Acústica 2008
20 - 22 de Outubro , Coimbra, Portugal
Universidade de Coimbra

TRANSFER PATH ANALYSIS AND SYNTHESIS FOR AURALIZATION

Michael Vorländer, Pascal Dietrich

Institute of Technical Acoustics
RWTH Aachen University
Neustr. 50, 52056 Aachen, Germany
mvo@akustik.rwth-aachen.de

Abstract
A key component of auralization in product sound design is the subdivision of the problem into the emission from primary sources and sound & vibration transmission and radiation. This contribution focuses on general aspects of the source and transfer path coupling and the consequences for simulation and auralization models. Experimental and theoretical approaches are discussed which allow the impedance match of sources and transmission systems studied and used for auralization models. The problem is discussed on examples from building acoustics and product sound design.

Keywords: Simulation, Auralization, Transfer path analysis.

1 Introduction

Problems of noise control and sound design require a methodology to predict the sound character during the procedure of product design. In rapid prototyping of new products this methodology is mainly based on computer simulations. As concerns the acoustic component of product design and rapid prototyping, simulation and auralization of complex systems is necessary. A key component of auralization is the subdivision of the problem into the emission from primary sources and sound & vibration transmission and radiation (see also [1]).

The term transfer path analysis (TPA) is meant to be a general term for the characterization and determination of sound transmission from a source towards a receiver at a point in space. On the transfer paths, fluid-borne, structure-borne or air-borne sound transmission can occur in arbitrary order. The special case is the binaural transfer path analysis (BTPA) that also accounts for the fact, that sound is received by two ears at the listener. Therefore, it becomes possible to reproduce sounds in 3D and the listener can localize the sounds. Making the measured system or components audible is generally called auralization. By using the results from TPA with a measured source signal, e.g. compressor (a small vibrating motor), it becomes possible to auralize a product. The process of assembling the results from TPA measurements or simulations of transfer elements is called transfer path synthesis (TPS) or in case of binaural signals BTPS. In case simulations and measurements are used for the synthesis it is often called hybrid model. The main advantage of this procedure is the possibility to analyze the contribution of each source and all transfer paths onto the overall sound or noise separately. Fig. 1 shows a simplified model of an airborne and a structure-borne transmission.

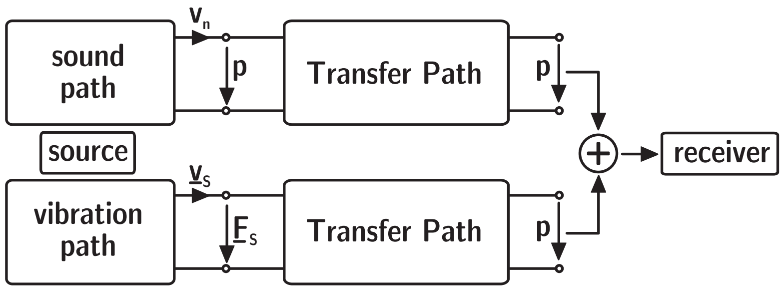

Figure 1 – Simplified block diagram of transfer path synthesis (after [1])

The resulting signal that contains the source signal and the sound transmission by the transfer paths is obtained by convolution of the input signal $s(t)$; $s(\omega)$ and the impulse responses or transfer functions $TP_i(t)$ and $TP_i(\omega)$,

$$\begin{aligned} g(t) &= s(t) * TP_i(t) \\ G(\omega) &= S(\omega) \cdot TP_i(\omega) \end{aligned} \tag{1}$$

