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Challenges and New Solutions for Transfer Path Analysis

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Abstract

Exact knowledge of chassis transmission paths is essential for an effective and purposeful interior noise / noise quality development process. One possible approach to obtain this required information is the application of a Transfer Path Analysis (TPA).
When applying this analysis method care has to be taken in choosing the appropriate algorithm and the corresponding setup. Therefore this paper first focuses on the most important errors concerning existing TPA methodologies and their consequences on the result, starting from difficulties in locating the excitation position of the applied forces via deviations in excitation direction up to differences in chassis temperatures.
Accordingly solutions for elimination or reduction of these errors are presented. Additionally a completely new TPA approach is introduced which is faster and more accurate than currently approved methods.

1 Introduction

A common tool to determine contributions of different sound sources to a target position e.g. in the car interior is the Transfer Path Analysis (TPA). As the information about contribution of different sources to the overall sound at target positions is highly necessary during the sound engineering process, the quality of results out of TPA analyses is crucial for sound improvements.

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

In the first part of this paper valuable results concerning possible problems in TPA analysis are introduced. Afterwards promising approaches for enhancements of common TPA methods are discussed. Finally a completely new method for inertance determination is introduced and first verification results are presented.

2 Motivation

Nowadays several software tools to accomplish a TPA analysis are available. Including new acceleration based approaches which have been presented in the recent past. [1] The research project mentioned above was motivated by inconsistent results between those commercially available TPA Tools for the same set of data. An example of occurring inconsistencies is given in Figure 1.

Although the same time data has been used for all different TPA tools the results differ between all commercial TPA software tools. Additionally all computed results differ from the measured overall sound pressure level at the regarded target point.

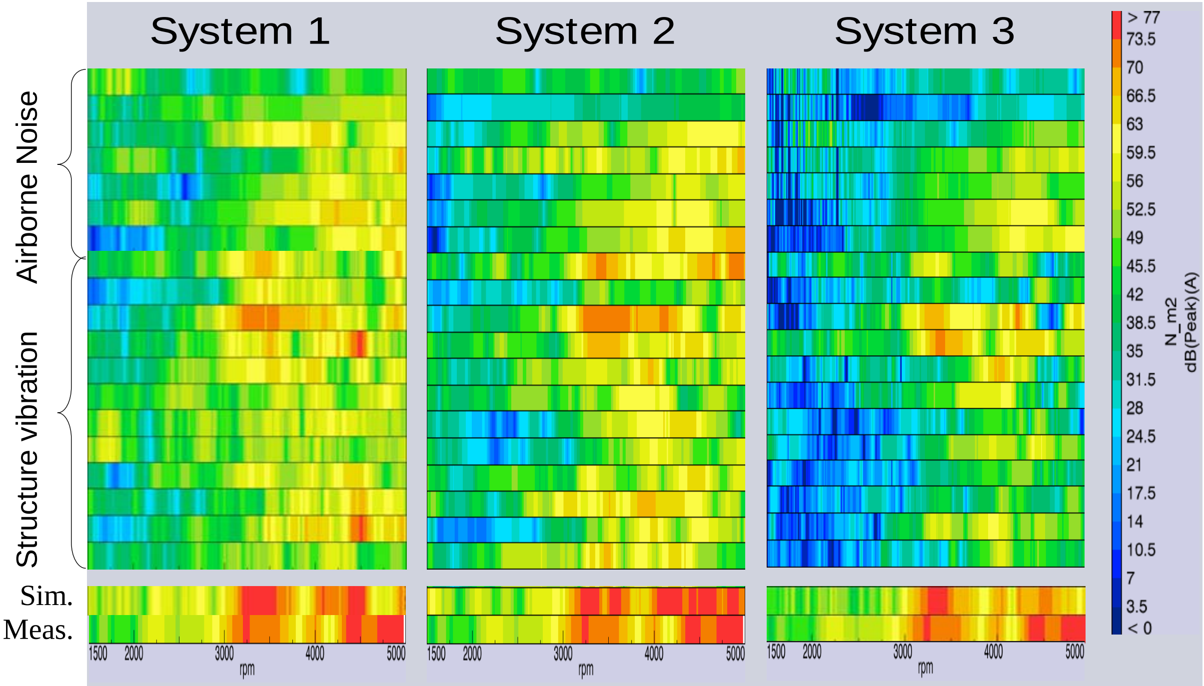

Figure 1: Contributions from TPA results for 2nd engine order in a 3rd gear WOT run-up of a fully equipped mid size passenger car using three different analysis systems (upper part) and comparison of overall interior noise results actually measured and obtained via TPA (lower part)

3 Detailed TPA Analysis

Based on a detailed analysis a specification of possible errors that might influence the results of a TPA was developed. Figure 2 shows a classification of possible TPA errors into measurement based and mathematically based influences.

