HEAD acoustics

APPLICATION NOTE

About this document

Content

This document is the third of five application notes on transfer path analysis (TPA). The first chapter describes the fundamental procedure of an in-situ TPA. The following chapters show some tools provided by HEAD acoustics to perform TPA in practice.

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 – in-situ TPA, tools

1. In-situ TPA with Matrix Inversion

Powertrain TPA

In this chapter, the principal procedure and measurements for in-situ TPA with Matrix Inversion are described in more detail using the example of a powertrain TPA. In a powertrain TPA, the engine and the transmission are considered as the source. The powertrain mounts and the vehicle body form the passive part of the structure. The receiver position is the driver's ear. For aurally-accurate playback, measurements are performed at the receiver position using an artificial head microphone, and the transmission paths to the left and the right ear are modeled (binaural TPA, BTPA).

Example of a receiver sensor:
Artificial head measurement system for performing BTPA

Crosstalk compensation

When performing the TPA on a vehicle body, it must be taken into account that, with the car body being a coupled system, a force applied at one location will result in measurable system responses throughout the body. In order to correctly estimate the applied forces and thus the noise contributions of the various paths, this crosstalk must be considered in the transfer function matrices. A transfer function matrix can be set up to compensate for crosstalk by determining the transfer functions to all relevant points. If crosstalk is not considered, it is only the transfer functions of the diagonals that must be determined. If only the crosstalk within an application point is considered for a structure-borne sound path, e.g., crosstalk of the x-direction to the y- and z-direction of the same point, the 3x3 blocks of the diagonals need to be considered. Considering the complete matrix is necessary if crosstalk between all points is to be taken into account.

$$\boldsymbol{I} = \begin{pmatrix} I_{1,1} & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & I_{2,2} & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & I_{3,3} & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & I_{4,4} & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & I_{5,5} & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{6,6} & \cdots & 0 \\ & & & & & & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & I_{M,N} \end{pmatrix}$$

$$\boldsymbol{I} = \begin{pmatrix} I_{1,1} & I_{1,2} & I_{1,3} & 0 & 0 & 0 & \cdots & 0 \\ I_{2,1} & I_{2,2} & I_{2,3} & 0 & 0 & 0 & \cdots & 0 \\ I_{3,1} & I_{3,2} & I_{3,3} & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & I_{4,4} & I_{4,5} & I_{4,6} & \cdots & 0 \\ 0 & 0 & 0 & I_{5,4} & I_{5,5} & I_{5,6} & \cdots & 0 \\ 0 & 0 & 0 & I_{6,4} & I_{6,5} & I_{6,6} & \cdots & 0 \\ & & & & & & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & I_{M,N} \end{pmatrix}$$

$$\boldsymbol{I} = \begin{pmatrix} I_{1,1} & I_{1,2} & I_{1,3} & I_{1,4} & I_{1,5} & I_{1,6} & \cdots & I_{1,N} \\ I_{2,1} & I_{2,2} & I_{2,3} & I_{2,4} & I_{2,5} & I_{2,6} & \cdots & I_{2,N} \\ I_{3,1} & I_{3,2} & I_{3,3} & I_{3,4} & I_{3,5} & I_{3,6} & \cdots & I_{3,N} \\ I_{4,1} & I_{4,2} & I_{4,3} & I_{4,4} & I_{4,5} & I_{4,6} & \cdots & I_{4,N} \\ I_{5,1} & I_{5,2} & I_{5,3} & I_{5,4} & I_{5,5} & I_{5,6} & \cdots & I_{5,N} \\ I_{6,1} & I_{6,2} & I_{6,3} & I_{6,4} & I_{6,5} & I_{6,6} & \cdots & I_{6,N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ I_{M,1} & I_{M,2} & I_{M,3} & I_{M,4} & I_{M,5} & I_{M,6} & \cdots & I_{M,N} \end{pmatrix}$$

Inertance matrices with and without crosstalk compensation

Overdetermined matrix

However, considering crosstalk in matrix inversion can be problematic unless the system of equations is properly conditioned. Matrix conditioning can be improved by overdetermination. For an overdetermined matrix, more response positions are recorded than input positions. This means that with M acceleration sensors and N force application points, $M > N$. However, an overdetermined matrix showing more rows than columns can no longer be inverted directly. In this case, the pseudoinverse of the matrix is determined for the subsequent calculations. Singular value decomposition is a relatively simple tool for calculating the pseudoinverse and, at the same time, it is the most commonly used tool for TPA.