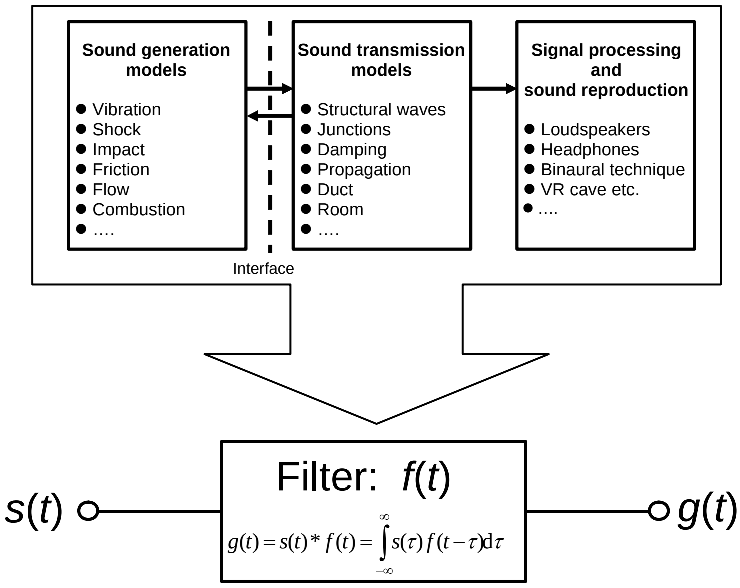

Figure 2 – Projection of the vibroacoustic signal path into a signal processing model ([1]).

The transfer function can also be defined binaurally. Hence, the obtained signals correspond to the sound pressure at the listener's ears. Every source signal can be transferred in a correct binaural signal by using the direction of sound incidence and the head-related transfer function. This is necessary if the binaural air-borne transfer function from the vibrating structure to the listener has not been measured. For this purpose, databases containing the HRTF for various directions can be used. The exact geometry of the system has to be considered. In automotive industry the aspect of binaural measurements has gained high acceptance and therefore most measurement methods available are designed for the automotive sector. In fact the human perception is part of the measurement, which makes the obtained signals suitable for listening tests. In order to consequently apply TPA and TPS, the product has to be strictly divided into sources and transfer paths (TP).

Auralization is then obtained by mapping the vibroacoustic problem of generation at the source and transmission into a signal processing (filter) approach, like illustrated in Fig. 2.

2 Theoretical background

In case of exclusive airborne sound transmission the coupling between the source and the transfer paths and the transfer paths among each others can be neglected. When considering structure-borne sound transmission the coupling can only be neglected in some special cases as explained in 2.1 in more detail. But most transfer path measurements practiced implicitly assume these cases. Furthermore, the fact that structure-borne sound sources in general have six degrees of freedom is neglected. Most measurements only account for the translation component in normal direction towards the structure. The other components can also have a significant contribution as already shown by Petersson and Gibbs [2]. The general case for a one point contact source coupled to a structure is depicted in Fig. 3.

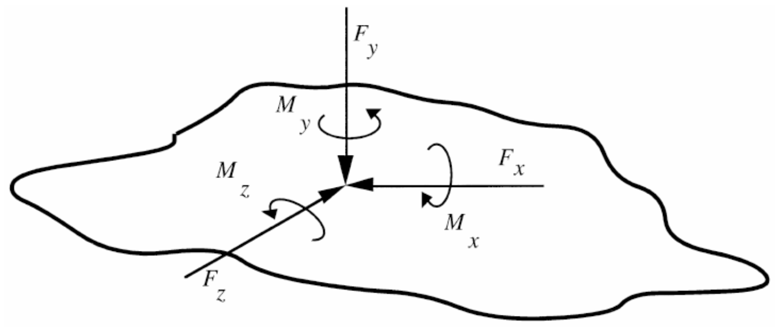

Figure 3 – Point contact of a source with complex description of the force transmission, three orthogonal forces and three moments (after [2]).

The correct application therefore accounts for full description and measurement of the source. In a next step, by applying reasonable assumptions, the model can be reduced by neglecting minor contributions.

Furthermore, the acoustic impedances of the source and receiver have to be measured. Mostly the situation is also reduced to a single point contact. But there are various applications where a multi-point contact or a contact over an area is more realistic. The interaction between the contact points and the reaction on the source can also be investigated in more detail. In addition, the transfer paths and impedances have to be considered for the six degrees of freedom separately. Only if the transmission is fully described reasonable assumptions can be applied. On the excitation side, called (sound generation models), different types of excitation are distinguished. Depending on the excitation the modeling is chosen for the path. By considering further knowledge and data, simplifications can directly be applied. In the middle part (sound transmission models) the transmission is modeled. The excitation and the transfer path can be measured or simulated. For reproduction there are already techniques available, such as headphones, binaural loudspeaker technique or other surround sound systems [1].

