HEAD acoustics

APPLICATION NOTE

About this document

Content

This document is the second of five application notes on transfer path analysis (TPA). The first two chapters provide information on TPA modeling as well as on the advantages of a structure-independent source description using the so-called Blocked Forces. The last chapter provides basic information on the quantities measured and calculated in the TPA.

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 – basics, theory

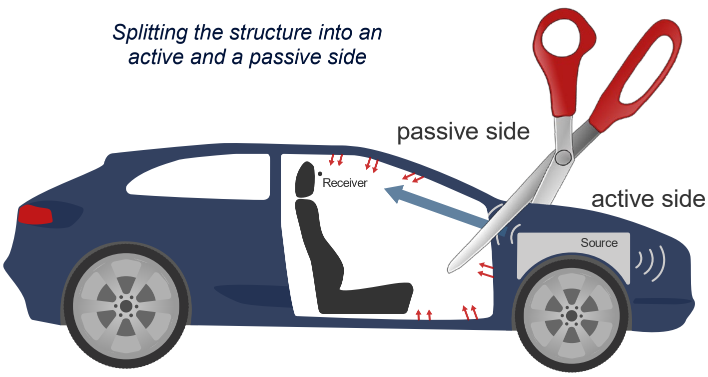
1. TPA model

Splitting into an active and a passive part

In a TPA, the starting point is an active component, i.e., the source connected to a passive structure, causing it to vibrate and emit airborne sound. The receiver characteristics determine the structure's response signals caused by this excitation. The system consisting of excitation, transfer paths, and receiver is modeled using the TPA model. The transfer paths are mathematically described by the transfer functions. Thus, the TPA model links the input quantities of the source with transfer functions to determine the noise contributions for each transfer path and to synthesize the signals.

For the modeling, the system under investigation needs to be split into an active and a passive side. The active side includes the source, while the passive side includes all receivers and also the transfer paths. The cutting plane is usually positioned at mechanical coupling points. Both the objective and the fundamental purpose of the TPA determine where exactly the split is to be made (close to the source or close to the

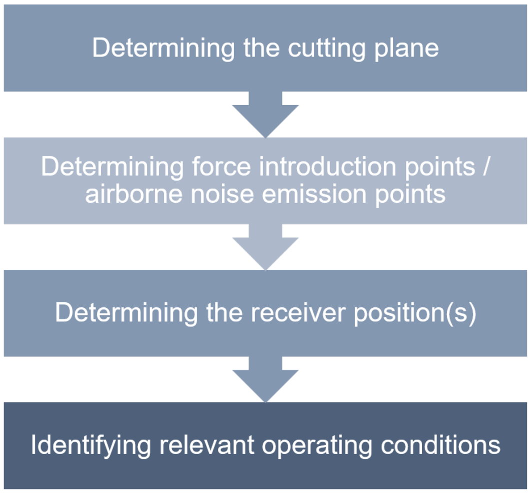
Splitting the structure into an active and a passive side



receiver). Take the example of noise in a vehicle cabin: If the noise is expected to be caused by excitation from the engine („engine is too loud"), the cutting plane should be close to the engine. However, if the noise is expected to be caused by the vehicle cabin responding too sensitively to the applied forces, or if problems occur due to cabin resonances, the cutting plane needs to be placed along the transition to the vehicle cabin. If no prior knowledge of the structure is available, simultaneous measurements can be performed on two cutting planes. However, in order to define a valid model, the two cutting planes must not be combined in a common system of equations.

Process of model definition

Once the cutting plane has been defined, it is necessary to determine all relevant force application points of the source into the passive structure or, for airborne noise, the critical airborne noise emission points of the source and their noise transmission paths. The next step is to determine the receiver position for which the noise composition is to be investigated.
In addition, it is necessary to identify the relevant operating conditions for which the input signals are to be measured and the TPA is to be performed.



2. Structure-independent source description

Independent source description

A structure-independent description of source properties has several advantages. For example:

- Sources can be easily exchanged for synthesis (e.g., different drive variants measured on the test bench)
- Simulation results can be integrated into the noise synthesis (e.g., virtual source signals calculated from simulation)

Virtual integration of a drive into different vehicles

However, there are certain limits to the transfer to other structures, i.e., deviations between the calculated sound and the actual sound are quite possible. For example, when measuring an engine or powertrain on the test bench, no chassis is connected and thus no tire-road contact is present. This leads to a lack of interaction between powertrain and chassis during both the recording and the noise syntheses based on it.
Nevertheless, meaningful noise predictions can be made by using appropriate methods with structure-independent source descriptions.

