Optimised TPA approach for improving interior sound engineering

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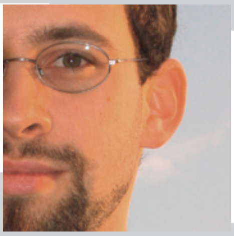

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Abstract

In this publication a validation of common Transfer Path Analysis (TPA) methods on a passenger car is presented to motivate the necessity of further improvements of the current approaches. During the improvement process a specific setup for verification measurements has been designed. This setup eliminates errors corresponding to unconsidered noise sources, bad accessibility for excitation points of the applied forces and temperature influences. Additionally the design allows the measurement of all applied forces and therefore establishes the possibility to compare calculated forces of each source to actually applied forces.

Based on these measurement results new TPA approaches could be developed. Those improved TPA strategies and their potential will be presented in this paper. Their application will optimize and increase the efficiency of passenger car interior noise improvement in the vehicle development process.

Introduction

In order to provide a passenger car with the required interior noise quality, exact knowledge of its acoustic behaviour is required. Needed chassis transmission paths from different sources to the interior target microphones and their contributions can be analysed by applying TPA.

To analyze common TPA methods and design potential improvements a research project has been set up by AVL in cooperation with Acoustic Competence Center (ACC) and the Institute of Electronic Music and Acoustics (IEM).

Presenting essential results of the research project this paper first focuses on magnitudes of potential errors and their effect on TPA results. Afterwards possible improvements developed within this research project are illustrated.

Motivation

Currently various commercial software tools are available to perform a TPA. In order to compare the methodologies and the results of these tools, an analysis using three commercially available TPA tools has been accomplished. (e.g.: [1], [2], [3], [4])

For this TPA a fully equipped mid sized passenger car powered with a 4 cylinder Diesel engine has been measured at an acoustic chassis dynamometer. Within the scope of these extensive measurements all individual requirements of the different systems have been taken into account.

Conventional TPA Results

To assure comparability between the different results the same time data was used for all three TPA systems. Figure 1 and Figure 2 show two results of this analysis.

As plotted in Figure 1 the simulated interior overall noises simulated via TPA differ between the systems at 3850 rpm, in the 3rd gear and at full load. Additionally all simulated results deviate from the measured interior overall noise in certain frequency bands.

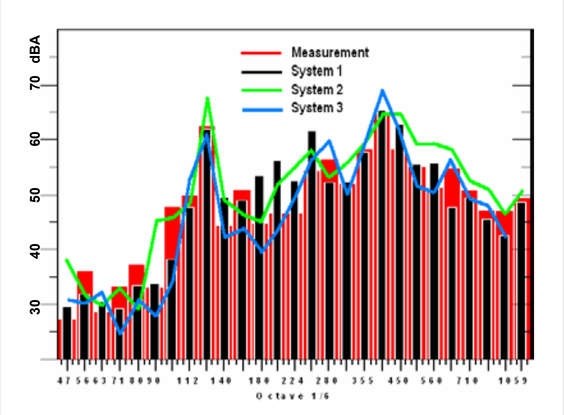


Fig. 1: *Comparison of 1/6 octave interior overall noise for measured sound pressure and results simulated by three different systems. TPA accomplished at 3850 rpm, full load, 3rd gear for a fully equipped mid size passenger car.*

Taking a closer look, the overall interior noise and the calculated contributions for 2nd order in 3rd gear at full load are plotted in Figure 2. Comparison of the simulated contributions in detail showed that depending on the applied measurement system different solutions for the same interior noise problem are necessary.