2.1 Sources

In order to characterize a sound source and its mounting for auralization correctly a set of parameters describing the source situation has to be generated, which describes the source in a sufficient manner. This set of parameters can then be measured for each source. In the simplest case of a small contact situation and a transfer path with a huge input impedance compared to the impedance of the source, the source can be described by only one parameter, its force F. In a next approach the model could be extended by adding the impedances and next by extending to three orthogonal forces. In general, for each contact point of a source, six complex powers and six corresponding impedances have to be determined if cross-coupling between these components is neglected. It is mostly reasonably assumed for the orthogonal components to not distract each other in any way. Once this cross coupling shows significant contributions an Impedance matrix containing 36 elements has to be measured, each for the source and the receiving structure.

The approach of directly applying fully determined impedance or admittance matrices for all degrees of freedom in a multi-point contact situation leads to numerical and algorithmic problems. Therefore Petersson und Gibbs [2] try to avoid this be introducing an effective admittance Y,

$$Y_{ii}^{nn\Sigma} = Y_{ii}^{nn} + \sum_{j=1,\, j\neq i}^{6} Y_{ii}^{nn} \frac{F_j^k}{F_i^n} + \sum_{k=1, k\neq n}^{N} Y_{ii}^{nk} \frac{F_i^k}{F_i^n} + \sum_{k=1, k\neq n}^{N} \sum_{j=1,\, j\neq i}^{6} Y_{ij}^{nk} \frac{F_j^k}{F_i^n} \qquad (2)$$

The first term expresses the ordinary one point admittance, the second term the coupling of various components in one point (point cross coupling) and the last term the coupling of the point among each others (transfer cross coupling). Petersson und Gibbs [2] emphasize that only one fourth is related to translation and three fourths are related to rotation which is completely underestimated in praxis. Fig. 4 illustrates the equation and the raising measurement effort if cross-coupling cannot be neglected.

There are also cases where the introduced structure-borne and airborne modeling is not covering all effects. Pulsation of fluids in tubes can generate remote-controlled structure-borne sound [3].

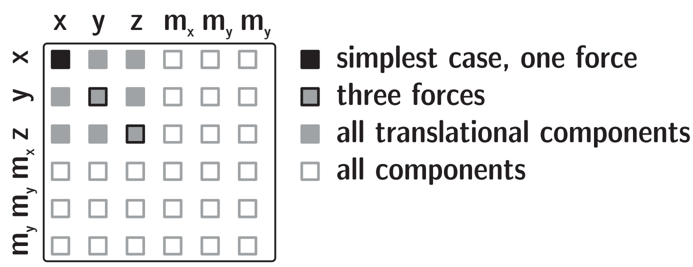

Figure 4 – Impedance or mobility matrix representation showing the six degrees of freedom and the interaction between them.

2.2 Transfer paths

The characterization of transfer paths is in parts analog to the characterization of sources. For example, LMS has put up a basic tutorial on the measurement procedure [4, 5]. Fig. 5 describes the interaction between the already introduced two-ports and also shows the role of the transfer paths in more detail compared to Fig. 1. The given block diagram depicts the auralization of a noise source with structure-borne and airborne paths. Besides the impedances for the structure-borne paths, transfer paths can be measured frequency-dependent.

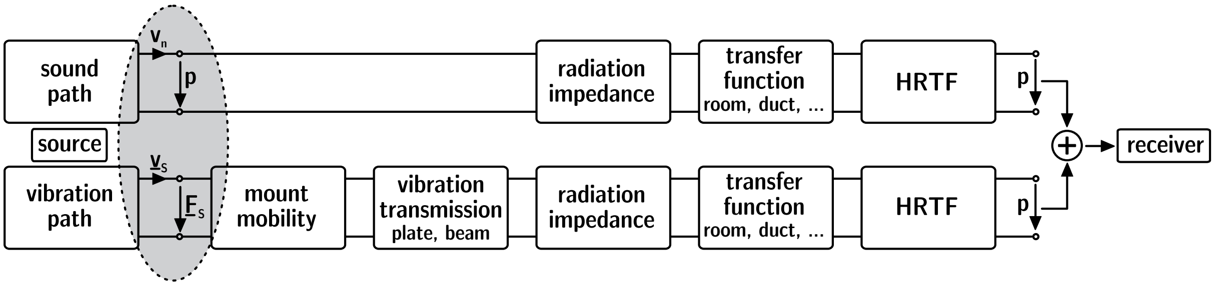

Figure 5 – Detailed block diagram of binaural transfer path synthesis (after [1])