Structure-independent description of structure-borne sound excitation

Blocked Forces

As described in the previous chapter, the cutting plane divides the system into an active and a passive side. The forces calculated in the TPA describe the force application at this cutting plane. The Blocked Forces TPA focuses on determining structure-independent forces on the receiver side. With the description of the excitation being independent of structure, the calculated forces can be transferred to other receiver structures. For calculating the sound at the receiver position, both the forces and the receiver transfer function are required. The latter may originate from any arbitrary system (e.g., from a competitive vehicle, a predecessor model or a virtual vehicle).

Structure-independent description of airborne sound excitation

Volume velocities

Sound pressure in the near field of a source depends very much on the room properties (e.g., room volume, reflection and absorption properties). For this reason, sound pressure is not suitable for structure-independent source description. However, the principle of structure-independent source description via the forces for structure-borne noise-induced sound contributions is also applicable to airborne transfer paths. In simple terms, this means that the forces are equated with volume velocities, while the resulting accelerations are equated with the sound pressure in the near field. Using transfer functions, sound pressure measured in the near field can be converted into a volume velocity that is independent of the surrounding room (acoustic admittance). Since, unlike sound pressure, volume velocities are independent of the room, they are suitable for describing the airborne noise emission of a source.

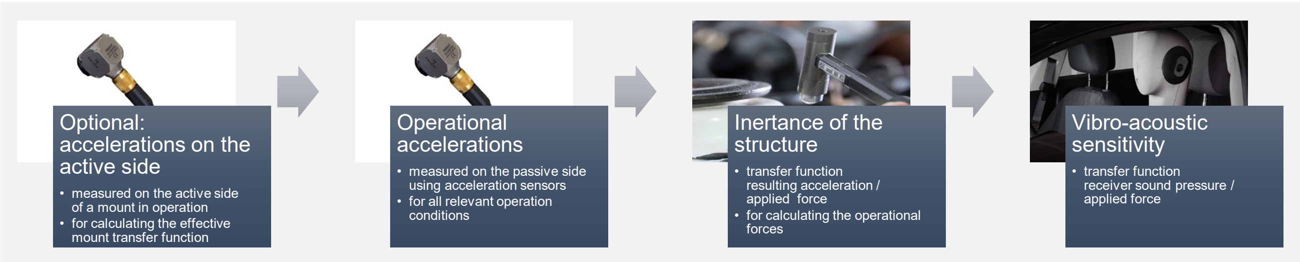
3. Measured and calculated quantities for TPA

The formulæ in this chapter illustrate the interrelationships in a simplified way. For example, when working in the time domain, the impulse responses of the transfer functions need to be determined first. Afterwards, the time-domain signals of the input variables will be convolved with these impulse responses. In order to increase the legibility of the formulæ and to represent the interrelationships as comprehensibly as possible, no special reference is made to this effect in the following formulæ.

Structure-borne sound-induced sound contributions

Overview

By supporting itself against the structure, the source applies forces to the structure at the cutting plane. This force application causes the structure to vibrate. The following information on the structure is required to calculate the structure-borne noise-induced sound contributions:



Direct measurement of the forces

Direct measurement of the forces applied to the passive structure by the source during operation can be achieved by installing force sensors at the cutting plane. On the one hand, this way of measuring forces is very accurate, but, on the other hand, it is a very complex method which has a considerable impact on the structure to be measured. In other words, the measurements do not reflect the forces and transfer functions of the original system, but rather those of the modified one. This limits the informative value for the original system.

Indirect measurement of the forces

Thus, since the forces applied by the source (operational forces F_n^{op}) are often not directly measurable in practice, the indirect force measurement method is used instead. This method is much less complex and minimizes the impact on the system. The operational forces are indirectly determined using the mathematical method of matrix inversion through accelerations on the passive side (measured during operation $a_m^{ps,op}$) and the inverted inertance matrix $\boldsymbol{I}$:

$$F_n^{op} = \boldsymbol{I}^{-1} \cdot a_m^{ps,op}$$

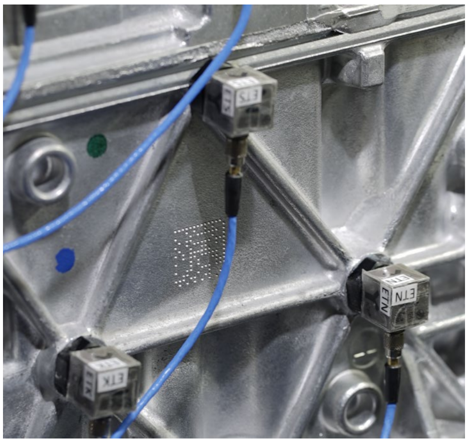
Inertance matrix

The inertance matrix $\boldsymbol{I}$ describes the compliance (in second derivative) of the structure. This matrix is spanned by the system excitation during force application at the coupling points of the cutting plane as well as by the system responses, by measuring the accelerations on the passive side of the structure. An element of this matrix represents the transfer function between the acceleration a_m at point *m* and a force F_n applied at point *n*:

$$I_{m,n} = \frac{a_m}{F_n}$$

Operational accelerations and transfer functions

To measure the accelerations, accelerometers are mounted on the passive side near the force application points. These points are used to measure the accelerations during operation ($a_m^{ps,op}$) in the relevant operating conditions. In addition, these points are used to measure the transfer functions for the inertance matrix. For these measurements, the force applied by an impact hammer or shaker is synchronously recorded with the accelerations.



Accelerometers on a test structure

Vibro-acoustic sensitivity

These measurements also allow the vibro-acoustic sensitivity of the force application point to be measured at the same time (Receiver Transfer Function, RTF). This is the transfer function of the force F_n applied by the impact hammer or shaker to the sound pressure at the receiver position $p_j^{receiver}$:

$$RTF_{j,n} = \frac{p_j^{receiver}}{F_n}$$

Effective mount transfer function

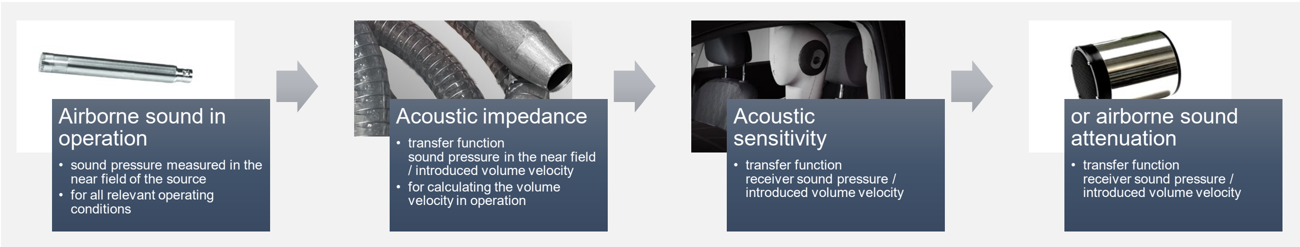
If the TPA is performed on a mounted source (e.g., rubber mounts with significant isolation), the transfer path also includes the effective mount transfer function (EMTF). TPA actually assumes linear, time-invariant systems. However, non-linear elements such as rubber mounts can still be considered by describing the mounting behavior at a linear operational point. As a result, the effective mount transfer function cannot typically be determined by a static impact hammer measurement, since, among other things, the mounting bias loading is not given in the non-operating state. Instead, the necessary operational measurements are performed in a test condition for which the mount transfer function can be assumed to be constant (linear). In order to perform these operational measurements, additional triaxial acceleration sensors are applied on the active side, i.e., on the active side of the engine mounts, and the accelerations are measured during operation for all relevant operating states ($a_m^{as,op}$). In comparison to the accelerations measured on the passive side of the mount, the accelerations measured on the active side of the mount have the advantage that they are less affected by sources of interference (such as excitation due to the rolling of the tires). For this reason, force syntheses based on accelerations measured on the active side of the mount only contain components that correlate with the associated vibrations of the source on the active side. The effective mount transfer function results from the transfer functions from active-side accelerations $a_m^{as,op}$ in operation and the passive-side operational forces F_n^{op}:

$$EMTF_{m,n} = \frac{F_n^{op}}{a_m^{as,op}}$$

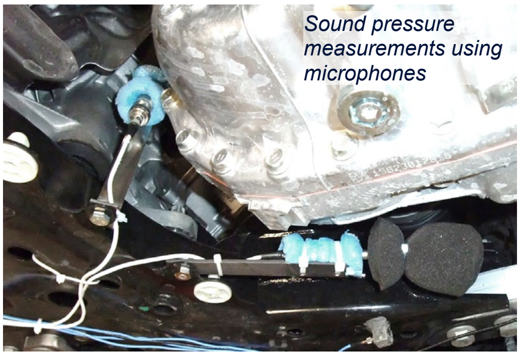
Airborne sound-induced sound contributions

Overview

In addition to the structure-borne sound input, the airborne sound caused by vibrations and emitted at the interfaces of the source can be taken into account. The following information is required for calculating the airborne sound-induced sound contributions:



The sound pressure in the near field of a source depends very much on the room properties (e.g., room volume, reflection and absorption properties). Using acoustic impedance, sound pressure measured in the near field can be converted into a volume velocity that is independent of the surrounding room. Since, unlike sound pressure, volume velocities are independent of the room, they are suitable for describing the airborne sound emission of a source.