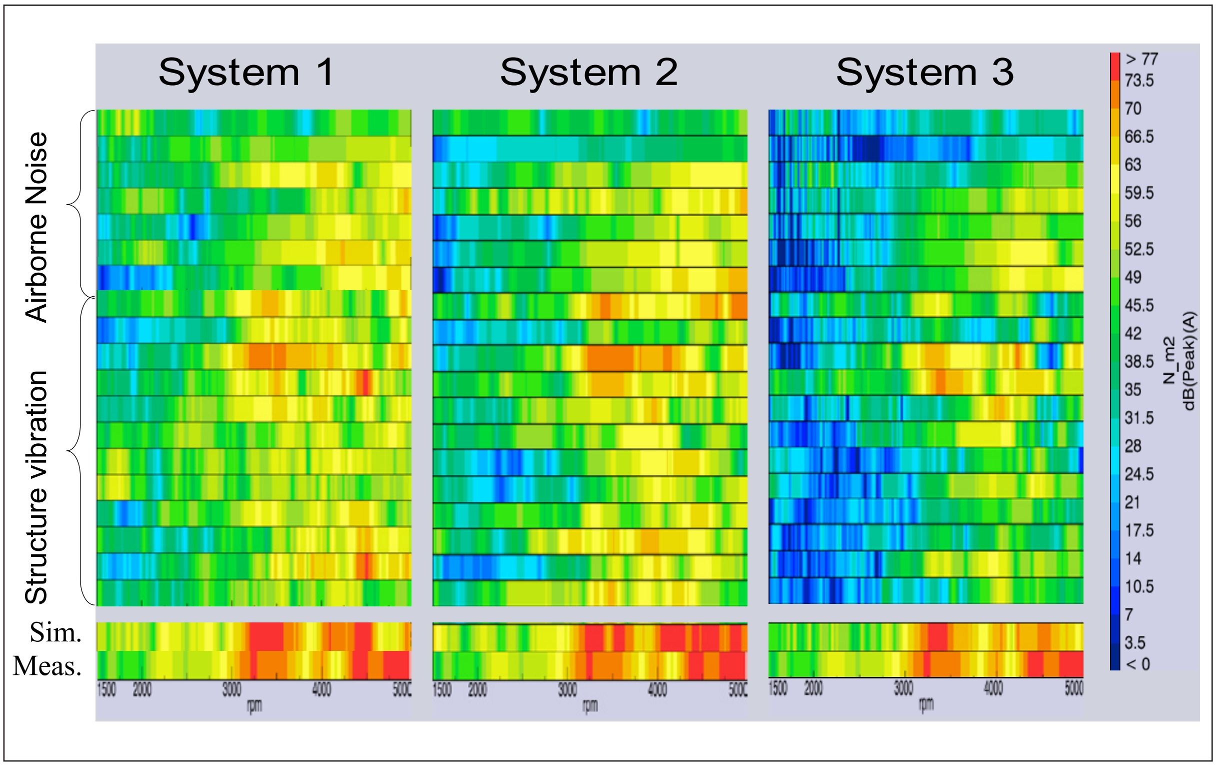


Fig. 2: Contributions for 2nd engine order from TPA results of a fully equipped mid size passenger car using three different analysis systems (upper part) and comparison of overall interior noise results actually measured and obtained via TPA (lower part)

Verification Measurement

Due to accessibility problems in today's engine compartment, measuring forces and contributions is not possible during operational measurement. Therefore a detailed verification of simulated forces and contributions and their comparison to measured values is not feasible.

In order to verify simulated forces and accelerations with measured data, a particular measurement setup was developed. In this setup operational conditions were substituted by six shakers which were fixed to the chassis and operated simultaneously. Additionally a force transducer was placed between each shaker and the chassis. Through this procedure a possibility to measure the exciting forces in operational condition is provided. An example for a shaker and a force transducer fixed at the rear torque support is shown in Figure 3.

A further aim of this setup was the elimination of measurement based errors. By using the exciting shakers additionally for inertance and FRF determination, no deviations in excitation position and excitation direction exists.

Fig. 3: Shaker and force transducer fixed to chassis using X60 glue.

Additionally, there is no difference in temperature between the FRF and the "artificial" operational condition because shakers are used for operational condition.

In Figure 4 the simulated contributions of two force based TPA methods on the sound pressure of a target microphone in the car interior are compared to the measured forces and the overall SPL. As operational condition a full load run up in 3rd gear was simulated by shaker excitations. A second order extraction of this simulated run up was utilized.

As can be seen from Figure 4, the simulated results (blue and green line) fit well to the measured contribution (red line) for an engine speed up to 3000 rpm (corresponding to 100 Hz). Above this speed however, the simulated contributions are much higher than the measured values.

By comparing measured and simulated contributions to the plotted overall SPL at the target interior microphone (black line), dominance of measured and simulated contributions can be estimated. While measured contributions above 3000 rpm can be neglected, simulated contributions are dominating the overall SPL. Therefore it can be concluded, that using simulated contributions might lead to wrong conclusions for interior noise optimization.