The formulæ on the following pages 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 are convolved with these impulse responses. In order to increase the clarity 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 paths

Measurements with the source installed

With in-situ TPA, all measurements are performed with the source installed. This has the advantage that the time-consuming removal of the source can be omitted. To determine the structure-borne sound-induced sound contributions of the vehicle, the following input variables and transfer functions are measured.

Operating accelerations on the active side

Triaxial accelerometers are applied on the motor side in front of all engine mounts where the source applies force. Accelerations are measured for all relevant test conditions.

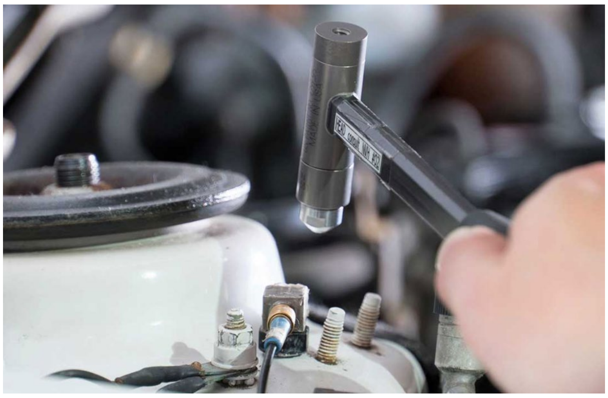
Operating accelerations on the passive side

Triaxial accelerometers are applied on the body side behind the engine mounts at all points where force is applied into the receiver structure. The accelerations are measured for all relevant test conditions.

Inertance of the structure

Determining the inertances

A defined force is applied to the structure at *N* positions on the body side using an impact hammer or shaker. At the same time, the system responses are measured using the accelerometers applied to the body side (at *M* positions). In order to determine correctly the compliance of the structure, force excitation should occur in close proximity of the actual force excitation, and the acceleration is to be measured not far from this point. The acquired transfer functions $\frac{a_m}{F_n}$ are summarized in the inertance matrix. This matrix considers crosstalk between the transfer paths through the elements outside the matrix diagonals. To increase the accuracy and numerical stability of the matrix, the matrix can be overdetermined, i.e., the number of accelerometers is higher than the number of force application points $M > N$.



Determining the inertance by means of impact hammer measurements

Vibro-acoustic receiver transfer function

Vibro-acoustic sensitivities

The vibro-acoustic sensitivities of the respective force application point can be measured in parallel to the inertance. For this purpose, the sound pressure at the receiver, i.e., at the driver’s ear, is measured in addition to the applied force and the resulting acceleration.

Calculation of the structure-borne sound-induced sound contributions

Structure-borne sound-induced sound contributions

Now, the structure-borne sound-induced sound contributions of the individual transfer paths can be calculated from the measurement data collected in this way. First, the inertance matrix is determined from the impact hammer / shaker measurements: $I_{m,n} = \frac{a_m}{F_n}$. Once the matrix inversion is completed, the accelerations on the passive side can be used to determine the operating forces.

$$F_n^{op} = \left[I_{m,n}\right]^{-1} \cdot a_m^{ps,op}$$

Effective mount transfer function

Excitation due to tire-road contact

However, these operating forces may contain disturbing noise components, as the accelerations measured downstream the mount include not only the excitation of the engine, but also disturbing noise components such as excitations due to the rolling of the tires. The acceleration signals of the source measured on the active side during operation $a_m^{as,op}$ as well as the effective mount transfer function $EMTF_{m,n}$ can be used to calculate optimized forces F_n^{EMTF} that were caused only from the excitation on the active side:

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

The accelerations on the active side are less impacted by noise sources, as they are measured on the active side of the mount and the impact of the noise sources is minimized by the isolating effect of the mount. The effective mount transfer function can be used to separate the coherent and incoherent components that excite the engine, with only the coherent components being taken into account. Thus, the adjusted forces describe the passive-side forces that are actually caused by the engine. They do not contain any sound components that do not correlate with the excitation of the engine.[1]

To calculate the structure-borne sound-induced sound contribution of a path, the optimized forces F_n^{EMTF} still need to be filtered by making use of the vibro-acoustic receiver transfer function $RTF_{j,n}$:

$$p_n = F_n^{EMTF} \cdot RTF_{j,n}$$

[1] The effective mount transfer function describes the mount in its fitted position, i.e., the motor does not have to be removed for determination. However, while this ensures a significant time saving, it may also be a disadvantage, since no conclusion can be drawn about the mount transfer if the source is installed in a different receiver structure with a different mount. In this case, the mount parameters for simple mounts can be estimated using quadripoles and the Kelvin-Voigt model.