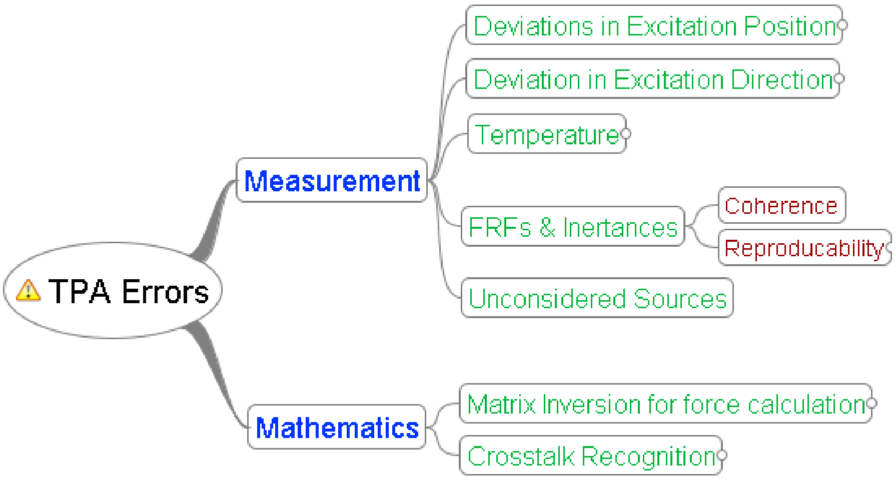

Figure 2: Overview of possible errors that influence TPA results

In order to develop new approaches to enhance currently used TPA methodologies detailed analyses have been accomplished for both error categories. In the context of mathematically based errors a verification measurement to validate currently used TPA methodologies has been performed. Additionally a substantial sensitivity analysis has been carried out to analyse measurement based influences which mainly concern problems in transfer function and inertance acquisition caused by deviations in excitation position, excitation direction and temperature.

3.1 Measurement Based Errors

In order to quantify errors that are based on measurement inaccuracies, various measurements have been made. Results of these measurements concerning deviations in excitation direction, excitation position and temperature are plotted in Figure 3.

To measure the needed inertances and Frequency Response Functions (FRFs) an artificial excitation like an impact hammer or shaker has to be used. Due to severe limitation in space, especially within engine compartments of nowadays passenger cars, deviations in excitation direction and excitation position might occur.

To analyse the influences of these deviations, a substantial sensitivity analysis was performed. Representative examples for influences of the mentioned deviations are plotted in Figure 3. More information about the results of this sensitivity analysis are given in [2] and [6].

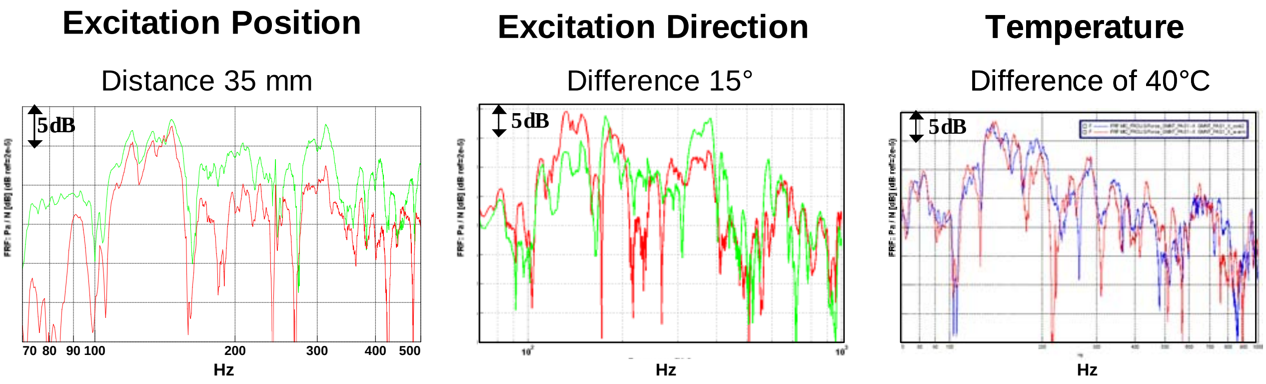

Figure 3: Comparison of measured FRFs at one engine mount with deviations in excitation position (left), excitation direction (middle) and temperature (right).