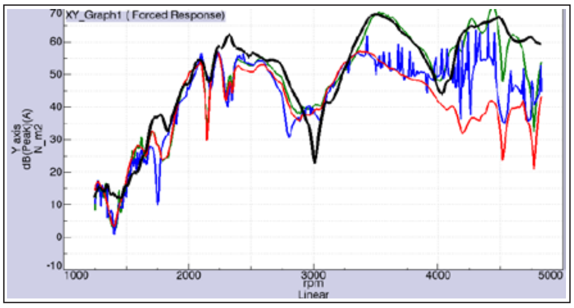


Fig. 4: Comparison of contributions for one excitation position showing results of two force based TPA methods (blue and green line), the measured contribution (red Line) and the overall noise level in the interior (black line).

Beside force based TPA methods, acceleration based methodologies [4] can be applied. Again the extracted 2nd order has been analyzed. As can be seen from Figure 5 the simulated contributions of the two applied acceleration based methods differ from the measured values too. As well as with the considered force based methods a interior noise optimization based on these simulated results would lead to wrong conclusions.

As TPA software tools apply different approaches, it is not obvious which method yields most precise results. Additionally, the procedure of crosstalk recognition within some of the systems is unknown.

Therefore the presented results enforced further investigations on the errors in TPA simulation. Parts of this research and possible solutions for enhancements are summarized in the following chapters.

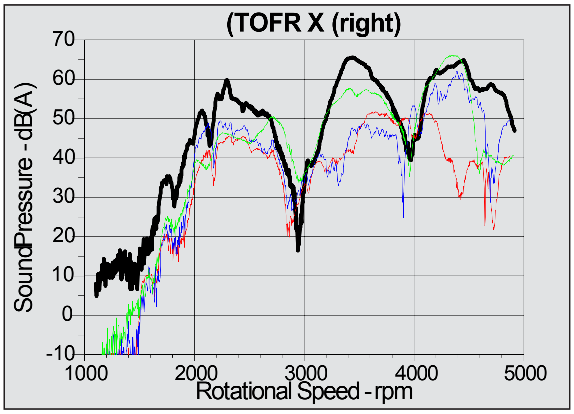


Fig. 5: Comparison of contributions for one excitation position showing results of two acceleration based TPA methods (blue and green line), the measured contribution (red Line) and the overall noise level in the car interior (black line).

TPA Challenges

For computation of sound source contributions on target microphones in the car interior, TPA methods depend on measured data as well as on mathematical analyzing techniques. Therefore generated errors can be related to one of these two categories.

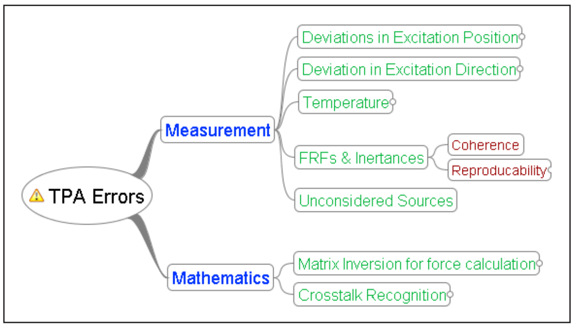


Fig. 6: Overview of possible errors occurring in TPA analysis.

Measurement Based Errors

Depending on the applied methodology errors caused by measured data can mainly originate from demanding definition of excitation positions, deviations in excitation direction and temperature differences between operational and inertance analysis.

Excitation Position

Errors caused by deviations in excitation position are based on two factors. The first problem is related to a correct definition of excitation positions for all considered sources. Namely in such a complex environment as a passenger car engine bay, the definition of an appropriate location for all existing excitations is a quite challenging task.

Defining an adequate excitation position leads to the second problem concerning excitation position errors. To measure the needed inertances and Frequency Response Functions (FRFs) an artificial excitation like an impact hammer or shaker has to be used to excite at the defined position. Due to severe limitation in space, especially within engine compartments of nowadays passenger cars, an excitation at the defined excitation position might not be possible.

Therefore, an accessible position close to the defined excitation position has to be used to measure the needed FRFs and inertances. This deviation in excitation position additionally causes errors on FRFs and inertances. Especially errors in FRF determination are directly forwarded to the simulated results in most TPA methods.

To analyse the effects of deviations in excitation position a substantial sensitivity analysis was performed. As an example, two FRFs from adjacent excitation positions at the engine mount to the same target microphone in the interior compartment are plotted in Figure 7. It can be seen that for this example errors up to 10 dB can be caused by small deviations in excitation position.

