

An Artificial Head which Speaks from its Ears: Investigations on Reciprocal Transfer Path Analysis in Vehicles, Using a Binaural Sound Source

Roland Sottek

HEAD acoustics GmbH, Herzogenrath, Germany

Philipp Sellerbeck, Martin Klemenz

Institute of Technical Acoustics (ITA), Aachen University of Technology, Germany

Copyright © 2003 SAE International

ABSTRACT

The usefulness of reciprocal transfer path analysis is becoming increasingly known. We will discuss the requirements of noise measurements in vehicles and the advantages of reciprocal methods. An acoustic model of a binaural sound source, approximating the shape of the human head, has been developed. This sound source is used for the characterization of airborne and structure-borne sound transfer functions in vehicles, automatically including the effect of the head on the sound field. In this paper, calibration procedures and technical limits of this technique are discussed, and some preliminary examples of its application are demonstrated.

INTRODUCTION

Reciprocal techniques for determining acoustic transfer functions are becoming increasingly common in NVH applications. This development is driven by a number of advantages provided by reciprocal methods. What does reciprocity mean?

In a linear elastic system, vibrational excitation at one point causes a response at another point. Generally speaking, if the system is passive and time-invariant, the transmission of vibration is invariant with respect to exchange of the points of excitation and observation. Such a system is reciprocal. In other words, reciprocity states that the transfer path in one direction equals the one in the opposite direction. The principle is valid in mechanical, electrical and acoustical systems as well as hybrid systems, e.g. acoustic transducers.

Considering the very different space requirements of sound sources and sensors, measurements of acoustic transfer functions are often much easier done reciprocally. A typical example 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 speaker, whereas in the cabin there should be enough space for a sound source. Furthermore, reciprocal measurements can offer better results, and again size is a reason. Small sensors can be placed much closer to sound-radiating surfaces to which transfer functions are to be determined, and measurement positions can be chosen almost without restriction. Thus the local sound field is sampled better than by the direct measurement, which employs a sound source (inside the engine compartment) that usually cannot be placed at the exact point of interest. Hence the reciprocal transfer function may approximate the real transfer path better than the direct measurement. Moreover, 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.

Acoustic reciprocity was first mentioned by Helmholtz 1860 regarding sound transmission through pipes [1]. A general theory of reciprocity, not limited to acoustics but valid for arbitrary systems containing friction and viscous damping, was developed by Rayleigh 1873 [2]. Lyamshev published a formal proof of these assumptions in 1959 [3]. He stated that any vibrating structure can be incorporated in the reciprocal system, thus paving the way for modern NVH applications.

A general derivation of the principle from four-pole theory is given by Ten Wolde 1973 [4]. Practical applications of the theory are also presented. Another comprehensive summary is published by Fahy 1995 [5]. Based on Rayleigh's work, he derives reciprocity for dipole sources and confirms the validity of the principle

for vibrating fluid-structure boundaries. Several NVH applications are presented, including reciprocal measurements in vehicles and sound source identification at complex vibrating structures.

A detailed description of reciprocal transfer path analysis in vehicles as well as source calibration can be found in [6], though only structure-borne noise is considered. In this work by Pankoke, the idea of a sound source approximating the human head is already implemented in a simple way, but binaural technology is not employed.

Further reciprocal measurements of structure-borne noise in vehicles are presented in [7], also describing the importance of in situ calibration of the source at low frequencies. The reciprocal investigation of airborne noise transfer paths from the tires to the ear is described in [8]. An omnidirectional source is placed in the cabin, and a microphone is brought close to the tire surface. A similar method can be employed to measure airborne noise paths from an engine to the driver as presented in [9]. Source calibration and a procedure to determine effective sound sources at the engine surface are also described in that paper.

The acoustic (airborne sound) and vibro-acoustic (structure-borne sound) reciprocity relations, which are useful in our NVH applications, are summarized in the following paragraphs.

ACOUSTIC RECIPROCITY

Acoustic reciprocity in fluids is used to determine airborne sound transfer functions. A volume velocity source Q_1 at position 1 generates a sound pressure p_2 at position 2 (Fig. 1a).

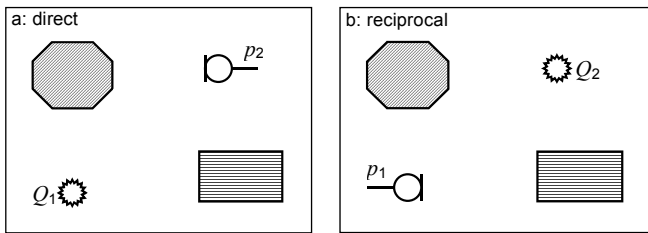


Fig. 1: acoustic reciprocity in fluids with scattering structures [5]

In the opposite or reciprocal, experiment the volume velocity Q_2 at position 2 generates the pressure p_1 in position 1 (Fig. 1b). Scattering structures in the sound field do not violate reciprocity. At each position, both source and receiver must have the same directivity (e.g. monopole characteristics).

$$\frac{p_2}{Q_1} \Big|_{Q_2=0} = \frac{p_1}{Q_2} \Big|_{Q_1=0} \quad (1)$$

VIBRO-ACOUSTIC RECIPROCITY

Furthermore, when investigating structure-borne noise, vibro-acoustic reciprocity based on fluid-structure interaction is also employed. When excited by a point force F_1 at position 1, the structure under investigation generates the sound pressure p_2 at position 2 (Fig. 2a).