When it comes to the description of transfer elements, two-ports are advantageous. In acoustics the behavior is analog to the behavior in electrical system theory. But instead of voltage V and current I the acoustic measurement quantities velocity v or acceleration a and the force F are used. A two-port can either be fully defined by its impedance matrix or by its transfer matrix. Therefore, it contains all information on the input, output, and transfer impedances from input to output of the system and vice versa. In case of linear symmetric systems the matrix is also symmetric due to the reciprocity principle. In automotive industry, Sottek [6] already introduced a two-port concept for the binaural transfer path analysis in cars. The principle of acoustic modeling with a source, a transfer element and a terminating impedance is shown in Fig. 6. First the force of the source and the impedances have to be obtained. Step 1 requires determination of the load towards the source. In step 2 the actual velocity v_s at the source can be determined and the transmission towards the receiver can be calculated.

When using two-ports it can also be advantageous to group transfer elements, which is then called sub-structuring. Elements, which are always used in combination in the manufacturing process can be grouped reasonably and be handled as a subgroup or substructure. It can be understood as a flow process of sound energy between the two-ports [1].

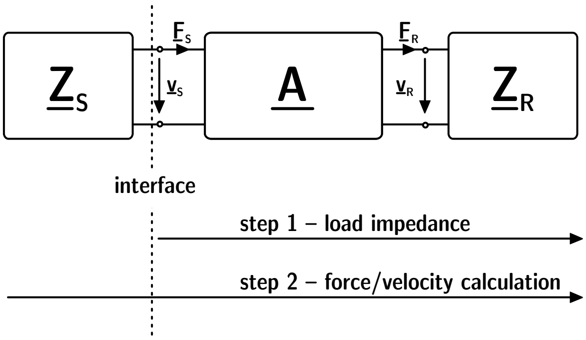

Figure 6 – Two-port as a central coupling element of TPA (after [1]).

The measurement standard for impedance measurements is ISO 7626 [7]. There are various definitions of acoustic impedances in literature so far. For structure-borne sound transmission the impedance used here is the quotient of measured force and velocity,

$$Z(\omega) = \frac{F(\omega)}{v(\omega)} = j\omega \frac{F(\omega)}{a(\omega)} \tag{3}$$

If only the acceleration can be measured the impedance can also be calculated as shown in the equation. The admittance is reciprocal to the impedance and therefore,

$$Y(\omega) = \frac{v(\omega)}{F(\omega)} = \frac{a(\omega)}{j\omega F(\omega)} \tag{4}$$

Various special measurement methods have been developed in the past to improve measurement quality or the comfort or in some cases these methods even made measurements at certain components possible for the first time. A special role is contributed to indirect measurement methods, which try to determine the force at the source in running conditions. This is of great advantage if the source cannot be measured without the structure or if a force transducer cannot be placed at the coupling position.

The complex stiffness method (CSM) [4] is such an indirect method. It assumes that the contact situation of the mounting is already known by its complex stiffness $K(\omega)$. By measuring the displacement at the source side x_s and at the transmitter side x_t, The frequency dependent force $f(\omega)$ of the source can be determined by

$$f(\omega) = K(\omega) \cdot \left(x_s(\omega) - x_t(\omega)\right) \tag{4}$$

The mounting situation has also been considered when the complex stiffness is measured, in the best case at the correct impedances.

Another indirect method is the matrix inversion method (*MIM*), which is very useful if the complex stiffness is very high. In this case the difference in displacement is probably very small and measurement uncertainty increases accordingly.

Firstly the method requires measurement of various transfer paths from the source to the receiver. Measurements have to be carried out for each receiving point i on the structure by measuring the acceleration $a_{i,j}$ and the corresponding force F_j at transfer path j. Therefore, the transfer path can be described by

$$TP_{i,j} = \frac{a_{i,j}}{F_j} \tag{5}$$

as illustrated in Fig. 7. In the second step the source is connected to the structure and the signal is measured at the same positions as the transfer path in the first step. Therefore, it is possible to obtain the force of the source at the contact by describing the system in matrix formulation

$$\begin{bmatrix} F_1 \\ \dots \\ F_n \end{bmatrix} = \begin{bmatrix} TP_{1,1} & .. & TP_{1,n} \\ : & & : \\ TP_{m,1} & .. & TP_{m,n} \end{bmatrix}^{-1} \cdot \begin{bmatrix} a_1 \\ : \\ a_m \end{bmatrix} \tag{6}$$

In the general case the matrix has to be fully measured, but there are also cases where assumptions can be reasonably applied, e.g., if coupling can be neglected. It can be seen, that the number of measurement positions m has to be equal or even greater than the number of forces n to be determined. If the system of equations is over-determined the evaluation becomes less sensitive to measurement uncertainties. This method also assumes that the mounting is very stiff and impedances can be neglected as expressed by Padilha und Arruda [8].