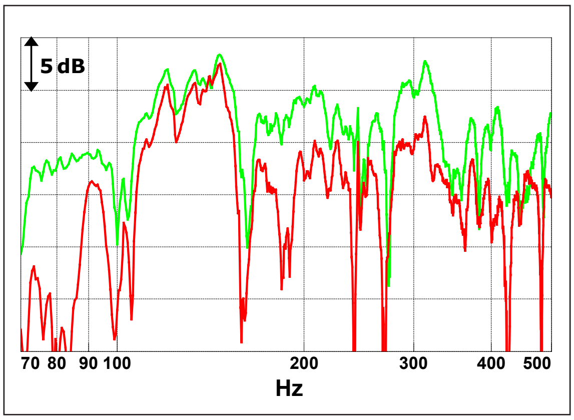


Fig. 7: Comparison of FRFs measured by exciting two adjacent positions (distance 35mm) at one engine mount.

Excitation Direction

Beside deviations in excitation position, errors are based on variances in excitation direction. Again a limited space within engine compartments of passenger cars is the main reason for these deviations.

For a quantification of this error results from the mentioned sensitivity analysis are used again. Two measurements with a deviation in excitation direction of 15° are plotted in Figure 8. It can be seen that deviations up to 10 dB between the resulting FRFs occur.

Therefore deviations based on excitation direction can be of the same magnitude as errors based on deviations in excitation position. This leads to the conclusion that care has to be taken of deviations in excitation position as well as deviations in excitation direction.

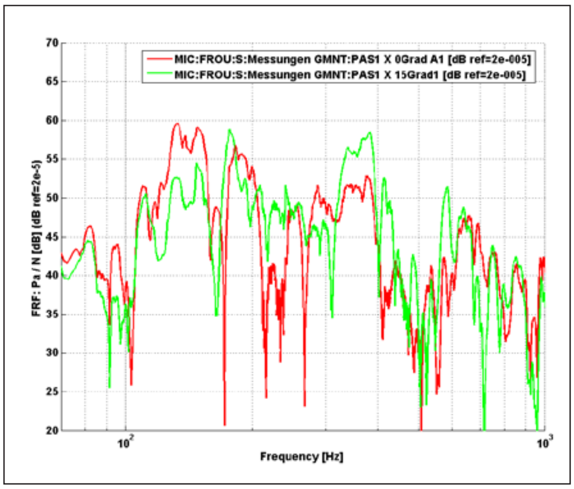


Fig. 8: FRF from one engine mount to interior noise under two different angles of shaker excitation (0°, 15°)

Temperature

In most of the common TPA methods a measurement of FRFs and inertances at the excitation positions is needed. Due to practical reasons, measurement of these data is done separated from the operational measurement. Therefore differences in chassis temperature between the initial FRF and inertance measurement on the one hand and the operational measurement on the other hand will occur.

Within the accomplished sensitivity analysis this influence was analysed too. In order to determine the influence on FRFs and inertances, a shaker was directly fixed to the chassis. FRFs and inertances were first measured in cold condition (20°C chassis temperature). Afterwards the vehicle was operated until temperatures reached operational level (60°C chassis temperature). Afterwards the engine was stopped and immediately the same FRFs and inertances were measured again.

In Figure 9 a comparison for one measured FRF in cold (blue line) and warm (red line) condition is displayed. It can be seen that discrepancies up to 5 dB between the warm and cold FRF occur. As this FRF is needed to compute the contribution from applied forces this 5 dB error is added directly to the error of the TPA result.

Unfortunately very few reasonable measures can be applied to reduce this error. One possibility is the measurement of FRFs and inertances directly after the operational measurement. To keep the chassis temperature the engine could be started at periodic intervals.

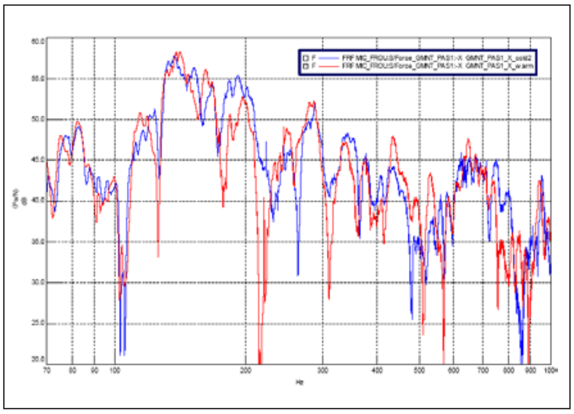


Fig. 9: Comparison of FRFs in cold (blue line measured at 20°C) and warm (red line measured at 60°C) condition.