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.

3.2 Numerically Based Errors

Beside errors that are based on measurement problems, errors based on numerical reasons contribute to the overall error of TPA calculations. In order to quantify those numerically based errors a special verification measurement setup and a substantial crosstalk influence analysis has been accomplished. Results of these analyses are described in the following chapters.

3.2.1 Verification Measurement Setup

Aim of this verification measurement was the comparison of different TPA methodologies in the face of numerical correctness. Therefore the elimination of all measurement based errors had to be satisfied by the verification measurement setup. In addition, acquisition of data needed for verification has to be considered in the verification measurement design process.

In order to eliminate all measurement based errors, Mini Shakers have been used to generate ‘operational conditions’. To prevent deviation in excitation direction and excitation position all shakers have been fixed to the chassis using X60 glue. By utilizing Mini-Shakers for excitation, the measurement based error caused by temperature differences is eliminated. Finally problems based on reproducibility, coherence of the transfer functions and unconsidered sources are eliminated due to the fixation of the shakers.

For verification purposes the exact knowledge of induced forces at all excitation positions is necessary. Therefore force transducers have been placed between the Mini Shakers and the chassis. Additionally the overall target sound pressure has been measured during ‘operational condition’.

Figure 4 shows one example for an excitation position setup including Mini Shaker, force transducer and accelerometers. For the whole verification measurement setup 6 Mini-Shakers have been used to generate ‘operational conditions’. As excitation signals for the Mini Shakers, acceleration signals measured during a 3rd gear WOT run-up at the positions of the Mini-Shakers have been used. Through this approach a 3rd gear WOT run-up could be generated.

Figure 4: Measurement setup for one excitation position including Mini Shaker, force transducer and accelerometers

3.2.2 Verification Results for Conventional TPA

Utilizing the generated ‘operational data’, TPAs using different TPA Tools have been accomplished. Due to the used methodology the tools have been separated into acceleration based and force (inertance) based methodologies.

Figure 5 shows the results for contributions of two acceleration based methodologies. Additionally the overall SPL at the target position (black) is plotted to clarify the importance of the regarded contribution on the SPL at the target microphone. To verify the calculated contributions the forces measured under ‘operational condition’ were multiplied by the transfer function from the force position to the target position to achieve a measured contribution.

As can be seen in Figure 5 the calculated and measured contributions show a good agreement at low rotational speeds. At higher engine speeds however the calculated results differ up to 20 dB from the measured contributions.

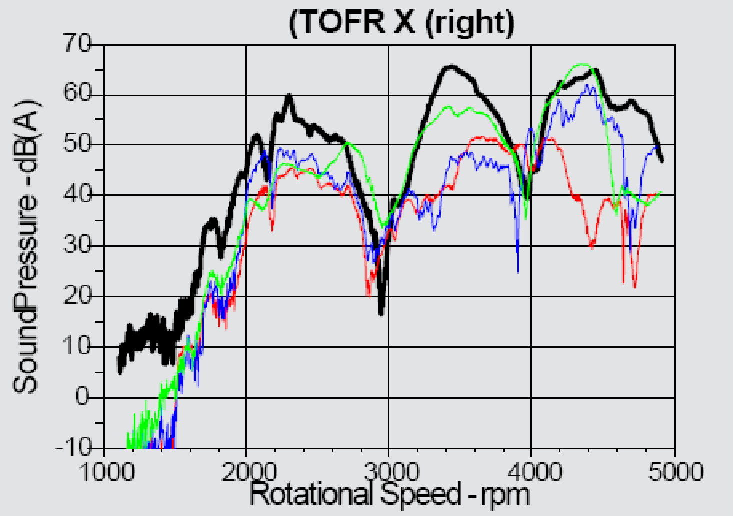

Figure 5: 2nd order overall SPL at target microphone (black), measured contribution from verification measurement (red) and contributions calculated by using two acceleration based methodologies (blue and green) for a 3rd gear WOT run-up