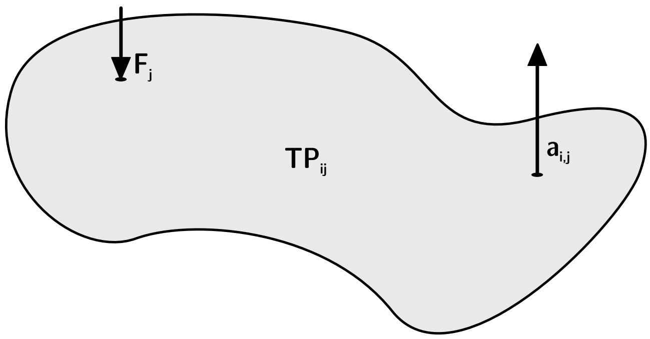

Figure 7 – Definition of the measurement quantities for the matrix inversion method.

The most widespread measurement method which is inherent in most complex measurements uses the principle of reciprocity, which is true for structure-borne and air-borne sound as well. In automotive industry an artificial head with loudspeakers mounted at the ear positions is used. This method is advantageous if an artificial source cannot be placed in a product or if it is required to measure transfer paths from different sources to a receiving position in one single step, using multiple channels. But to measure the impedances at the different coupling positions, additional measurements still have to be carried out.

3 Applications

3.1 Impact sources in buildings – The source problem

Auralization of airborne sound transmission in buildings has been thoroughly described in [9]. It was shown that by using information about the sound reduction index of all separate building elements and room acoustics in the receiving room, it is possible to accurately predict the hearing impression caused by the sound reduction. For the auralization of impact sound the matter is complicated because the interaction between the structure-borne vibration (a person walking, for example) and the floor is a crucial factor for the power transfer between the source and the receiver. The source cannot be treated as an ideal source with an infinite internal mobility acting independently of the coupled receiver mobility. Such interaction also exists while measuring impact sound insulation with the ISO standardized tapping machine on floors with a high mobility. By using a detailed description of the coupling between the tapping machine and a certain floor (with its known impact sound level), the coupling with a different source can be accounted for if the mobility of the floor is known from predictions or measurements. In the case of a substitution by a person walking it will enable the prediction of the sound pressure level in the receiving room. For this purpose the interaction between the floor and a person walking has to be investigated in more detail.

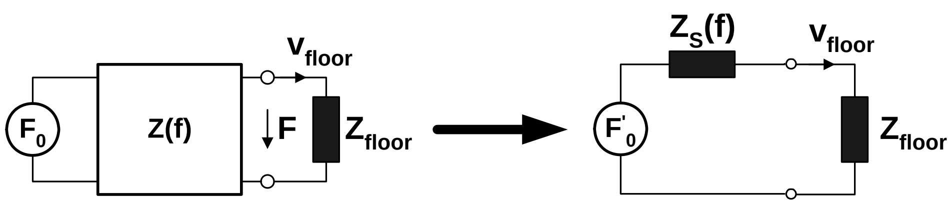

Figure 7 – Definition of a real vibration source with blocked force F_0 and inner impedance Z_s.

Following the concept of transfer path analysis, the problem is best illustrated by Fig. 7. The feedback can be expressed by using the impedance model. Since the measurements are carried out in a static condition, the results may differ from the actual impedance during walking. To account for this effect, a measurement method based on a two-port model can be used. This is explained in more detail in [10]. If the floor impedance is known, the actual force injected into the floor can be calculated.
Going into more detail (see also [10]), the foot and the whole human body is represented by its source mobility Y_S and the blocked force term F_{BS}. The floor is characterized in the form of a receiver mobility Y_R. The main argument for the use of a time-invariant model is the importance of the first 100 ms of the blocked force after high-pass filtering the blocked force at 10 Hz (c.f. [11]). Therefore if the acoustically relevant excitation dominates during the first 100 ms and the source mobility is assumed constant during this very short period of time as well, the system is reduced to a time invariant system. The transferred power for the mobility model is