Airborne sound emission in operation

In order to measure the sound pressures (p_k^{op}) emitted by the source during operation, several microphones are placed in the near field of the emitting surfaces (at least one microphone on each side of the source).

Acoustic impedance

A volume velocity source is usually used to measure the acoustic impedance. The volume velocity source is placed at the critical airborne sound emission points around the source. In addition to the introduced volume velocities, the sound pressures are determined with the near-field microphones. The ratio of the introduced volume velocity Q_l to the sound pressure in the near field (p_k^{near}) represents the acoustic impedance matrix $\boldsymbol{AI}$:

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

The volume velocity in operation Q_l^{op} can be determined by matrix inversion of the impedance matrix (acoustic admittance) and the sound pressures recorded in operation:

$$Q_l^{op} = \boldsymbol{AI}^{-1} \cdot p_k^{op}$$

Acoustic sensitivity

While measuring the acoustic impedance, the acoustic sensitivity or Receiver Transfer Function RTF for the airborne sound can be determined as well. The latter results from the ratio between the introduced volume velocity Q_l and the sound pressure at the receiver's ear $p_j^{receiver}$:

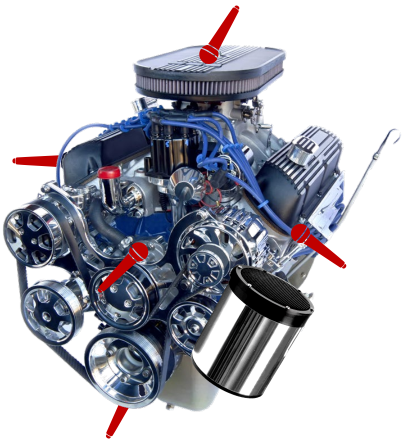
$$RTF_{j,l} = \frac{p_j^{receiver}}{Q_l}$$

Airborne sound attenuation method

No independent source description is required, if the only objective of TPA is to learn more about the transmission paths and the origin of the sound at the receiver position. In this case, the airborne sound attenuation method can be used to determine the airborne sound-induced sound components. This method can provide results quickly and requires relatively little measurement equipment[1]. However, since the source description is not structure-independent, the results of the TPA cannot simply be transferred to another structure or the source simply be exchanged. In addition to the measurements of the sound pressures in operation, the airborne sound attenuation method also requires airborne sound transfer functions.

Airborne sound transfer function

In order to determine these transfer functions, a loudspeaker is placed close to each near-field microphone and the sound pressure at the near-field microphone p_k^{near} as well as that at the receiver position $p_j^{receiver}$ are recorded simultaneously. The ratio of these two sound pressures gives the airborne sound transmission for the different positions. The determined transfer functions depend on both the location and the orientation of the measurement loudspeaker. One source of error of this method is that the emission characteristics of the loudspeaker and those of the source may differ. If the source is modeled with more than one near-field microphone, the individual contributions need to be adjusted by means of a coherence correction. For this purpose, a coherence correction filter is determined from the number of near-field microphones and the averaged coherence of the operating sound pressures and applied to the sound contribution.



Measuring airborne transfer paths

By summing the sound contributions determined with these quantities, the overall noise at the receiver position can then be synthesized.

TPA variants

The procedure described in this chapter depicts the fundamental process of a TPA. With different types of TPA developed, the actual measurements required may differ from those listed above. For example, with the Operational TPA method (OTPA), transfer functions are not measured separately, but are estimated exclusively from the quantities recorded during operation. This means a significant time saving, since with increasing complexity of the model, the measurement of the transfer functions can be very time-consuming. However, OTPA is not suitable for all fields of application and does not offer only advantages, as the accuracy of the predictions is sometimes lower.

In addition, the measurement conditions may differ depending on the TPA method selected. For example, the transfer functions in classical TPA are determined with the source removed, whereas the source can remain installed in in-situ TPA or Blocked-Forces TPA.

➜ Proceed *to the third application note on transfer path analysis providing a description of in-situ TPA and the TPA tools from HEAD acoustics.*

[1] No calibrated volume velocity source is required.