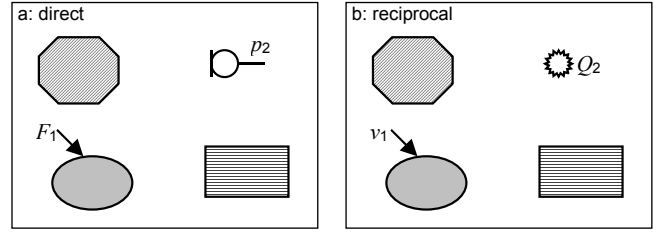


Fig. 2: Vibro-acoustic (fluid-structure) reciprocity [5]

In the reciprocal experiment, a volume source Q_2 at the former receiver position causes the surface velocity v_1 on the structure (Fig. 2b):

$$\frac{p_2}{F_1} \Big|_{Q_2=0} = \frac{v_1}{Q_2} \Big|_{F_1=0} \quad (2)$$

From the above explanations we see that a calibrated volume velocity source is necessary for reciprocal acoustic measurements. Therefore, the volume velocity Q has to be determined with sufficient precision.

VOLUME VELOCITY CALIBRATION PROCEDURES

The volume velocity of a sound source cannot be measured directly. However, various methods exist for deriving Q from sound pressure or velocity measurements.

POINT SOURCE IN FREE FIELD

An omnidirectional point source producing the volume velocity Q generates the sound pressure p at distance r . Under free field conditions, the volume velocity can be calculated from a sound pressure measurement (ρ_0 : air density, f : frequency):

$$\tilde{Q} = \frac{2 r \tilde{p}}{\rho_0 f} \quad (3)$$

While such a point source exists only in theory, it is approximated by any monopole source that is small compared to the wavelength. The volume velocity of an acoustic monopole can also be calculated from its radiated sound power (c : speed of sound):

$$P = \frac{\rho_0 \omega^2 \hat{Q}^2}{8 \pi c} \quad (4)$$

For arbitrary sound sources, such a simple relation does not exist and volume velocity can only be predicted numerically.

REVERBERATION CHAMBER

The volume velocity of a sound source can be derived from the total radiated power in a reverberation chamber. In such a room, for the stationary state, the supplied acoustic power P equals the power loss due to the equivalent acoustic absorption A and can be calculated from the averaged mean square sound pressure:

$$P = \frac{A \bar{p}_m^2}{4 \rho_0 c} \quad (5)$$

The microphone has to be placed in the diffuse field, i.e. outside of the critical distance to the source. Again assuming a monopole, with (4) the volume velocity of the sound source can be expressed by

$$\tilde{Q} = \sqrt{\frac{A}{4\pi}} \frac{\bar{p}_m}{\rho_0 f} \quad (6)$$

As this method considers effective power of the source, phase information is lost. The result may still be useful if phase is not important or for comparison with other methods.

RECIPROCITY CALIBRATION WITH KNOWN VOLUME VELOCITY SOURCE

With the acoustic reciprocity relation (1), the volume velocity of an arbitrary sound source may be derived from an auxiliary measurement using a calibrated volume velocity source. If the auxiliary source has the characteristics of a point source, its volume velocity Q_2 can be identified by (3). During the auxiliary measurement, the sound pressure p_1 (generated by Q_2) is measured at the position of the unknown source. During the main measurement, the latter is active and the sound pressure at the position of the auxiliary source is recorded, allowing calculation of the unknown volume velocity:

$$Q_1 = p_2 \frac{Q_2}{p_1} \quad (7)$$

LASER VIBROMETER

If the sound source has a visible diaphragm, the surface velocity v can be measured with a laser vibrometer. The volume velocity can be calculated considering the effective sound radiating area S :

$$Q = \int v dS \quad (8)$$

Most diaphragms act as a piston at low frequencies thus a single point measurement should be sufficient, assuming the total surface of the diaphragm as effective area. Above a critical frequency, depending on mechanical properties, partial oscillations of the diaphragm may occur. In this case, effective subareas have to be found, and the vibration velocity of each subarea has to be measured.

Of course, several other vibration measurement transducers, e.g. piezoelectric accelerometers, exist, but due to their mass, they likely influence diaphragm motion and are not further considered here.

PARTICLE VELOCITY PROBE

Using a miniature particle velocity probe (Microflown [10], Fig. 3) the sound particle velocity can be measured directly without employing pressure measurements. The volume velocity is then calculated according to (8), considering an appropriate cross section, e.g. orifice area. In contrast to the well-known intensity probes employing two microphones, this technique offers almost point-size measurements with a very small probe covering a wide frequency range and is therefore of special interest for us.