$$P(\omega) = \frac{|F_{BS}|^2 |Y_s|^2 \Re(Y_R)}{2|Y_R + Y_s|^2} \tag{7}$$

This calculation is compared with the directly measured power,

$$P(\omega) = \frac{1}{2}\Re(F_R v_R^*) \tag{8}$$

and with the power transfer in the case of an ideal force source,

$$P(\omega) = \frac{|F_{BS}|^2}{2}\Re(Y_R) \tag{9}$$

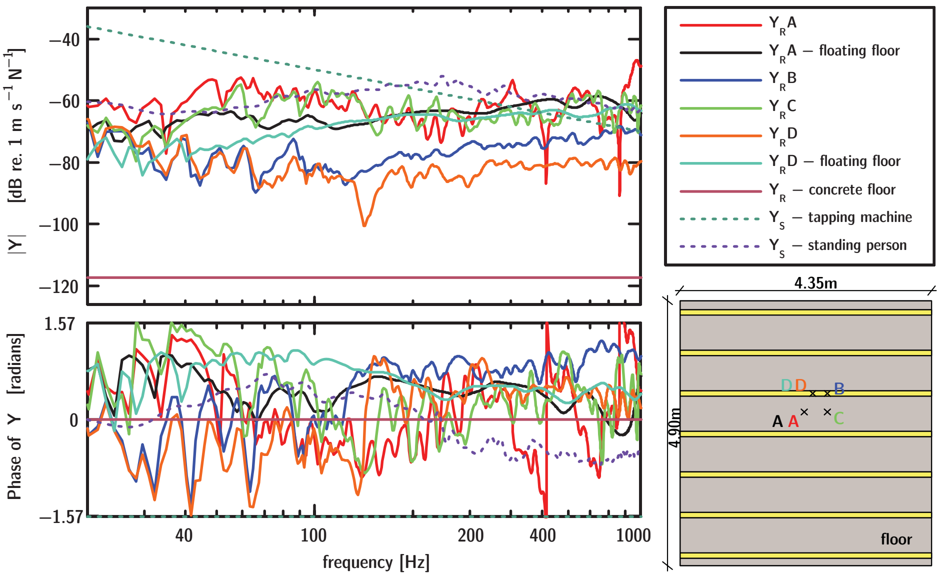

Figure 9 – Floor and source mobilities. Note the dependence on the source position on the timer joist floor (after [10])

For an ideal force source the very high source mobility is neglected compared to the receiver mobility and the transferred power becomes independent of the source mobility. This assumption can only be used for the characterisation of different floor constructions if all sources (e.g. tapping machine, person walking, ...) acting on a range of floors behave as ideal force sources. In the case of ”light” sources on ”heavy” floors this assumption is generally valid. For lightweight floors the tapping machine is an ideal force source only below 100 Hz as shown in Fig. 9. A person walking on a lightweight floor is not an ideal force source.

3.2 Household appliances – The transfer path problem

In the field of household appliances – considering larger machines, such as washing machines, dish-washers, refrigerators, or vacuum cleaners – a variety of sound sources can be found. Often the appliances consist of several smaller parts such as small pumps, fans, motors or compressors in an open or closed housing. Each source has to be considered separately, by neglecting interaction between them. In contrast to vehicle acoustics, the transfer path problem goes beyond 1 or 2 kHz as measurements of the radiated sound often show high contributions in the high frequency range.

When considering noise sources based on mechanical rotation, high tonality can be observed, which can be seen as distinct lines in frequency domain. In case the basic rotational frequency of the motor is fixed, inverse methods are no longer applicable, as no information on the transfer path can be given at the frequencies not excited by the source. Sources which allow a variation of the rotational frequency can be used to sweep through rotational frequencies and obtain valid measurement data for all frequencies of interest. In combination with the operation TPA approach [5,12] this could lead to a powerful tool to measure transfer paths in-situ and at positions where a substitution of the noise source by an artificial one is not applicable.

