

To verify some of the aspects related to sound fields in ducts, it is very useful to perform simulation studies for optimizing design parameters. Some studies have investigated the influence of the surroundings on the duct output and the interference effect of placing microphones inside the duct for measuring 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 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; this can result in large errors in the calculated volume velocity spectrum. This will be evident when dealing with narrow ducts.

We modeled the setup from the low-mid-frequency sound source, with 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 (inner diameter 3.8 cm) containing the two microphones and the two spacers was modeled using acoustical finite elements. The duct is excited at 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]

The output from the simulation will now be the particle velocity, integrated over the opening of the duct, which will be the simulated volume velocity (also termed as exact). Furthermore, we can take the simulated sound pressures integrated over the microphone diaphragm boundaries, process that data using the volume velocity estimation method (described earlier), and finally compare this 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 20 Hz-10 kHz and, as expected, at high frequencies the influence of obstacles inside the duct is quite significant. An example of a surface pressure distribution is given in Figure 4 for a frequency of 8 kHz. Locally, around the position of the microphones, the sound field changes and does not consist of plane waves.

A comparison of the direct simulated volume velocity output spectrum and what was predicted based on the simulated sound pressures inside the duct at the microphone diaphragms is shown in Figure 5 for the full frequency range considered. 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, 50 Hz-6 kHz, the error is always less than 1.5 dB, and for most of the frequency

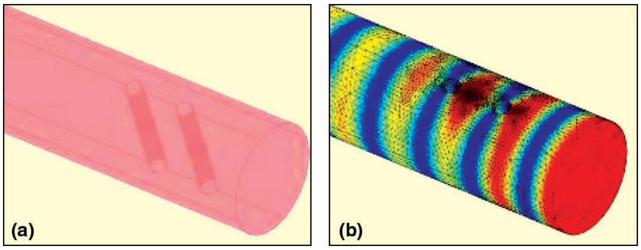

Figure 4. Setup of microphones (a) inside duct and (b) sound pressure distribution at duct end for a frequency of 8 kHz.

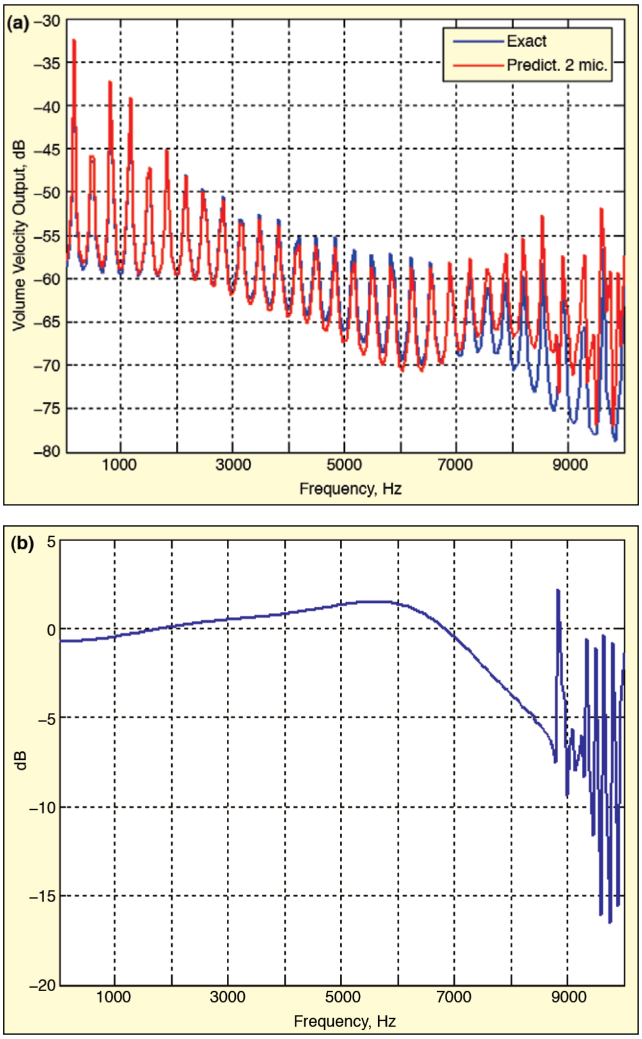

Figure 5. Comparison of simulated and predicted volume velocity output from duct with two microphones inside. (a) Volume velocity spectra; (b) Difference between spectra.

range, the error is actually less than 0.5 dB.