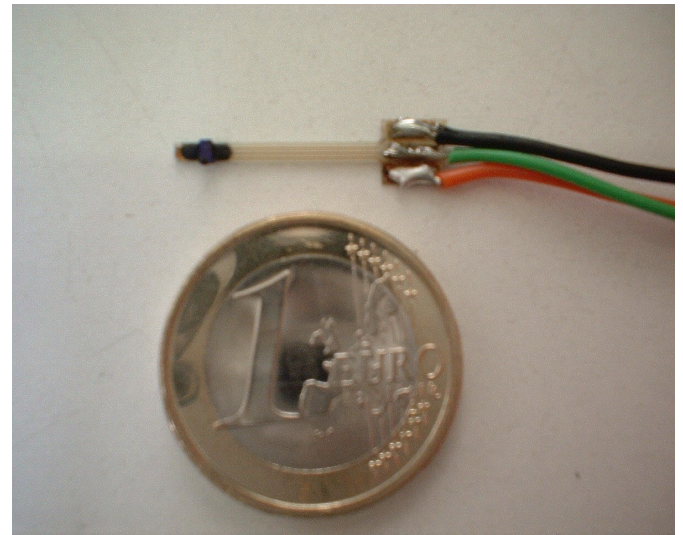


Fig. 3: Microflown particle velocity probe

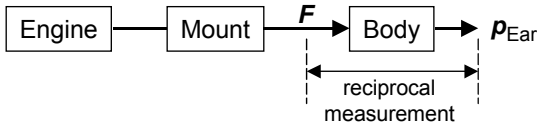
A BINAURAL SOUND SOURCE FOR TRANSFER PATH ANALYSIS

Based on the demands of the automobile industry, Binaural Transfer Path Analysis and Synthesis (BTPA and BTPS) techniques have been developed for the prediction of sound quality in vehicles, not only in terms of numbers and graphs, but also for binaural auralization.

BTPA is a measurement procedure for characterizing individual vehicle noise paths [11]. The results can be used to create an accurate model for path-related noise heard anywhere inside the vehicle, thus yielding

possibilities for troubleshooting and sound design. For structure-borne sound, transfer functions from engine mount to ear are measured for each individual noise path (Fig. 4). For airborne noise, acoustic transfer functions are determined similarly. For the latter, all relevant sound sources have to be known, especially because no discrete reference points exist as they do in the case of structure-borne sound.

Structure-borne noise path:



Airborne noise path:

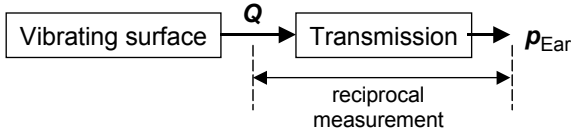
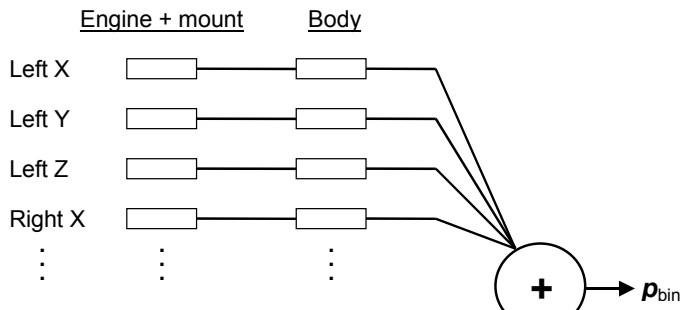


Fig. 4: Transfer functions measured by BTPA

BTPS (Binaural Transfer Path Synthesis) is the process of synthesizing interior noise by combining selected noise paths (Fig. 5). For engine and transmission mounts, vibration signals in all three directions (x, y, z) are considered. Each individual path or combination of paths can be listened to independently, in order to assess their respective impact on the overall sound quality. Paths can be modified to simulate countermeasures and their effect on the interior noise. Operating data measured on different sources, such as an engine test rig, may also be put into the model to predict how interior noise is influenced by the different sources [12, 13].

Structure-borne noise



Airborne noise

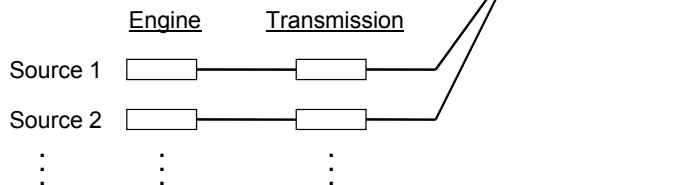


Fig. 5: Binaural synthesis based on airborne and structure-borne sound transfer paths

Using the reciprocity relations described in section 1, the acoustic (Q to p) and vibro-acoustic (F to p) transfer functions can be measured reciprocally. As binaural technology employs individual transfer functions for left and right ear, the sound source has to be binaural, too.

DESIGN OF THE SOURCE

In order to perform BTPA reciprocally, a binaural sound source has been developed based on an artificial head system HMS III (Fig. 6). Inside the head, each ear contains an electrodynamic horn loudspeaker. With this design, effective sound radiation from about 200 Hz to above 8 kHz is possible.



Fig. 6: Artificial head HMS III

DIRECTIVITY

The sound source is implemented as an artificial head in order to fulfill another requirement of reciprocal measurements: The directivity of the source replacing the receiver must be identical to the receiving characteristic of the latter [5]. To verify the directivity, the sound pressure generated by the binaural source was measured at a distance of 2 m in steps of 10° around the source. From that data, the free-field HRTFs (Head Related Transfer Functions, normalized by transfer function of front direction) were calculated and compared to those of the HMS III receiver. Both the mean HRTF results (averaged over all directions) and those for discrete directions show a good match for frequencies of about 200 Hz to 6 kHz (Fig. 7).