The airborne noise can become significantly high for the high frequency range in case the housing is open at some point, e.g. due to cooling reasons. Measuring these airborne contributions can mostly only be done reciprocally when the housing is too small to mount an omni-directional loudspeaker at the noise source position. Airborne noise sources are currently mostly considered as omni-directional sound sources, which is generally not applicable at least for higher frequencies. Building a characteristic loudspeaker representing the directional pattern of the noise source for a wide band of frequencies has shown to be very problematic and needs deeper investigation. Furthermore, correctly compensating the loudspeaker's response is not a trivial task. Nevertheless, first experiments have shown realistic audible results.

In case of compressors or small liquid pumps fluid-borne noise or pulsation is introduced as an additional noise path, which is mostly transmitted over a structure-borne coupling to the housing where it radiates to the room. Current research and measurements show that there is a possibility to measure these fluid-borne transfer paths under the assumption of linearity. The actual fluid-borne noise can be substituted by an artificial noise source using a special loudspeaker device. Flow noise cannot be measured using this idea, as there is no simple and linear relationship between the radiated signal and the initial flow introduced by the pump.

Vibration isolators are commonly used to mount the components in the housing, to minimize the structure-borne sound transmission. The high frequency range of interest makes it difficult to measure impedances and therefore the frequency-dependent four-pole matrix of the isolators. Up to a range of approximately 1 kHz the comparison between the TPS results and the measurement of the source with these isolators on well-known termination impedances shows good agreement.

In summary, the auralization approach for household appliances needs further research and improved measurements as the already low sound levels do not allow high measurement uncertainties of the input data. The radiation of the already highly engineered appliances can only be reduced by a few dB. Therefore the prediction by TPS requires high accuracy which is currently still problematic.

Conclusion

Auralization based on transfer path analysis is a powerful tool for vibroacoustic problems. Details, however, may reduce the reliability of the method drastically. Mostly the separation of sources, multi-dimensional force and moment interaction and the connection between source and structure can become very difficult. Experimentally some problems were solved, but a generalization and directly applicable toolbox is impossible, due to various practical constraints. In a number of examples, however, TPA and auralization were applied with success, at least in first-order approximation. For impact sound in lightweight constructions an intensive discussion can be observed, and first results are being transferred into measurement standards and rating schemes. For sound design of products TPA models are available, too, but often there is lack of knowledge about source mechanisms others than direct vibration sources. This applies to secondary excitation due to fluid-borne sources such as flow noise, fans or noise introduced by pumps. More research is therefore necessary, but the field of application is manifold.

References

[1] Vorländer, M. *Auralization*. Springer, Berlin, 2007.

[2] Petersson, B.A.T.; Gibbs, B.M. Towards a structure-borne sound source characterization. *Applied Acoustics*, 61 (3), 2000, p. 325.

[3] Trdak, K.; Badie-Cassagnet, A.; Pavic, G. Characterisation of small circulation pumps as sources of vibroacoustic energy. *Proc. Internoise 2000, Nice, France.*

[4] LMS, Transfer Path Analysis: The Qualification and Quantification of Vibro-Acoustic Transfer Paths, LMS International, Application Note, LMS, 1995.

[5] LMS, Next generation Transfer Path Analysis to pinpoint noise and vibration problem sources. LMS Engineering Services pioneers new TPA techniques to accelerate troubleshooting throughout the development process, LMS, 2007.

[6] Sottek, R. Description of the broadband structure-borne noise transmission from the powertrain using four-pole parameters. *Proc. Internoise 2006, Honolulu, Hawaii, US.*

[7] ISO 7262-1. Vibration and shock – Experimental determination of mechanical mobility. Part 1: basic definitions and transducers, 1986.

[8] Padilha, P.E.F.; Arruda, J.R. Comparison of estimation techniques for vibro-acoustic transfer path analysis. *Shock and Vibration* 13 (4), p. 459.

[9] Vorländer, M.; Thaden, R. Auralisation of Airborne Sound Insulation in Buildings. *Acustica united with Acta acustica* 86 (1), 2000, p. 70.

[10] Lievens, M. Force Measurements of a Person Walking on a Lightweight Floor. *Proc. DAGA08*, Dresden, 2008

[11] Lievens, M. Model of a person walking as a structure borne sound source. *Proc. ICA*, Madrid, 2007

[12] Yoshida, J.; Noumura, K. Transfer Path Analysis Method and Application Using Operational Data, JSAE, 2006