Verification of Volume Velocity Source

Verification measurements were done using the low-mid-frequency sound source to explore some of the aspects explained earlier. The basic parameters describing the sound source were already presented,[2] like maximum output power, directivity characteristics, etc. Here we present some other measurements verifying the concept of the volume velocity sound source. One of the ideas behind using the two-microphones for volume velocity estimation is that the 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. Photos of the different setups are shown in Figure 6.

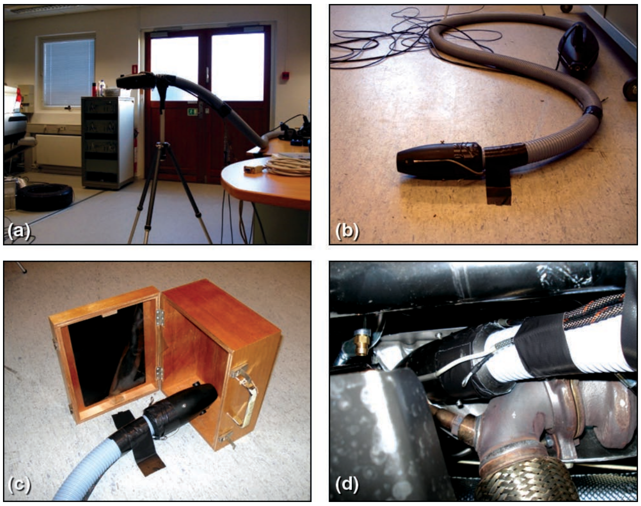

Figure 6. Sound source placed in different environments: (a) inside room away from the walls; (b) close to floor; (c) radiating into box; and (d) inside engine compartment.

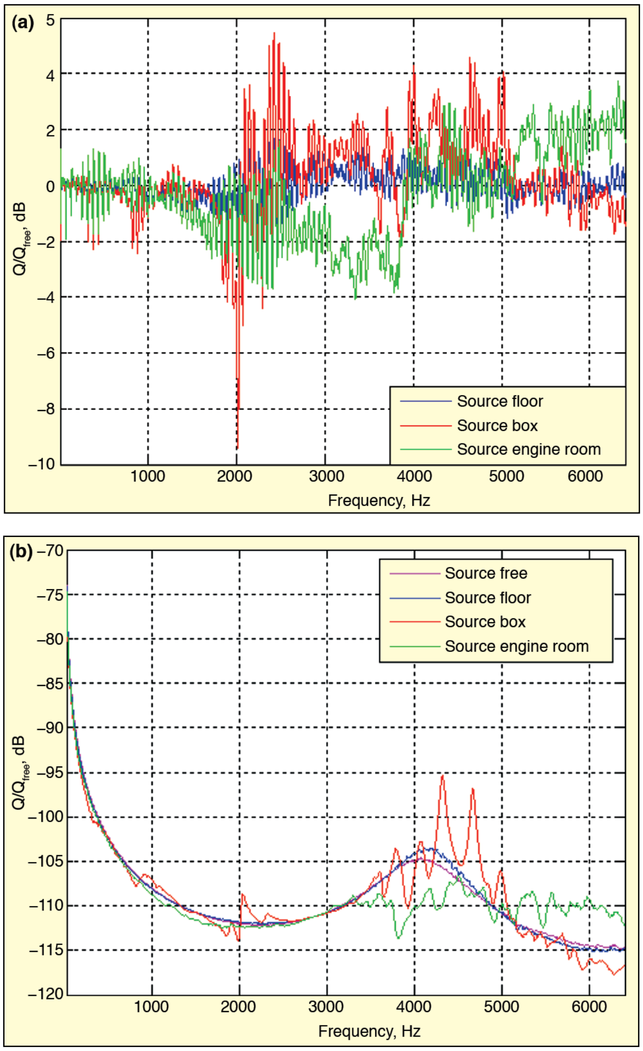

Figure 7. (a) Calculated volume velocity output spectrum relative to free space for three different environments; (b) Volume velocity to reference sound pressure ratio for all environments.