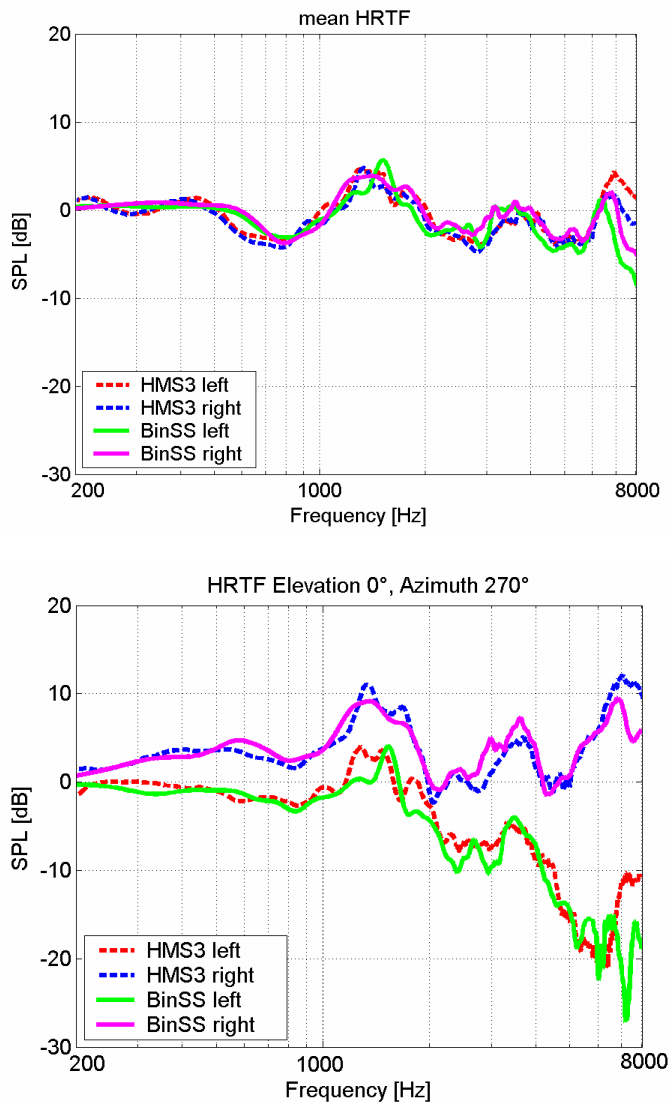


Fig. 7: Comparison of HRTFs (HMS III: dotted lines, binaural sound source: solid lines), top: all directions averaged, bottom: single direction

WAVE PROPAGATION IN EAR CANAL

The reciprocity requirement regarding source and receiver was investigated further. In the artificial head used for sound recording, plane waves are supposed to approach the microphone diaphragm in the ear canal. We defined the position of the diaphragm as a reference plane for reciprocity measurements. The sound source used does not have to be a monopole; it just has to equal the characteristics of the reciprocal receiver [5]. Thus the same plane wave conditions must exist at the reference position in the ear canal of the binaural sound source. In order to check whether this is correct even in the asymmetrical horn, point measurements on the reference plane were carried out with a probe microphone. The results show a symmetrical pressure distribution indicating the presence of plane waves below 6 kHz (Fig. 8).

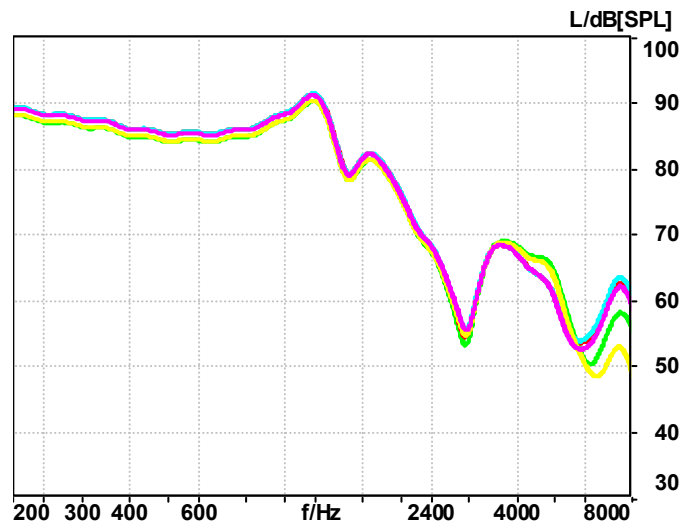


Fig. 8: Sound pressure measured at five points in the reference plane

CALIBRATION

All calibration procedures described before were applied to the binaural sound source. Both ears were calibrated separately. Each time, a linear sine sweep from 200 Hz to 8 kHz was used as the excitation signal.

