HEAD acoustics

APPLICATION NOTE

About this document

Content

This document is the first of five application notes on transfer path analysis (TPA). It describes the objective and the fields of application of TPA. It also illustrates possible applications of the completed TPA model. The last chapter includes a glossary with brief explanations of the most important technical terms used in the following application notes.

Target group

The following text is primarily intended for (potential) ArtemiS SUITE users who want to familiarize themselves with the basics of TPA.

Questions?

Do you have any questions? Your feedback is appreciated!
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For technical questions on our products: SVP-Support@head-acoustics.com

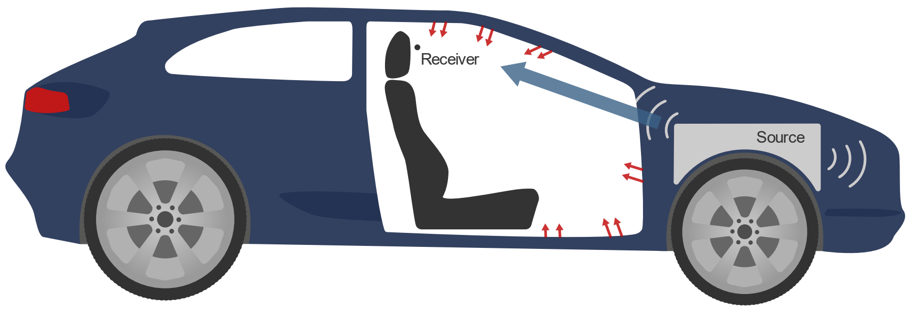
Transfer path analysis – objective, glossary

1. Objective of transfer path analysis

Where does a sound come from and what is it composed of?

Key question

This is the key question to be answered in transfer path analysis (TPA). For this purpose, TPA determines the transfer paths of airborne and structure-borne noise from a source to a receiver and thus finds, for example, the causes of disturbing noise / disturbing vibrations. TPA is primarily used to investigate complex structures where contributions from the noise sources and transfer paths involved are not obvious and easy to derive.



Airborne and structure-borne transfer paths in a vehicle

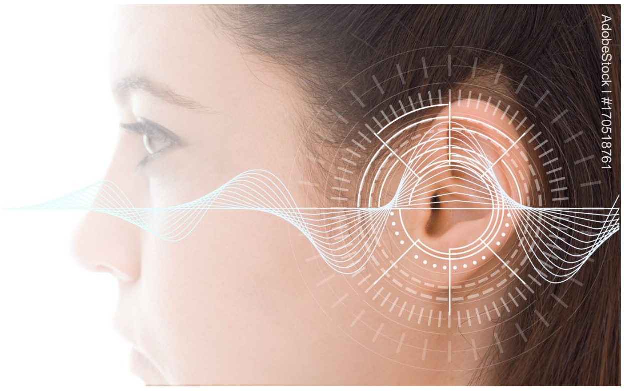
The following questions can be investigated in detail:

- Which path does the disturbing noise take to reach the receiver? Which path contributes most to the overall noise or to a specific (disturbing) noise pattern?
- Is it a connectivity problem, an excitation problem, or a sensitivity problem of the path?
- How do the transfer paths interact? What do the individual transfer paths contribute to the overall noise?

Once these questions have been resolved, system modifications can be found to improve the product noise quickly and efficiently.

Noise optimization for humans

With products from HEAD acoustics, TPA is performed in the time domain, which is why all TPA results can be auralized. This means that not only the overall signal, but also individual noise contributions and the various modifications for noise optimization can be listened to. This allows for an easier and intuitive evaluation of the sounds with your own ears rather than just from diagrams. Ultimately, all measures should be applied with the aim of optimizing the listening experience for end users and their ears.



Sound evaluation with one's own ears

2. Fields of application

TPA methods are very versatile and applicable in many areas in order to identify essential system properties and to gain a deep understanding of the system. From classical troubleshooting to target noise definition, TPA can be used in any step of product development to shorten development times and save costs.

Typical applications

Typical fields of application are as follows:

- Troubleshooting & Sound Design
  - Troubleshooting analysis
  - Identification of the causes of disturbing noise / disturbing vibrations
  - Noise optimization, estimation of potential for optimization

- Target noise definition
  - Targeted improvement of sound quality, no trial & error
  - Modification of excitation and transfer paths for sound noise optimization
  - Determination of thresholds for transmission and / or source excitation

- Virtual Reality / Virtual Prototyping
  - Numerical modifications of single paths or components based on CAE models
  - Hybrid modeling: combination of measured and simulated excitations / transmissions
  - Real-time modeling of driving noise in the NVH simulator

TPA methods

Different TPA methods have been developed for the different fields of application and objectives, e.g.:

- **Classical TPA:** Classical TPA investigates the noise transmission in existing products. The operational measurements are made with the source installed. For the determination of the transfer functions, the source is removed. The transfer functions exclusively describe the receiver system, with the determined source quantities only being valid for the entire system consisting of source and receiver.
- **In-situ TPA:** With in-situ TPA, both the operational measurements and the measurements of transfer functions are made with the source installed (in situ). Thus, the transfer functions describe the entire system consisting of source and receiver, with the determined source quantities representing only the source.
- **Binaural TPA (BTPA):** BTPA is a special form of TPA and can be regarded as an extension of both classical TPA and in-situ TPA. In contrast to these, it works in the time domain and with a binaural sensor as receiver. The synthesized results can be reproduced binaurally and thus allow a valid, perceptual evaluation on the part of the listener.
- **Operational TPA (OTPA):** With this TPA method, transfer functions are not measured but estimated from the quantities recorded during operation. This results in significant time savings but may also lead to a lower accuracy of the sound synthesis.