The sound source was driven by a band-pass filtered (bandwidth 6.4 kHz) 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 7a, where three of the calculated spectra are shown relative to the measurement where the source was placed freely in the room away from the walls. Below a certain

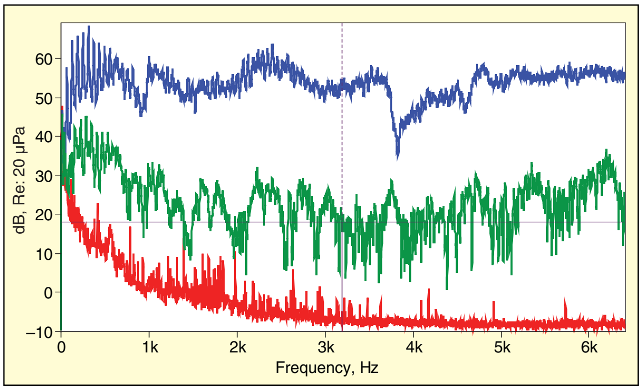

Figure 8. Sound pressure measured 30 cm in front of open/blocked orifice of low-mid frequency source.

frequency (around 1.5 kHz) the different outputs from the source are all within a few dB, 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 that also changed accordingly.

Some of the 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 can then be translated into a volume velocity spectrum using the calibration curve.

But the question is, what influence will the acoustic environment have on the volume velocity estimations we measured, since the actual measurement environment may be very confined (like inside an engine compartment). In our test cases, we use the signal from the microphone closest to the opening as a reference to examine this ratio for our four setups. Figure 7b shows the individual curves, and we see less variation in the ratio compared to the volume velocity spectrum. However, some errors are introduced if the environment becomes more confined. Especially at high frequencies, there are quite large differences. At the same time, we should remember that the source itself is only omnidirectional up to 3 kHz, 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 to investigate if the sound was radiated mainly from the opening of the tube (as desired) or if the driver and tube walls contributed significantly. A microphone was placed 30 cm 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 with the opening 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 this case are more than 20 dB lower than the case of the open duct over the complete frequency range for that source. When the source was blocked, some sound was transmitted through the damping at the duct opening, especially at lower frequencies. Otherwise, only sound coming directly from the driver itself was identifiable. Altogether, we concluded that sound produced by the assembly of driver and hose is mainly radiated from the duct orifice, which means it can be used as a monopole to measure vibro-acoustic transfer functions.

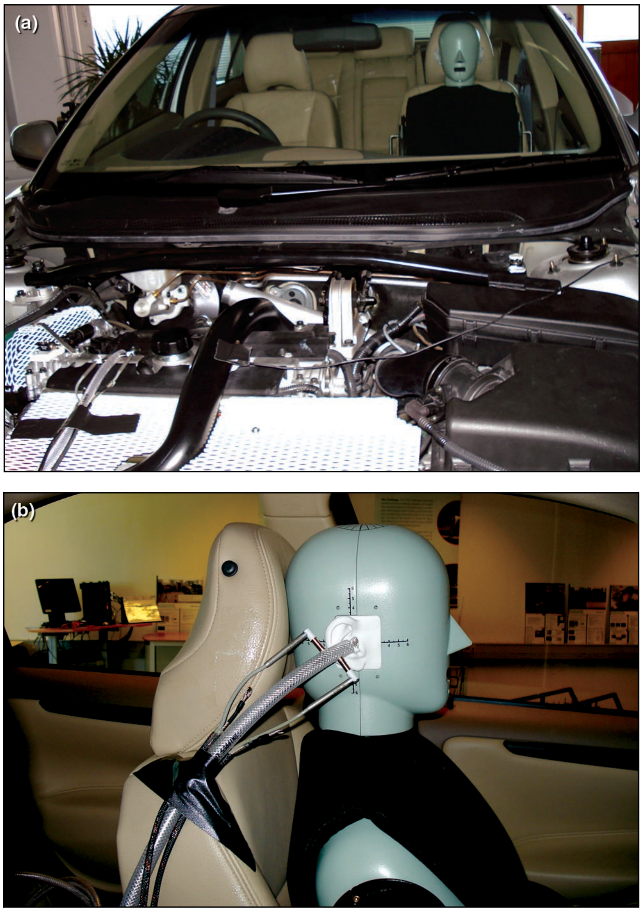

Figure 9. Measurement of acoustic transfer function from top engine surface point to left and right ear, using the mid-high frequency sound source: (a) Hose at engine source position for direct transfer function measurement; (b) Positioning of sound source at right ear for reciprocal transfer function measurements.

Application of Volume Velocity Sources

The volume velocity source described so far has been used to measure acoustic transfer functions between an assumed source position inside an engine compartment 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 (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 practical using the current sound sources, so in this experiment, the orifice of the adapter was placed as close to the ear microphones as possible but still outside the pinna/concha.