Free field calibration was done in an anechoic chamber using a calibrated omnidirectional microphone. In order to take the directivity of the source into account, the microphone was placed on a rotating boom at a distance of 2 m from the head. Point measurements were carried out in 10° steps on a spherical area around the source. The total source power was calculated by summing up the sound intensities of the partial areas corresponding to the individual point measurements:

$$P = \frac{r^2}{\rho_0 c} \sum_{\vartheta} \sum_{\varphi} \tilde{p}^2(\vartheta, \varphi) \sin \vartheta \Delta \vartheta \Delta \varphi \quad (9)$$

The volume velocity was then calculated using the point-source assumption (4), resulting in

$$\tilde{Q} = \sqrt{\frac{cP}{\rho_0 \pi f^2}} \quad (10)$$

Further calibration measurements were carried out in the reverberation chamber. Three microphone positions were averaged. Volume velocity was calculated from (6).

Theoretically, reciprocity calibration can be performed in any room; nevertheless, the anechoic chamber was used in order to eliminate environmental noise. A point source developed at the ITA was used as an auxiliary volume velocity source. Sound pressure measurements were carried out using a calibrated probe microphone in the ear canal and an omnidirectional microphone at the location of the auxiliary source.

In the case of the binaural sound source, only the middle part of the diaphragm can be seen through the ear canal and therefore be reached by the laser vibrometer. Thus it is not possible to measure partial oscillations, and the method is limited to low frequencies. However, high accuracy is expected in that range as the origin of volume velocity, diaphragm motion, is captured.

The miniature particle velocity probe is very suitable for our application as it can be placed inside the ear canal, and particle velocity can be measured directly in the reference plane. But the available sensor must be calibrated itself, e.g. in free field or in a standing wave tube. As the probe is very sensitive to fluctuations of temperature or humidity, both measurements were performed consecutively in the same environment. Three sensor positions in the ear canal were averaged.

EXCITATION SIGNALS

For calibration measurements as well as for transfer path analysis in vehicles, sine sweeps were chosen as the excitation signal. Sweeps are the preferred choice for most transfer function measurements. The most important advantages of these signals are high dynamic range, low crest factor and the possibility to discard harmonic distortion [14].

REACTION OF THE SOUND FIELD

Standing waves inside the vehicle are likely at low frequencies and may cause feedback on the radiation of the source. Thus the binaural sound source would need to be calibrated in each individual vehicle. In order to minimize this influence of the surrounding room, the sound source inside the head was designed to behave independently of the sound field. However, to test whether this design is effectively rejecting reaction, an electrical impedance measurement was carried out in the vehicle as well as free field conditions.

The equivalent circuit of an electrodynamic speaker reveals that the electric input impedance is influenced by the acoustic load [15]. If the velocity of the diaphragm – and thus the radiation – would be influenced by the sound field, the impedance should also change. Measurements covering the complete frequency range of interest showed no difference of impedance between free field and vehicle interior (Fig. 9).

Direct measurement of diaphragm velocity using a laser vibrometer revealed comparable results. Thus the calibration of the source can be considered valid inside the cabin.

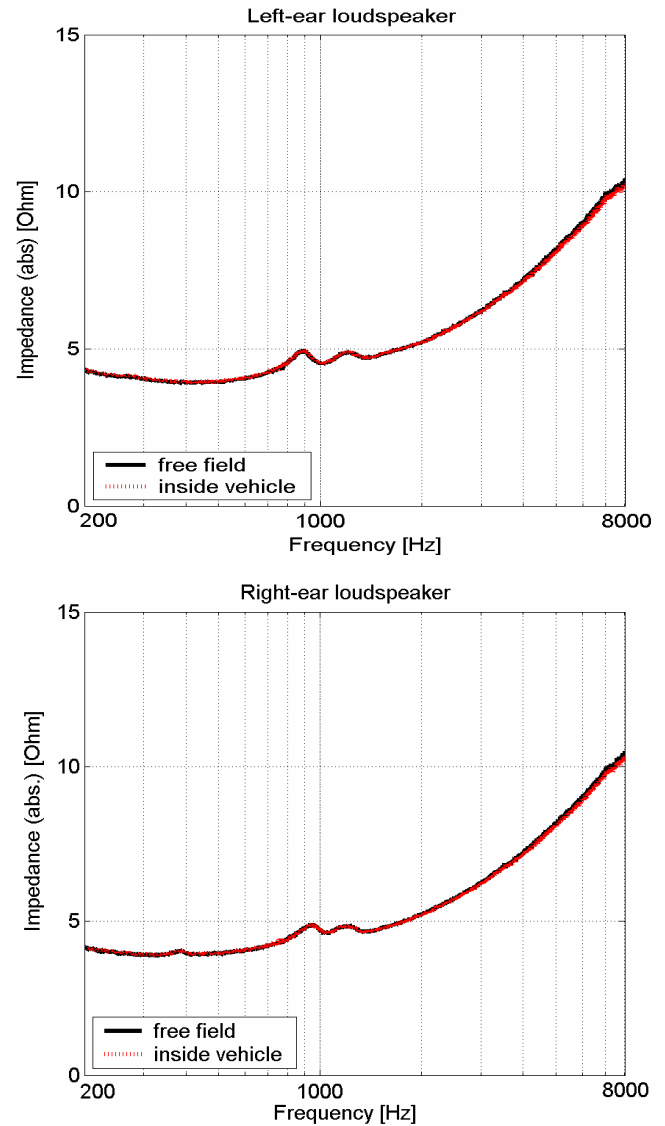


Fig. 9: Comparison of speaker input impedance in free field and in the vehicle, top: left ear, bottom: right ear

RECIPROCAL MEASUREMENTS

BINAURAL RECIPROCITY TEST

In order to verify reciprocity in the case of the combination of binaural sound source and binaural receiver, a simple experiment was carried out in the laboratory. A suitable structure (empty 20 l gas can) was excited by the binaural sound source, and the surface velocity was measured using a laser vibrometer. In a second experiment, the canister was excited by an impact hammer. At the former position of the binaural source, sound pressure was measured binaurally using a HMS III artificial head. Excitation force was measured simultaneously. Both the direct and reciprocal transfer functions are shown in Fig. 10.