Airborne paths

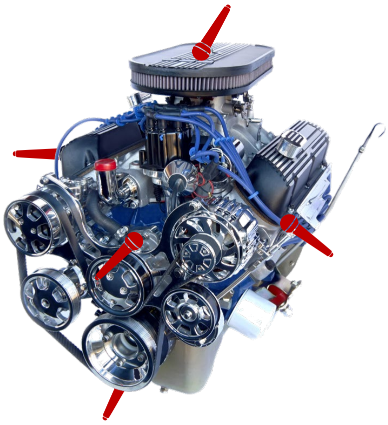
Determining the airborne-induced sound contributions

During operation, the surfaces of a sound source vibrate and thus excite the surrounding air to oscillate, i.e., the source emits airborne noise. To determine the airborne sound-induced sound contributions of the vehicle, the following input variables and transfer functions are measured.

Airborne sound emission during operation

Sound pressure measurements in the near field

Microphones in the near field of the emitting surfaces are used to record the sound pressure while the source is in operation. (At least one microphone is positioned on each side of the source, while larger and more complex surfaces usually require multiple microphones.)



Sound pressure measurement in the near field of the source

Acoustic impedance

Measuring by using a volume velocity source

A calibrated volume velocity source is placed at the critical airborne noise emission points, and the sound pressure is recorded at the near-field microphones and at the receiver position. The critical emission points can be identified beforehand, e.g., with an acoustic camera or a particle velocity probe during the operation of the source. The ratio of the introduced volume velocity to the sound pressure in the near field represents the acoustic impedance matrix. This matrix considers the crosstalk between the transfer paths through the elements outside the matrix diagonals. Crosstalk is typically stronger in the low frequency domain than in the high frequency domain.

Acoustic receiver transfer function

Acoustic sensitivity

The acoustic sensitivity or receiver transfer function can be determined synchronously with the determination of the acoustic impedance. For this purpose, the sound pressure level at the driver's ear is measured in parallel with the introduced volume velocity.

Calculation of the airborne sound-induced sound contributions

Airborne sound-induced sound contributions

The airborne sound-induced sound contributions of the individual transfer paths are calculated from the collected measurement data. The first step is to calculate the acoustic impedance: $AI_{k,l} = \frac{p_k^{near}}{Q_l}$. After the matrix inversion, the sound pressures measured during operation can be used to determine the volume velocities in operation:

$$Q_l^{op} = \left[AI_{k,l}\right]^{-1} \cdot p_k^{op}$$

To calculate the airborne sound-induced sound contribution of a path, the volume velocities still need to be filtered using the vibro-acoustic receiver transfer function $RTF_{j,l}$:

$$p_l = Q_l^{op} \cdot RTF_{j,l}$$

Synthesis of the overall noise at the receiver position

Overall noise

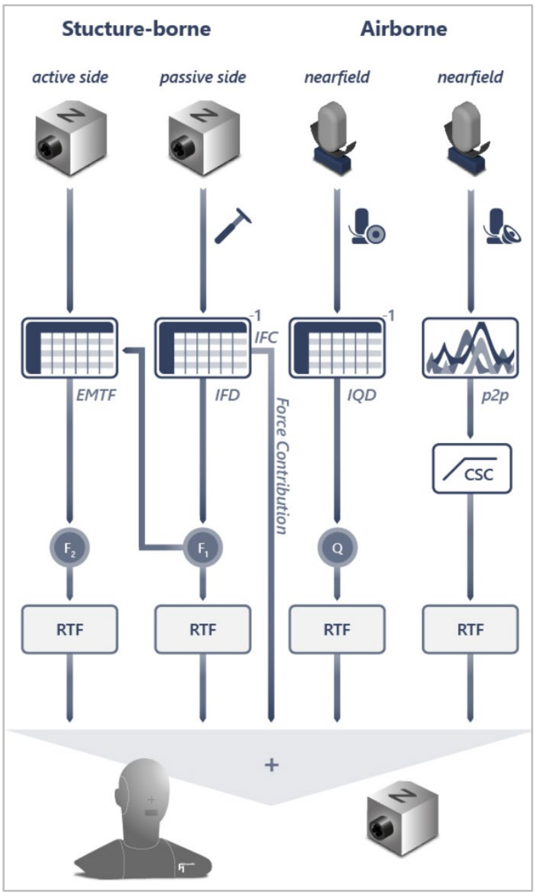
The sum of all noise components in the model (structure-borne noise and airborne noise induced) results in the overall noise.