3. Using the completed TPA model

TPA model

TPA represents the object of study through the TPA model. The excitation of the source is modeled by excitation signals and the transfer paths with the help of transfer functions. Once the TPA model has been completed and validated, modifications to the excitation or the transfer paths can first be simulated in the TPA model, and the effects be made audible through auralization. This allows the effectiveness of the NVH measures to be checked and evaluated before they are actually implemented, which usually involves high costs. In addition, numerical and experimental data can be combined. In this way, components that previously only existed as CAE models can be made something to be experienced acoustically.

Possible applications of the TPA model

The completed TPA model can thus be used in the following ways, for example:

- Estimating optimization potential for modifications
- Deriving indications for specific physical optimizations of the test object
- Preventing rather than troubleshooting by applying TPA at an early stage of development: measuring on the test bench, listening in the (virtual) vehicle
- Numerical optimizing of individual components and auralization of changes
- Combining TPA results with the NVH driving simulator PreSense
- Linking TPA findings with the results of an operational deflection shape analysis or a modal analysis for a deeper understanding of the system

Experiencing sounds in a virtual vehicle

Some of these topics are described in a little more detail below.

Virtual Prototyping

Virtual Prototyping uses the TPA model to make predictions about acoustics based on test bench measurements or simulations. The aim of Virtual Prototyping is to reduce development time and costs. This is to be achieved by predicting the NVH characteristics of components on the sound quality of the overall product as early as possible, thus enabling early problem identification and optimization. A reliable prediction of the final sound quality helps to significantly reduce the number of cost-intensive real prototypes during the development process.

Virtual Prototyping for cost reduction

Numerical optimization

Usually, for numerical optimization of individual components, the transfer path and the component causing the noise problem are first identified with the help of the TPA model. Then the transfer behavior of this component (e.g., its enclosure properties) is numerically modified/optimized by one or more virtual modifications. These results can be inserted into the original TPA model using the delta to the original transfer behavior or by directly calculating the component excitation. After that, the previously identified transfer path is modified and the time signals of the overall noise are synthesized again. The recalculated time signals can then be further investigated, e.g., by jury tests with a representative group of participants or by evaluation based on a noise metric determined in advance and suitable for the noise phenomenon. This will provide information as to which modifications are target-oriented and are actually to be made.

NVH Simulator PreSense

The NVH simulator PreSense makes it possible to virtually experience the results of a TPA in a vehicle. In this way, acoustics engineers are not only in a position to interactively test the vehicle acoustics of an existing vehicle, but also to experience a specific component in a real context. For example, it is possible to factor in test bench measurements of a powertrain into a complete vehicle in order to perceptually evaluate the final product during a virtual test drive rather than just evaluating the acoustics of the powertrain on the test bench. In addition, this allows the effects of different powertrains on the acoustics to be compared directly, individual noise contributions to be analyzed, and, for example, target noises to be defined using interactive filters. Experiencing a sound interactively is much more revealing than looking at a diagram. This is particularly useful for decision-makers with no expert knowledge who are not familiar with numerical values and diagrams. Furthermore, as the sound of the product can already be evaluated before the final product is physically available, customer feedback can be obtained relatively early in the development phase.

NVH Simulator PreSense: experiencing the TPA of a vehicle virtually

Analyzing sound contributions - defining target sounds

Structural analysis

In addition, the TPA can be paralleled by an operational deflection shape analysis or a modal analysis in order to obtain a deeper understanding of the vibration characteristics of a test structure. In many cases, this does not even require new, time-consuming measurements. Instead, the operational measurements already acquired are simply loaded into an ArtemiS SUITE operating deflection shape project and individual phenomena at the frequencies of interest are analyzed.

Moreover, using the transfer functions, a modal analysis can be performed with the modal analysis project and the eigenmodes of the structure can be determined.

Further applications

Of course, TPA can be used for product optimization not only in the automotive sector. In principle, all products that can be divided into a source and a receiver structure can be analyzed using TPA methods. For example, the TPA method provides valuable information in order to improve the sound quality of household appliances, power tools, rail vehicles, etc.