To verify force (inertance) based methodologies again, calculated and measured contributions have been compared. In Figure 6 results for one contribution are displayed. Similar to the results of the acceleration based methodologies results for lower engine speeds show a very good agreement between measured and calculated contributions. For higher frequencies however computed and measured values show big deviations. While the measured contribution (red) is more than 20 dB below the overall noise (black), the calculated contributions (green and blue) are dominant in these frequency ranges.

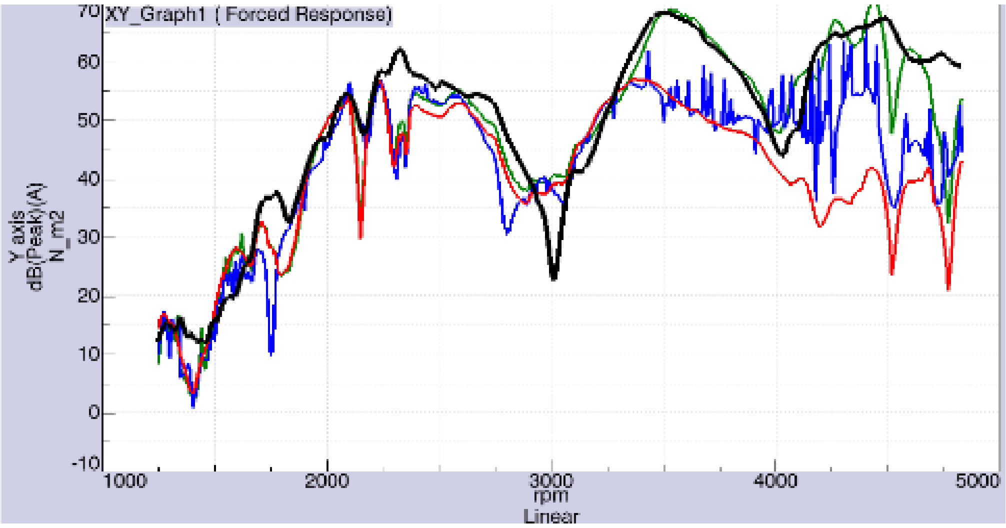

Figure 6: 2nd order overall SPL at target microphone (black), measured contribution from verification measurement (red) and contributions calculated by using two force (inertance) based methodologies (blue and green) for a 3rd gear WOT run-up

3.2.3 Crosstalk Influence

One main reason for the bad agreement between measurement and calculation is the consideration of influences of different excitations on the measured accelerations. In such a complex environment as a passenger car accelerations are influenced by different sound sources. In the frame of TPA these interactions are defined as crosstalk (XT).

In this investigation 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 the excitation.

In Figure 7, 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 the energy transferred in excitation direction. 0 dB therefore 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.