Summary of Measurement Based Errors

Concluding from the presented results deviations in excitation position, excitation direction and differences in temperature concerning FRF and inertance measurements can cause substantial errors on the simulated TPA result.

Therefore the development of new methods which avoid or reduce the mentioned deviations during measurements would directly improve the quality of simulated TPA results.

Numerically Based Errors

Beside errors caused by deviations within accomplished measurements, numerical procedures contribute additional discrepancies between measured and simulated interior noise.

Two main reasons can be identified when investigating errors in TPA analysis based on numerical problems. Firstly the recognition of crosstalk between the defined excitations seems not to be adequately considered in some of the currently available software tools. Secondly the error amplification of the used TPA methodology based on numerical operations has to be taken into account.

Crosstalk Recognition

In such a complex environment as a passenger car interactions between sound sources via the chassis structure are common. In the frame of TPA these interactions are defined as crosstalk (XT).

In this context XT for each source is defined as the ratio of the sum of energies transmitted through all side paths divided by the energy transmitted through the main path of excitation.

In Figure 10, the XT for one powertrain mount direction is plotted based on the results of the sensitivity analysis. It is calculated by dividing the energy, which is transferred through the two other directions of the mount, through to the energy transferred in excitation direction. Therefore 0 dB indicates that the same amount of energy is transferred through the main and the two auxiliary paths. A positive dB number indicates that more energy is transmitted through the auxiliary paths and a negative dB number indicates that more energy is transmitted through the main path.

Based on this XT definition the induced error in force calculation by omitting the XT can be estimated. This estimation is plotted on the right ordinate in Figure 10 and Figure 11. As plotted in Figure 10 errors up to 8 dB can arise by omitting XT within engine mounts in force calculation.

Beside the XT within mounts the XT between different mounts can be considered. For that purpose the summed energy transmitted through all other mounts is divided by the energy transmitted through

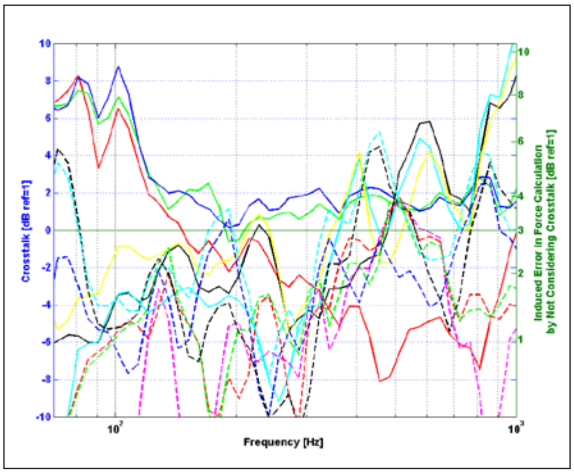


Fig. 10: Crosstalk for each excitation at chassis side engine mount positions within each powertrain mounting positions in x, y, z direction.

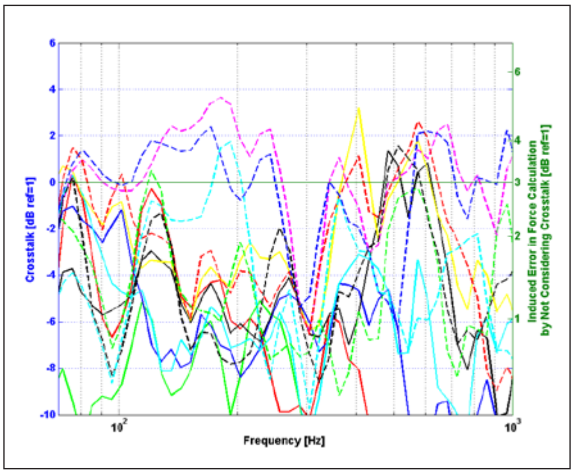


Fig. 11: Chassis crosstalk between 4 powertrain mount positions in x, y, z direction

the main excitation path. Results of this investigation are given in Figure 11.