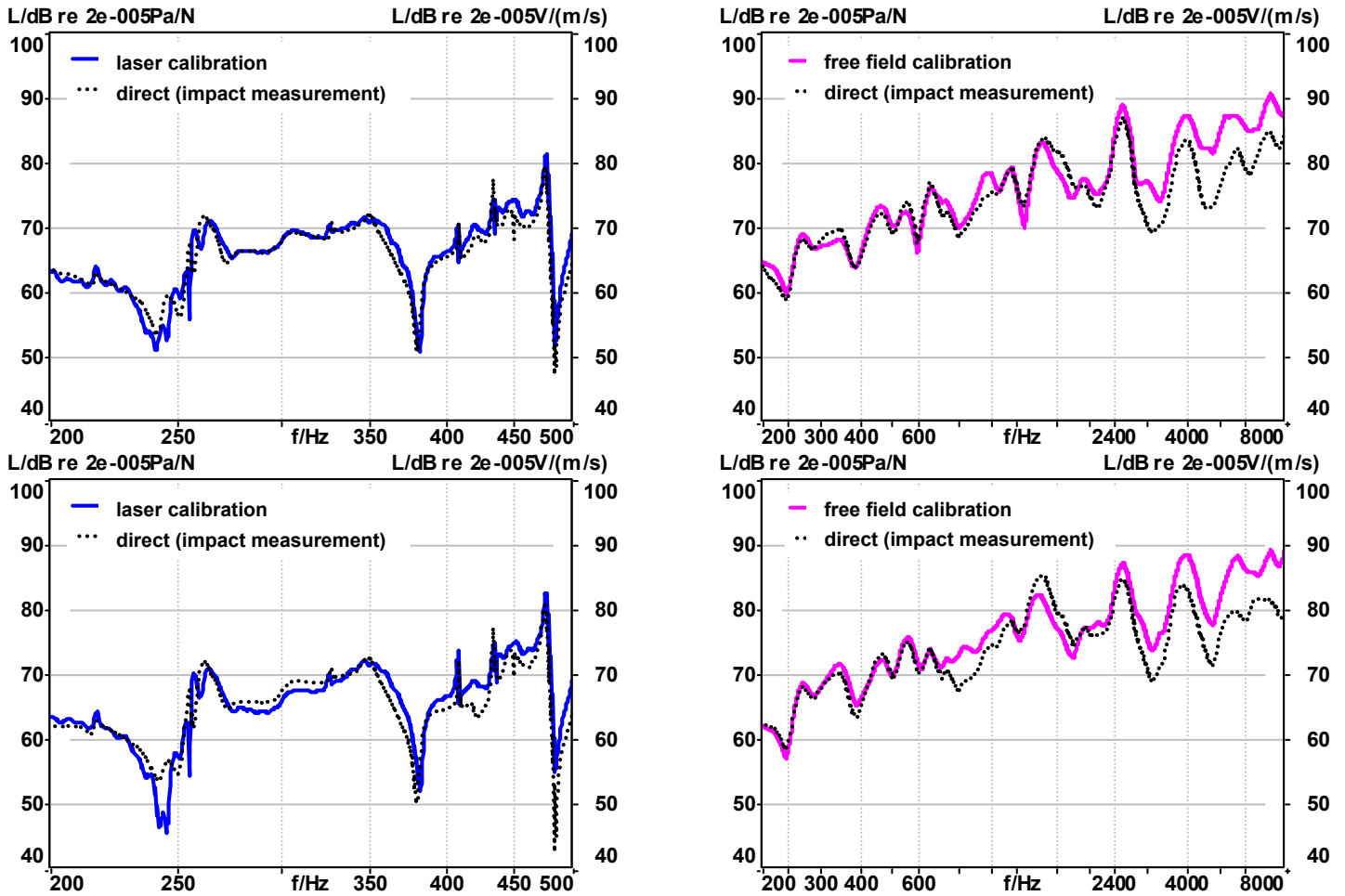


Fig. 10: Vibro-acoustic transfer functions of the test structure, direct measurement (dotted lines) and reciprocal measurement (solid lines) based on two calibration methods. Left: laser calibration, results shown with high frequency resolution up to 500 Hz, right: free field calibration, smoothed data (1/24 octave) for full frequency range; top: left channel, bottom, right channel

MEASUREMENTS IN A VEHICLE

Along with conventional BTPA measurements, the binaural sound source was used to determine airborne and structure-borne noise transfer functions in a medium-class car reciprocally. Therefore, the binaural sound source was placed on the driver seat. First, signal-to-noise ratio was analyzed in order to predict the usable frequency range of the method. For structure-borne sound, an upper critical frequency of 2 kHz was found.