2. The TPA Project in ArtemiS SUITE

TPA Project in ArtemiS SUITE

When performing a TPA, large amounts of data need to be acquired and organized. Input data and transfer functions need to be gathered correctly and combined, as otherwise the calculated noise syntheses may be subject to errors. In the TPA Project of ArtemiS SUITE, all information is clearly structured and users are guided step by step through the model creation, the measurements, the determination of forces and volume velocities as well as the sound syntheses.

Available methods



Overview of methods of the TPA Project (ArtemiS SUITE)

The TPA Project provides different methods for transfer path analysis. A schematic representation of these methods is given in the overview of methods of the TPA Project:

- Structure-borne sound:
  - Indirect Force Determination (**IFD**) including matrix inversion
  - Effective Mount Transfer Function (**EMTF**)
- Airborne sound:
  - Indirect Q-Source Determination (**IQD**) including matrix inversion
  - Airborne Attenuation (**p2p**)

The determination of the Effective Mount Transfer Function (EMTF) is not a standalone method, but complements the IFD method for indirect force determination when TPA is applied to mounted sources. The EMTF is used to describe the characteristics of the mounts and to correct the sound syntheses.

In addition, the TPA Project provides the use of the Indirect Force Contribution (IFC) methods. This method gives an insight into the composition of the calculated forces. The application is only used to gain a better understanding of the underlying system of equations and is not a stand-alone method. Examining the composition of the forces builds on the Indirect Force Determination method.

IFD method

Indirect Force Determination

In the TPA Project, the IFD method can be used to determine the operational forces by inversion of the inertance transfer function matrix. In order to perform the force synthesis, the TPA Project requires the measured inertances (transfer functions from resulting acceleration to applied force) of all relevant force application points as well as the measured operational accelerations measured on the passive side. Additional acceleration signals at dedicated positions on the structure are used to overdetermine the inertance matrix. This serves, for example, to reduce measurement noise and thus obtain more stable calculation results. The matrix takes into account the crosstalk between the transfer paths through the elements outside the matrix diagonals.

EMTF method

Effective Mount Transfer Function

If the TPA is performed at a mounted source, the mount transfer can be considered in the TPA model. To this end, the EMTF method is used in the TPA Project as a supplement to the IFD method. In addition to the quantities measured for the IFD methods, the EMTF method also requires the operational accelerations measured on the active side.

IQD method

Indirect Q-Source Determination

The IQD method is used in the TPA Project to determine the volume velocities in operation by inversion of the acoustic impedance transfer function matrix. To this end, the measured transfer functions from the resulting sound pressure to the introduced volume velocity as well as the sound pressures emitted by the source during operation are required as input variables. The impedance matrix takes into account the crosstalk between the transfer paths through the elements outside the matrix diagonals.