Comparison of calculated XT plotted in Figure 10 and Figure 11 leads to the conclusion that XT within the engine mounts is substantial and would lead to estimated errors up to 10 dB when omitted. XT between the mounts however is less important and leads to estimated errors in force calculation up to 5 dB.

Error Amplification

Beside the XT recognition an error amplification based on the used mathematical operations has to be considered. This amplification results from the inversion of the inertance matrix, which is required to obtain the apparent mass matrix.

The amplification based on matrix inversion can be constrained by the condition number [5] of the inertance matrix. This constraint can be used to evaluate possible error amplification.

Enhanced TPA

Having described the most common errors in accomplishing a TPA, possible solutions for these problems are proposed.

In this paper two advancements for TPA are introduced. Firstly the mountwise calculation which is a new force based calculation methodology which reduces error amplification while considering essential crosstalk.
Secondly the TPA FORM approach. A new procedure for determining inertances from operational measurements, using additional reciprocally measured FRFs.

Making computed forces and contributions audible was another prerequisite for the enhanced TPA methods. Due to inversion, antiresonances in inertances lead to resonances in apparent masses. These resonances lead to excessive tonal components which cover close-by frequencies. In order to prevent those problems, a regularization method was developed in our approach. For this regularization a white noise signal is utilized, which is dependent on the original signal decreased by a predefined offset and has a smoother spectrum.

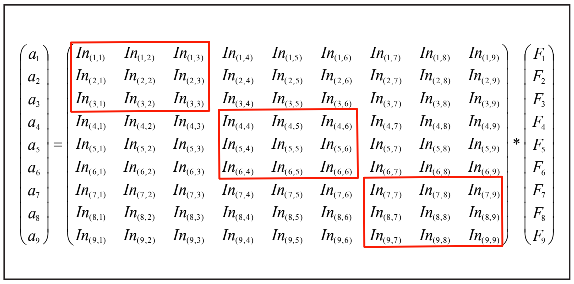
Mountwise Calculation

To reduce numerically based errors, crosstalk recognition and error amplification have been investigated. Usually an increase in crosstalk recognition leads to an increase in condition number. As the condition number is an indicator for the upper bound of the error amplification, increased crosstalk recognition might lead to increased error amplification.

Using more inertances for apparent mass calculation to increase crosstalk recognition, usually leads to a higher condition number of the inertance matrix. This increase in condition number is based on the low contributions of sources from other mounts which usually cause low eigenvalues (noise) in the inertance matrix. Therefore a mountwise consideration of forces usually leads to a decrease in condition number.

In order to balance influences of crosstalk recognition and error amplification only inertances within one mount are used for apparent mass calculation in this approach.

Motivation for this approach is plotted in Figure 10 and Figure 11. It is shown that crosstalk within one mount is in most cases noticeably higher than crosstalk between mounts. Therefore only those elements in the inertance matrix indicated in Figure 12 are used for apparent mass calculation.



$$\begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \\ a_8 \\ a_9 \end{pmatrix} = \begin{pmatrix} In_{(1,1)} & In_{(1,2)} & In_{(1,3)} & In_{(1,4)} & In_{(1,5)} & In_{(1,6)} & In_{(1,7)} & In_{(1,8)} & In_{(1,9)} \\ In_{(2,1)} & In_{(2,2)} & In_{(2,3)} & In_{(2,4)} & In_{(2,5)} & In_{(2,6)} & In_{(2,7)} & In_{(2,8)} & In_{(2,9)} \\ In_{(3,1)} & In_{(3,2)} & In_{(3,3)} & In_{(3,4)} & In_{(3,5)} & In_{(3,6)} & In_{(3,7)} & In_{(3,8)} & In_{(3,9)} \\ In_{(4,1)} & In_{(4,2)} & In_{(4,3)} & In_{(4,4)} & In_{(4,5)} & In_{(4,6)} & In_{(4,7)} & In_{(4,8)} & In_{(4,9)} \\ In_{(5,1)} & In_{(5,2)} & In_{(5,3)} & In_{(5,4)} & In_{(5,5)} & In_{(5,6)} & In_{(5,7)} & In_{(5,8)} & In_{(5,9)} \\ In_{(6,1)} & In_{(6,2)} & In_{(6,3)} & In_{(6,4)} & In_{(6,5)} & In_{(6,6)} & In_{(6,7)} & In_{(6,8)} & In_{(6,9)} \\ In_{(7,1)} & In_{(7,2)} & In_{(7,3)} & In_{(7,4)} & In_{(7,5)} & In_{(7,6)} & In_{(7,7)} & In_{(7,8)} & In_{(7,9)} \\ In_{(8,1)} & In_{(8,2)} & In_{(8,3)} & In_{(8,4)} & In_{(8,5)} & In_{(8,6)} & In_{(8,7)} & In_{(8,8)} & In_{(8,9)} \\ In_{(9,1)} & In_{(9,2)} & In_{(9,3)} & In_{(9,4)} & In_{(9,5)} & In_{(9,6)} & In_{(9,7)} & In_{(9,8)} & In_{(9,9)} \end{pmatrix} * \begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \\ F_8 \\ F_9 \end{pmatrix}$$