Fig. 11 shows acceleration signals at an engine mount in three directions (x, y and z) captured during excitation with the binaural sound source in comparison to the noise floor. These tests were done for measurement positions both on engine side and body side of an engine mount. As there is almost no signal present on the engine side, it is not possible to determine mount transfer functions with the reciprocal setup.

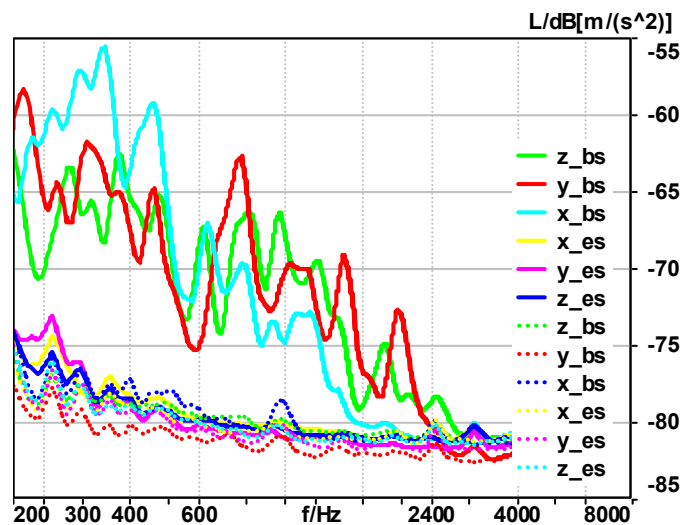


Fig. 11: FFT of acceleration signals at an engine mount, due to binaural excitation (solid lines) and background noise (dotted lines), each measured at engine side (es) and body side (bs)

For airborne noise transfer, the FFT spectra of 4 microphone signals are shown in Fig. 12.

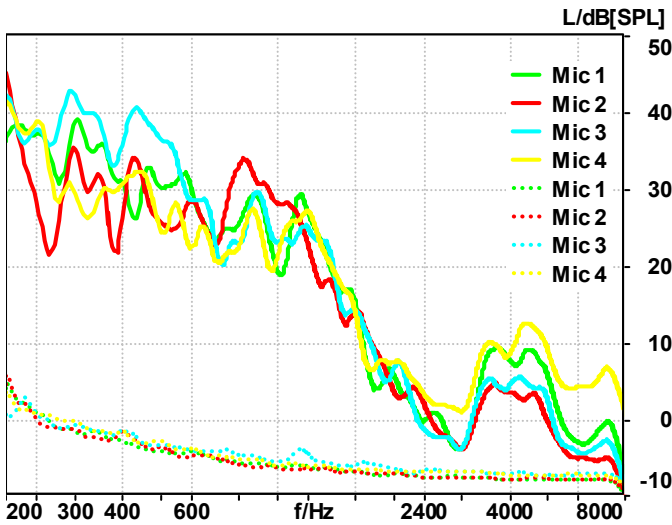
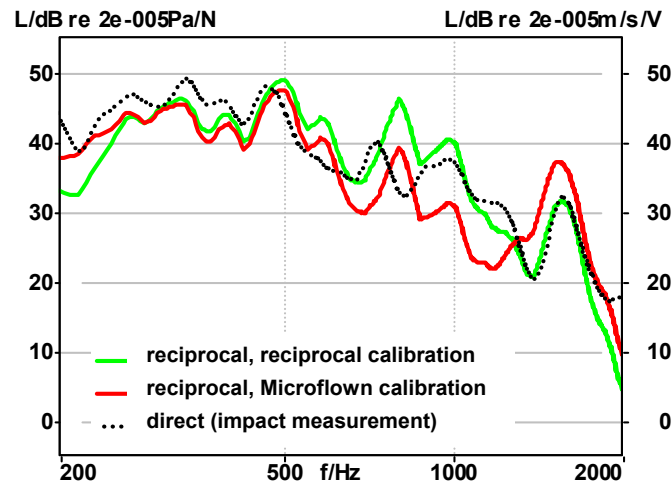


Fig. 12: FFT of 4 microphone signals around engine, due to binaural excitation (solid lines) and background noise (dotted lines)

The microphones were placed around the engine. In the operating frequency range of the binaural sound source (200 Hz – 6 kHz), the signal-to-noise ratio is sufficient.



An exception is the region around 3 kHz, where the prototype of the source lacks efficiency.

In the case of structure-borne sound, the reciprocal transfer functions can be directly compared to the conventional direct measurement. Fig 13 shows an example (body-side of an engine mount). The reciprocal curves are generated with Microflow and free field calibration. A very good agreement between direct and reciprocal results is found. A complete match is indeed not expected as both methods are subject to errors and reference positions are slightly different.

Currently, only reciprocal vibro-acoustical transfer functions are used for Binaural Transfer Path Synthesis. For airborne noise, transfer functions are usually measured with reference microphones at excitation positions (pressure reference) [13]. Therefore, reciprocal measurements, based on volume velocity reference, could not be compared directly with conventional measurements. It should be pointed out that advanced algorithms to describe the airborne sources using volume velocity are under development, and in this case, transfer functions can often only be measured reciprocally. This is evident because in the direct case, it is not possible to excite vibrations on individual sub-areas.