The effect of the head and torso is included in the reciprocal transfer functions. However, the full effect of the concha is not included, so 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 (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 it 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 a 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 10 mm, 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 passenger seat of this right-hand-drive car (see Figure 9).

Source Directivity

A couple of measurements were carried out with each of the investigated sound sources for the same source position on the top engine surface, where the orientation of the adapter 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 omnidirectionality. Figure 10 compares a transfer function measured with the low-mid frequency sound source for different orientations of the adapter; that is, pointing toward the rear, front or left side of the vehicle. The measured transfer functions are valid down to 50 Hz, where the output power of the loudspeaker starts to decrease significantly, and we see similar transfer functions for all three orientations up to 2-3 kHz. From that frequency on, the sound from the orifice of the adapter becomes more directive, as explained earlier; this can be seen from the plot in Figure 10b.

In all measurements, a white-noise signal band-limited to 6.4 kHz was driving the sound source at a maximum level. FFT processing and averaging were used to calculate transfer functions as FRFs with frequency resolution of 1 Hz.

Comparison of Sound Sources

Measuring the same direct transfer function from the top engine surface position to HATS ears was 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, while the mid-high frequency sound source was driven by a similar white noise signal high-pass filtered with cutoff at 800 Hz (so not to overload the driver at low frequencies). Transfer functions measured with the orifice pointing toward the vehicle rear were measured and are compared in the frequency ranges 0-2 kHz and 2-6 kHz for both amplitude and phase characteristics. Even though the signal for the mid-high-frequency sound source is high-pass filtered at 800 Hz, the transfer functions obtained by this source are valid down to 400 Hz, since sufficient sound output is produced by the source compared to background noise levels.

Figure 11 shows that the measured transfer functions using the two sound sources agree very well in both amplitude and phase from 400 Hz up to at least 2 kHz. Figure 12 shows similar amplitude and phase plots but now in the high-frequency range of 2-6 kHz, where deviations are in the range of 10 dB. This is expected, since the mid-high frequency source is omnidirectional to a much higher frequency than the low-mid-frequency source, and also the dimensions of the sources play a role at higher frequencies together with their different acoustic centers.

Direct vs. Reciprocal Measurements

Finally, we compare directly measured transfer functions to reciprocal transfer functions. In the case of reciprocal measurements, the HATS was still in place inside the vehicle, but now the sound source was 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 1/4-inch 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 adapter on the sound field locally around the engine surface position should be included by having them in place during reciprocal measurements. This effect was ignored, however, since it was not practical. That is, if we had wanted to include this effect, another piece of hose with a blocked orifice would have been necessary.

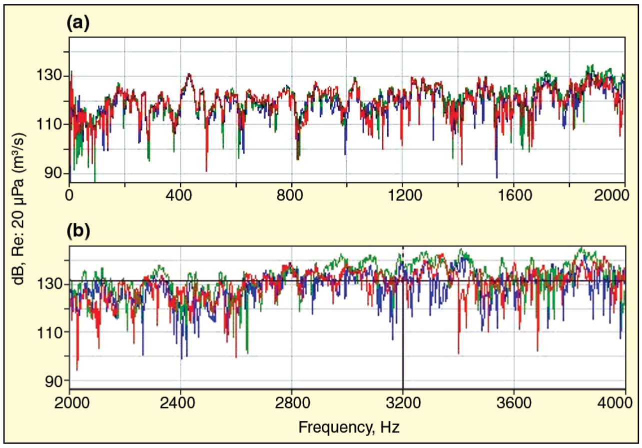

Figure 10. Acoustic transfer function measured between top engine position and HATS left ear for different nozzle orientations using low-mid frequency sound source. (a) 0-2 kHz; (b) 2-4 kHz.

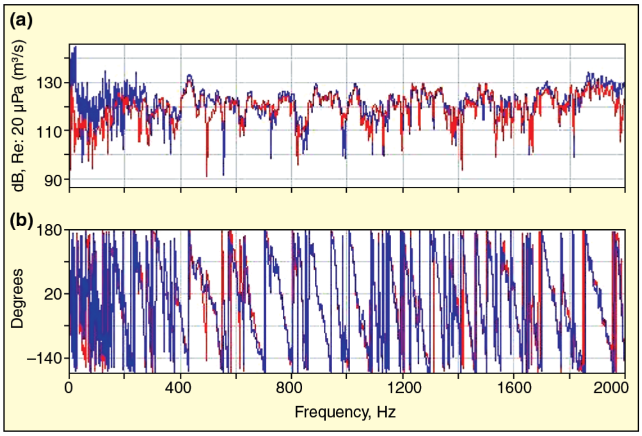

Figure 11. Amplitude and phase of acoustic transfer function from top engine surface to HATS left ear measured using low-mid frequency source (red curve) and mid-high frequency source (blue curve); 0-2 kHz.