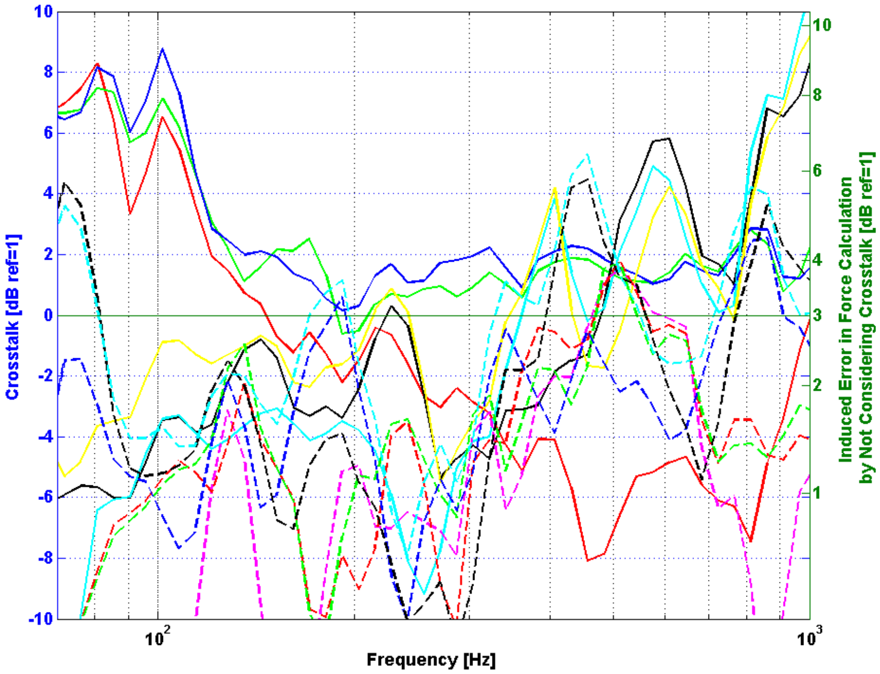

Figure 7: Crosstalk for each excitation at chassis side engine mount positions within each powertrain mounting positions in x, y, z direction

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 7 and Figure 8. As plotted in Figure 7 errors up to 8 dB can arise by omitting XT within engine mounts in force calculation.

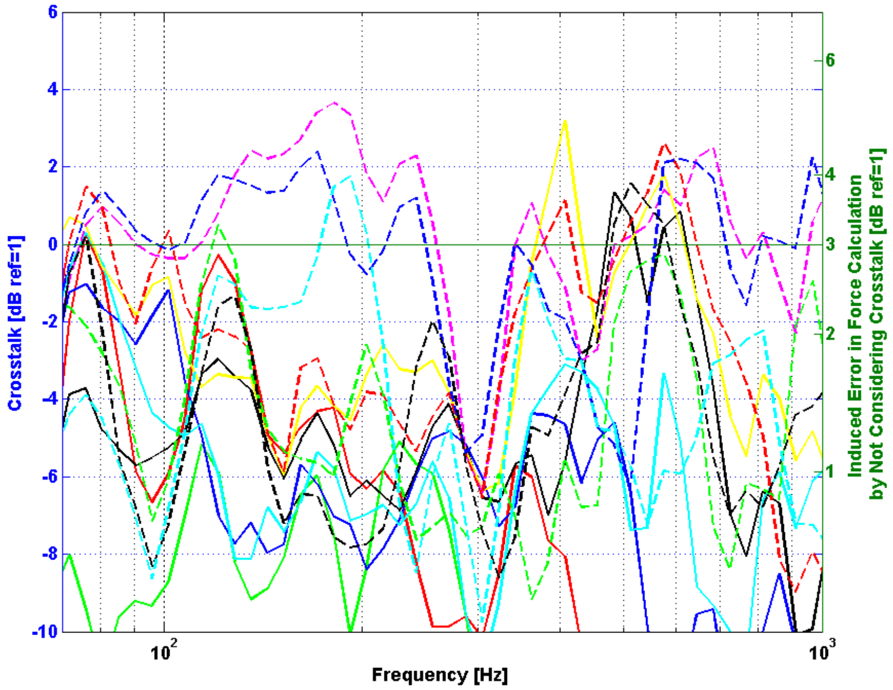

Figure 8: Chassis crosstalk between 4 powertrain mount positions in x, y, z direction

Beside the XT within mounts the XT between different mounts can be considered too. For that purpose the summed energy transmitted through all other mounts is divided by the energy transmitted through the main excitation path. Results of this investigation are given in Figure 8.

Comparison of calculated XT plotted in Figure 7 and Figure 8 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 of up to 5 dB.

4 Solutions for TPA Enhancement

4.1 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 given in chapter 3.2.3. It is shown that crosstalk within one mount is in most cases noticeably higher than crosstalk between mounts. Therefore only crosstalk within the mounts is considered in the mountwise approach.

The reduction of the number of inertances considered 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 9. As the condition number constraints the error amplification, this decrease in condition number leads to a decrease of possible error amplification.