Fig. 12: Mount blocks indicated in inertance matrix

The reduction of inertances used for apparent mass calculation for almost each frequency leads to a reduction of the condition number of the inertance matrix. One example is given in Figure 13. As the condition number constraints the error amplification, this decrease in condition number leads to a decrease of error amplification.

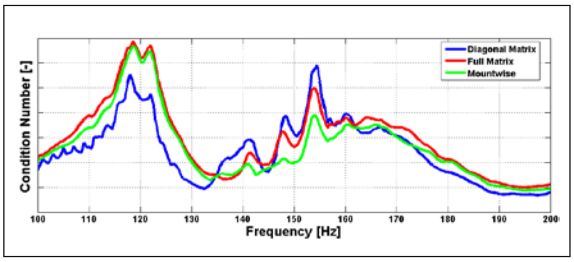


Fig. 13: Condition number for diagonal (blue), full (red) and mountwise (green) inertance matrix

In order to reduce error amplification while considering crosstalk, the mountwise calculation of apparent masses is proposed. Application of this method decreases the condition number while substantial crosstalk is considered.

TPA FORM

From **O**perational and **R**eciprocal **M**easurement

Introduction

Aim of this new method is a fast and accurate computation of forces and contributions in operational condition without initial inertance determination by shaker excitation.

As described before, one of the most time consuming and error-prone tasks is the measurement of inertances and source to target FRFs by artificial excitation. In order to avoid those measurements, this method computes inertances from a measurement in operational condition and reciprocally measured FRFs. ([11])

These calculated inertances are then used to determine applied forces in operational conditions. Using these forces allows a more precise evaluation and identification of contributions of corresponding sources on the SPL at target microphones.

Advantages

While the time saving aspect of this new method is obvious, the increase in result quality has to be described in detail. As stated before one of the most error-prone tasks while accomplishing a TPA are the measurements of inertances and source to target FRFs.

As described before, these errors are in large parts depending on deviations in excitation direction, deviations in excitation position as well as differing structure temperatures between operational and initial inertance, respectively FRF measurements.

Using reciprocally measured FRFs, the deviation in excitation direction is eliminated because the direction of the force of the measured FRFs is identical to the accelerometer axis.

Concerning deviations in excitation position, it is easier to place an accelerometer close to the origin of the exciting sources than to use a shaker or an impact hammer as excitation at these positions to measure the inertances and FRFs. For these reasons the error caused by deviation in excitation position and excitation direction is eliminated or at least reduced by this method.

Furthermore, the error based on temperature differences will be drastically reduced by the reciprocal measurement if it is accomplished directly after the operational measurement.

Compared to other acceleration based methods, TPA FORM is able to compute all considered forces and contributions using additional reciprocal measurements. Beyond other acceleration based methodologies, this computation of forces and contributions is able to consider crosstalk phenomena, which is not provided by currently available commercial acceleration based TPA tools.

Theory

To compute the inertances from operational and reciprocal measurement two steps are necessary. In Step 1 acceleration to pressure sensitivities are determined which are used in Step 2 to compute the inertances.

Step 1: Determination of Acceleration to Interior Microphone Sound Pressure Sensitivities

One way to determine the required acceleration to sound pressure sensitivities is the elimination of airborne sound pressure contributions. Following the nomenclature of Equation 1, p_{AB} has to be subtracted from the overall sound pressure p_{tot} at target microphones. Therefore in the further proceeding only structureborne sound pressure p_{SB} will be used.

$$p_{tot} = p_{SB} + p_{AB}$$

p_{tot} …Total sound pressure

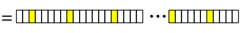
p_{SB} …Structureborne contribution on total sound pressure

p_{AB} …Airborne contribution on total sound pressure

Equation 1: Sound pressure definition

Assuming a measurement of p_{SB} during an engine run up, the calculation of the p_{SB} using the required acceleration to sound pressure sensitivities is given in Equation 2.