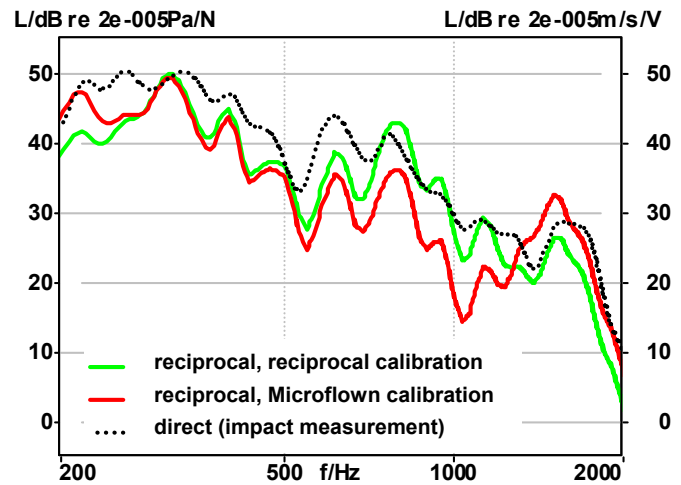


Fig. 13: Vibro-acoustic transfer functions (engine mount to driver’s ear), direct measurement and reciprocal measurement based on two calibration methods. Left: left channel, right: right channel

CONCLUSION

A binaural sound source is presented as a useful tool for NVH applications, particularly for Binaural Transfer Path Analysis and Synthesis (BTPA/BTPS). It can be used for measuring transfer functions from structure-borne excitations (or vibrating surfaces) to the ear of the driver in the reciprocal direction. This provides some essential advantages compared with the direct measurement, such as a reduced amount of measurement time and a higher precision. In some cases, it is even the only

option, e.g. if an extended vibrating surface must be divided into sub-areas which cannot be excited to independent vibration.

In order to introduce the binaural sound source, the principle of reciprocity was briefly described, and several calibration methods were documented. The directivity of the source was verified in comparison with an artificial-head receiver. Furthermore, the validity of reciprocity was tested including this source by measuring vibro-acoustic transfer functions in both directions, using both simple structures and a real vehicle.

In the field of BTPA/BTPS, significant research has already been done, and the binaural sound source can be considered an important tool for measurement. One of the final goals of the entire work will be the possibility to perform troubleshooting or simultaneous engineering by combining test-site measurements and individual transfer functions. This means that NVH problems can be identified by listening to single noise path contributions separately. However, applications of the binaural sound source are not restricted a priori to vehicle acoustics; as reciprocal transfer function measurements may also be useful in other disciplines (room acoustics, virtual reality).

REFERENCES

1. Helmholtz, H.: Theorie des Luftschalls in Röhren mit offenen Enden. *Crelle J.* 57 (1860), 1
2. Rayleigh, J. W.: Some general theorems relating to vibrations. *Proc. Lond. Math. Soc.* 4 (1873), 357
3. Lyamshev, L. M.: A question in connection with the principle of reciprocity in acoustics. *Soviet Physics Doklady* 4 (1959), 406
4. Ten Wolde, T.: On the validity and application of reciprocity in acoustical, mechano-acoustical and other dynamical systems. *Acustica* 28 (1973), 23
5. Fahy, F. J.: The vibro-acoustic reciprocity principle and applications to noise control. *Acustica* 81 (1995), 544
6. Pankoke, J.: Mechanism of structure-borne interior noise using acoustic reciprocity. MSc Dissertation, ISVR, University of Southampton (1994)
7. Plunt, J., Rigner, L. & Gabrielsson, L.: Noise/force sensitivity mapping for vehicle interior acoustics, using reciprocity techniques. *Proc. Inter-noise* (1995), 1101
8. Kim, G. J., Holland, K. R. & Lalor, N.: Identification of the airborne component of tyre-induced vehicle interior noise. *Applied Acoustics* 51 (1997), 141
9. Zheng, J., Fahy, F. J. & Anderton, D.: Application of a vibro-acoustic reciprocity technique to the prediction of sound radiated by a motored IC engine. *Applied Acoustics* 42 (1994), 333
10. de Bree, H.-E.: An overview of Microflown technologies. *Acustica – acta acustica* 88 Nr. 3 (2002)
11. Genuit, K. & Poggenburg, J.: The design of vehicle interior noise using binaural transfer path analysis. *SAE'99* (1999)
12. Genuit, K., Bohineust, X. & Rehfeld, M.: Binaural "hybrid" model for simulation of noise shares in the interior of vehicles. *Inter-Noise'97* (1997)
13. Genuit, K. & Bray, W. R.: Prediction of sound and vibration in a Virtual Automobile. *Sound & Vibration*, July 2002
14. Müller, S. & Massarani, P.: Transfer-function measurements with sweeps. *Journal of the AES* 49 Nr.6 (2001), 443
15. Olson, H. F.: *Acoustical Engineering*. Van Nostrand, New York (1957)