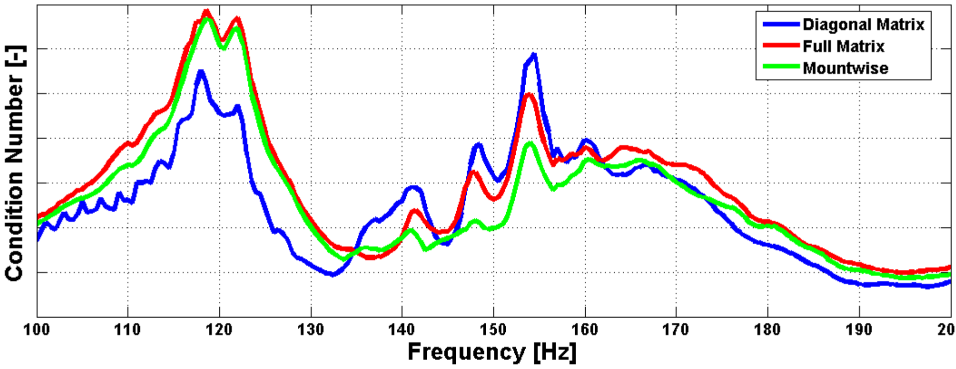

Figure 9: Condition number for diagonal (blue), full (red) and mountwise (green) inertance matrix

For verification of the mountwise approach data from the verification measurement described in chapter 3.2.1 was utilized. Due to the designed verification measurement setup no measurement based error occurs in this data set. Therefore deviations between measurement and calculation are only caused by numerical problems of the applied approaches.

As can be seen at the top of Figure 10 the calculation using the main diagonal of the inertance matrix shows very little agreement with the measured SPL at the considered target microphone. Utilizing the mountwise approach for target noise computation the agreement between measured and calculated SPL increases strongly. Through application of the full matrix approach further improvements in the agreement between measured and calculated SPL can be achieved.

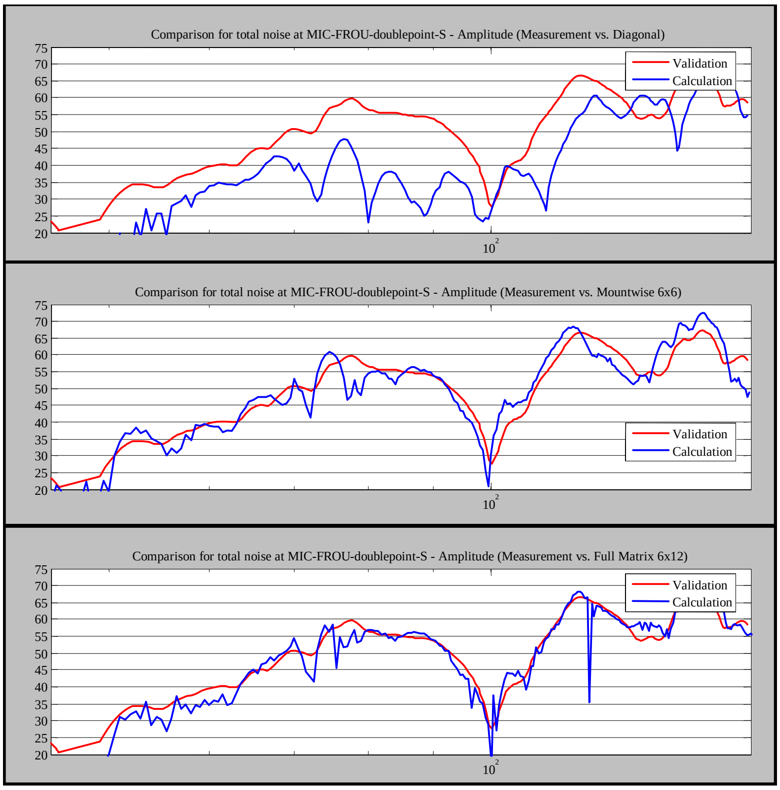

Figure 10: Comparison of measured total noise (red) and total noise calculated using the diagonal (top), mountwise (middle) or full matrix (bottom) approach.

4.2 TPA FORM

In cooperation between AVL, ACC and the Institute of Electronical Music and Acoustic (IEM) a new TPA Method was developed and patented. ([4], [5])

4.2.1 Assumptions

This method assumes that the excitation of all main sources is covered by measuring the accelerations or sound pressures close to all defined excitation positions. Additionally it is assumed that acceleration to sound pressure sensitivity functions are constant for all measurements in operational condition. This means that the structure (chassis in case of application on cars) temperature while measuring in operational conditions has to be as constant as possible.