$p_{SB\,i}(t)=$



$$\begin{bmatrix} p_{SB\,i}(f,t_1) \\ \vdots \\ \vdots \\ \vdots \\ p_{SB\,i}(f,t_m) \end{bmatrix} = \begin{bmatrix} a_1(f,t_1) & \cdots & a_n(f,t_1) \\ \vdots & & \vdots \\ a_1(f,t_m) & \cdots & a_n(f,t_m) \end{bmatrix} \cdot \begin{bmatrix} {p_{SB\,i}}/{a_1}(f) \\ \vdots \\ {p_{SB\,i}}/{a_n}(f) \end{bmatrix} =$$

$$= \begin{bmatrix} a_1(f,t_1) & \cdots & a_n(f,t_1) \\ \vdots & & \vdots \\ a_1(f,t_m) & \cdots & a_n(f,t_m) \end{bmatrix} \cdot \begin{bmatrix} S(i,1,f) \\ \vdots \\ S(i,n,f) \end{bmatrix}$$

i …Target microphone position

f …Considered frequency

$t_1 ... t_m$ …Considered timeslots

$a_1 ... a_n$ …Considered accelerations

$S(i,j,f)$ …Acceleration to pressure sensitivity for target microphone i and acceleration j for frequency f

Equation 2: Determination of acceleration to pressure sensitivities

For defined timeslots sound pressure and acceleration spectra in an adequate number are calculated from time data. In TPA FRFs and inertances are assumed to be constant for different operational conditions (timeslots in Equation 2). As acceleration to sound pressure sensitivities can be calculated from inertances and FRFs, these sensitivities are also assumed to be constant for all timeslots. Therefore, the system of equations given in Equation 2 can be solved to compute the required acceleration to sound pressure sensitivities.

Step 2: Determination of Inertances

Based on the reciprocity principle, reciprocally measured FRFs and FRFs in operational condition are equal. For determination of inertances reciprocally measured FRFs are compared to FRFs computed from the operational measurement.

As described in Equation 3 the FRFs in operational condition can be computed by utilizing the acceleration to sound pressure sensitivities determined in Step 1.

$$\frac{\vec{a}_{rec}}{\dot{Q}_{i\,rec}}(f) \equiv \frac{p_{i_{op}}}{\vec{a}_{op}}(f) \cdot \frac{\vec{a}_{op}}{\vec{F}_{op}}(f)$$

$\vec{a}_{rec}$ …Acceleration in reciprocal measurement in direction of $\vec{F}_{op}$

$\dot{Q}_{i\,rec}$ …Volumeacceleration in reciprocal measurement at target microphone i

$p_{i_{op}}$ …SPL at microphone i in operational condition

$\vec{a}_{op}$ …Acceleration in operational condition

$\vec{F}_{op}$ …Vector of applied forces in operational measurement

Equation 3: Comparison of reciprocally measured FRFs and FRFs computed from operational data

As the inertances are the only unknowns in this system of equations, they can be computed by utilizing appropriate mathematical methods. [11] In order to compute all inertances, multiple, sufficiently independent, target positions have to be used. To obtain this independence, a minimum distance between the target positions has to be kept.

Having determined the inertances from operational measurement and reciprocally measured FRFs, the required forces and source contributions, which yield the overall interior noise level in operational condition, can be obtained.

Summary of TPA FORM

As described above the TPA FORM method allows determination of inertances by eliminating errors based on deviations in excitation direction and excitation position. Additionally temperature effects are eliminated when reciprocally measured FRFs are detected directly after the measurement in operational condition. Therefore this new method is time saving and much more accurate than current conventional TPA methods.

Conclusion

It was shown in this publication that a number of errors can occur when applying a TPA on a passenger car. Additionally, it has been shown that these numerical, as well as measurement based errors can cause differences between simulated and actually measured source contributions to interior noise of more than 10 dB.

Therefore, optimized methods have been developed in order to open new ways to a more accurate and time saving TPA analysis procedure. Especially the TPA FORM approach has a high potential to fulfil these requirements.

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