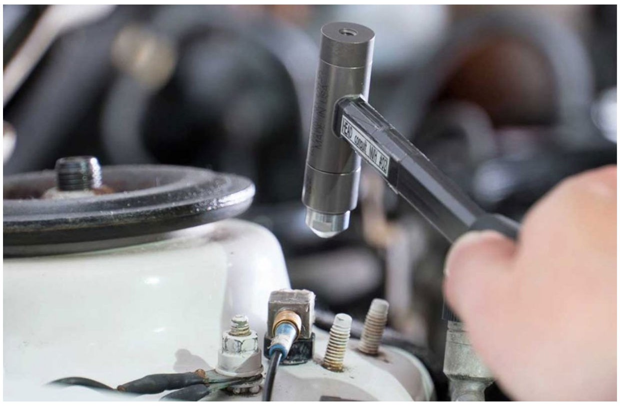
Even in the case of household appliances, TPA can be used to gain important insights into noise optimization.

4. Glossary

Airborne sound / structure-borne sound: Airborne sound is the sound that propagates through the air. A vibrating sound source surrounded by air excites neighboring air molecules, causing them to vibrate and, in turn, also excite neighboring air molecules. Structure-borne sound is a vibration process in solid objects. The sound is generated by mechanical excitation of an object and passes through it as structure-borne sound.
In transfer path analysis, the distinction between a structure-borne and an airborne transfer path always refers to the origin of the excitation. In a vehicle, for example, a force generated by the engine is applied into the car body as structure-borne noise via the engine mounts, causing vibrations along the structure. These vibrations propagate to the boundary surfaces of the vehicle cabin (e.g., windshield, roof, and floor). The surfaces excited by the vibrations emit some of the energy as airborne noise which eventually reaches the receiver (e.g., the driver's ear). Given the fact that the origin of this sound is an excitation of structure-borne noise, the associated transfer path is referred to as a structure-borne noise transfer path, although the corresponding sound contribution is perceived by the receiver as airborne noise.

Transfer function / Impulse response: The transfer function describes the relationship between an input signal applied into a linear, dynamic system and the output signal excited by it in the frequency domain. Both the transfer function and the impulse response of a system are related via the Fourier transformation.
Transfer function: Description of the system in the frequency domain
Impulse response: Description of the system in the time domain

Inertance / Apparent Mass: Inertance I is a structural system property and describes its compliance (in second derivative). It is described by the frequency-dependent transfer function of applied force (F_n) and resulting acceleration (a_m): $I_{m,n} = \frac{a_m}{F_n}$
To determine the inertance, a force is applied into the structure with an impact hammer or shaker while simultaneously measuring the acceleration at one or more positions using accelerometers.
The compliance of a complex system is described by an inertance transfer function matrix in which the inertances for N force application points and M accelerations are combined.



Determining the inertance by means of an impulse hammer

$$\boldsymbol{I} = \begin{bmatrix} I_{1,1} & \cdots & I_{1,N} \\ \vdots & \ddots & \vdots \\ I_{M,1} & \cdots & I_{M,N} \end{bmatrix}$$

The matrix of apparent masses (AM; second derivate of the rigidity) can be determined by inversion of the inertance matrix.

Acoustic Impedance / Acoustic Admittance: The acoustic impedance *AI* describes the resistance that opposes sound propagation. It results from the transfer function of the introduced volume velocity (Q_l) and the resulting sound pressure (p_k):

$$AI_{k,l} = \frac{p_k}{Q_l}$$

For a complex system, this results in the matrix of acoustic impedance, which combines transfer functions for *L* introduction points and *K* sound pressures:

$$\boldsymbol{AI} = \begin{bmatrix} AI_{1,1} & \cdots & AI_{1,L} \\ \vdots & \ddots & \vdots \\ AI_{K,1} & \cdots & AI_{K,L} \end{bmatrix}$$

The matrix of the acoustic admittance *AA* can be determined by inversion of the acoustic impedance matrix.

Matrix inversion: Matrix inversion inverts matrices. For a regular matrix *A*, the multiplication of this matrix with its inverse A^{-1} results in the unit matrix *E*: $\boldsymbol{A} \cdot \boldsymbol{A}^{-1} = \boldsymbol{E}$
There are different mathematical methods for the inversion of a matrix with *M* rows and *N* columns. A square matrix ($M = N$) can be inverted quite easily. If $M \neq N$, the matrix inversion cannot be done directly, since there is no exact solution. Instead, the inverse must be estimated, for example, via singular value decomposition (pseudo inverse).

Blocked forces / Interface forces: Blocked forces describe the source independently of the receiver structure and thus can be applied to other receiver structures. This means that blocked forces can be used to predict the noise generation of other structures. The transfer functions used to determine the blocked forces need to be measured with the source installed.
Interface forces describe the source as a function of the receiver structure. Interface forces are characteristic of the overall system, i.e., source and receiver structure and thus cannot be readily transferred to other receiver structures. To measure the required transfer functions, the source needs to be dismantled.
Blocked forces and interface forces are an intermediate result of TPA.

➞ *Proceed to the second application note on transfer path analysis providing information on modeling and basic descriptions of the required measurements and quantities.*