p2p method

Airborne Attenuation

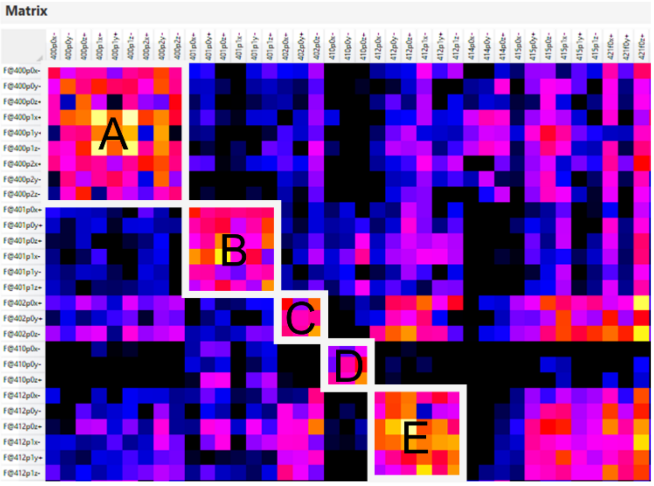
As an alternative to the IQD method, the p2p method can be used in the TPA Project to calculate the airborne sound-induced sound contributions. The p2p method can be used if the objective of the TPA is to learn more about both the transfer paths and the origin of the sound at the receiver position without determining source quantities. To perform the calculation, the transfer functions between the introduced and the resulting sound pressure are required (pressure to pressure, p2p). In addition, as with the IQD method, the sound pressures emitted by the source during operation are required. If the airborne attenuation of a source is determined with several microphones, the individual contributions must be adjusted by means of a coherent source correction (CSC).
This CSC filter is automatically determined by the TPA Project from the number of near-field microphones and the averaged coherence of the operational sound pressures, and is applied to the noise contribution.

Matrix inversion

Both the IFD and the IQD methods require the corresponding transfer function matrix to be inverted. In order to simplify this step and optimize the results, the TPA Project provides users with a number of useful tools. These include, for example, the mosaic view and the calculation of the matrix conditioning number.

Mosaic view

The mosaic view provides a sectional view of all transfer functions at a given frequency in the form of a matrix. The color displayed shows the amplitude, the phase or the coherence of the transfer function and thus visualizes the coupling between the various transfer paths. With this type of representation it is possible, for example, to identify coupled transfer functions and to distinguish local and global resonances. Thus, the mosaic view helps to better understand the system under investigation, to define appropriate submatrices, and to find the optimal matrix setup for matrix inversion.



Identifying coupled components in the mosaic view

Matrix conditioning number

The frequency-dependent matrix conditioning number describes the susceptibility of the transfer function to errors during inversion. It represents the impact of errors in the data on the result of matrix inversion. Its numerical value should be as small as possible. However, there is no universally accepted limit that ensures good matrix conditioning. For this reason, the conditioning number is not to be overestimated, but should always be considered in context instead. It is only one of several criteria for valid data.

Matrix regularization can be used to optimize the matrix conditioning number. However, this process also causes information to be lost. Therefore, matrix regularization should be used with care. In order to reduce the matrix conditioning number, it is also possible to change the matrix setup (e.g., by using submatrices) instead of performing matrix regularization. If a significant improvement of the matrix conditioning number is achieved by matrix regularization, this must also be reflected in the synthesized forces. If this is not the case, the matrix regularization was not successful.

3. Additional information obtained by operational deflection shape analysis

Operational deflection shape analysis (ODS)

The measured data can be used not only in the TPA project but also in the operational deflection shape analysis project of ArtemiS SUITE. Using this project, mode shapes can be visualized very easily. This allows a very intuitive interpretation of the mode shapes and potential subsystems and simplifies the identification of dominant or non-dominant motion directions for the relevant frequency domain.

Visualizing operational deflection shapes easily in ArtemiS SUITE

It is also possible to perform a modal analysis with the Modal Analysis Project and determine the eigenmodes of the structure.

4. OTPA with Prognoise

Operational TPA

No transfer function measurements are required when performing an operational TPA (OTPA). Instead, the transfer functions are estimated from the quantities recorded during operation. This means a significant time saving, since the measurement of the transfer functions can be very time-consuming as the complexity of the model increases. 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. To perform an OTPA, HEAD acoustics provides the Prognoise analysis software featuring the OTPA Wizard. This wizard is used to create the OTPA model and to structure the operational measurements. In addition, the overall sound as well as the individual sound contributions can be synthesized and auralized in Prognoise.

5. Auralization and jury tests

"Human sense of hearing" used as analyzer

In the TPA Project, both transfer path analysis and synthesis are performed in the time domain. This allows results to be auralized easily and, as a consequence, sounds to be evaluated with the "human sense of hearing" analyzer.

The jury testing module SQala of ArtemiS SUITE can be used to evaluate original sounds as well as sounds of different modifications calculated with the TPA model in a jury test. Jury tests provide an opportunity to gather customer feedback and to evaluate the acceptability of product sounds. The results of jury tests can then be used to find the optimum sound design for the intended target group.

Gathering customer feedback in a jury test

➞ *Proceed to the fourth application note on transfer path analysis providing information on sensor technology and how to perform the measurements.*