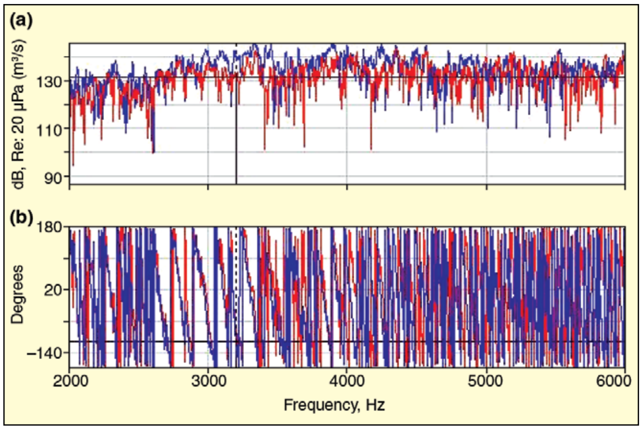

Figure 12. Amplitude and phase of acoustic transfer function from top engine surface to HATS left ear measured using low-mid frequency source (red curve) and mid-high frequency source (blue curve); 2-6 kHz.

Comparing direct and reciprocal measured transfer functions 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 3-4 kHz, the tendency remains the same for both curves. Above 4 kHz, the deviations become more pronounced. At these higher frequencies, the sound source is no longer acting as a monopole, and the effect of the concha in the reciprocal transfer function is missing.

Comparing direct and reciprocally measured transfer functions 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 a less sensitive array microphone for the reciprocal measurement and also because of poor

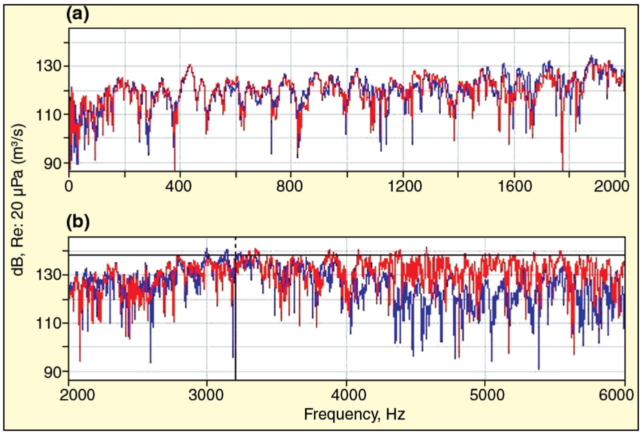

Figure 13. Direct (red curve) and reciprocal (blue curve) measurement of top engine surface to HATS left ear transfer function using low-mid frequency source: (a) 0-2 kHz; (b) 2-6 kHz.

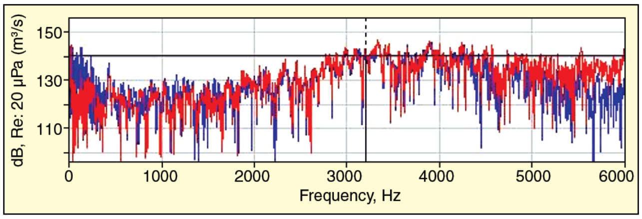

Figure 14. Direct (red curve) and reciprocal (blue curve) measurement of top engine surface to HATS left ear transfer function using mid-high frequency source; 0-6 kHz.

signal-to-noise ratio for that microphone. Otherwise, we see good agreement between the two transfer functions 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 measurements.

Conclusions

Sound sources for measuring vibro-acoustic transfer functions have been investigated, although the emphasis has been on 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 FRFs 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 binaural transfer functions reciprocally, with some confidence, by placing the orifice close to the entrance of the outer ear. In this case, a standard HATS and a volume velocity source can be used to do all operating and transfer function measurements related to source-path-contribution analysis (including binaural effects). Additionally, a sound source aimed for mid-to-high-frequency measurements was investigated and compared to the current low-to-mid-frequency sound source.

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