4.2.2 Advantages

The new approach of the developed method allows the computation of inertances from measurements in operational condition and reciprocally measured source to target FRFs. The advantages of this new method are its time saving approach and the elimination of common errors in inertance and FRF measurements.

While the time saving aspect of this method is obvious, the increase in result quality has to be described in detail.

One of the most error prone tasks while accomplishing a TPA are the measurements of inertances and source to target FRFs. 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. Additionally it is easier to place an accelerometer close to the origin of the exciting sources as 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 is reduced by this method.

Furthermore the error based on temperature differences is reduced by the reciprocal measurement if it will be accomplished directly after the operational measurement. Through this proceeding the problems based on the difference in temperature between the operational and the inertance resp. FRF measurement can be eliminated.

4.2.3 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 (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.

$$p_{tot} = p_{SB} + p_{AB} \qquad (1)$$

p_{tot} ...Total sound pressure
p_{SB} ...Structureborne contribution to total sound pressure
p_{AB} ...Airborne contribution to total sound pressure

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 (2).

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

$$\begin{bmatrix} \boxed{p_{SB\,i}(f,t_1)} \\ \vdots \\ \vdots \\ \vdots \\ \boxed{p_{SB\,i}(f,t_m)} \end{bmatrix} = \begin{bmatrix} a_1(f,t_1) & \cdots & a_n(f,t_1) \\ \vdots & & \vdots \\ a_1(f,t_m) & \cdots & a_n(f,t_m) \end{bmatrix} \cdot \begin{bmatrix} {}^{p_{SB\,i}}\!/\!{}_{a_1}(f) \\ \vdots \\ {}^{p_{SB\,i}}\!/\!{}_{a_n}(f) \end{bmatrix} = \begin{bmatrix} a_1(f,t_1) & \cdots & a_n(f,t_1) \\ \vdots & & \vdots \\ a_1(f,t_m) & \cdots & a_n(f,t_m) \end{bmatrix} \cdot \begin{bmatrix} S(i,1,f) \\ \vdots \\ S(i,n,f) \end{bmatrix} \qquad (2)$$

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

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

$$\frac{\vec{a}_{rec}}{\dot{Q}_{i\,rec}}(f) \equiv \frac{p_{i_{op}}}{\vec{a}_{op}}(f)\cdot\frac{\vec{a}_{op}}{\vec{F}_{op}}(f) \qquad (3)$$

$\vec{a}_{rec}$ …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

As the inertances are the only unknowns in this system of equations, they can be computed by utilizing appropriate mathematical methods. [3] 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. Following the presented TPA FORM approach all inertances can be computed considering with consideration of crosstalk effects.

Having determined all 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.

4.2.4 Verification of TPA FORM

To verify the developed TPA FORM method the following data requirements were defined.

- Data for TPA FORM
    - acceleration in operational condition at excitation position
    - pressure / acceleration in operational condition at target positions
    - reciprocally measured FRFs from target to excitation position
- Data for Verification
    - conventionally measured FRFs
    - conventionally measured inertances
    - measured forces

4.2.5 Measurement Setup

In order to fulfil those data requirements a verification setup was designed in which two Mini-Shakers were attached at mounting positions of the chassis using X60 glue. Between each Mini Shaker and the chassis a force transducer was placed to measure the forces that are induced to the chassis by each shaker.

To measure all necessary accelerations in operational condition two 3-d accelerometers were placed close to the defined shaker position. To deliver the required reciprocally measured FRFs eight 1-d accelerometers in structures mainly in the engine bay were used instead of microphones in the car interior. The reason for using reciprocally measured structure to structure (force to acceleration) instead of structure to airborne (volume acceleration to acceleration) transfer functions is based on measurement reasons. Due to restrictions in measurement equipment, especially in the low frequency range, the quality of structure to structure transfer functions is much better than the quality of structure to airborne transfer functions. Therefore structure to structure transfer functions have been used to reduce the error in TPA FORM computation.

To simulate operational conditions using both shakers, measured accelerations in operational condition close to each shaker position were utilized. As operational condition a 3rd gear WOT runup at a test bed was used. A layout of the verification measurement setup including accelerometer positions, shaker positions and the localization of target points for reciprocal acceleration measurements is given in Figure 11.

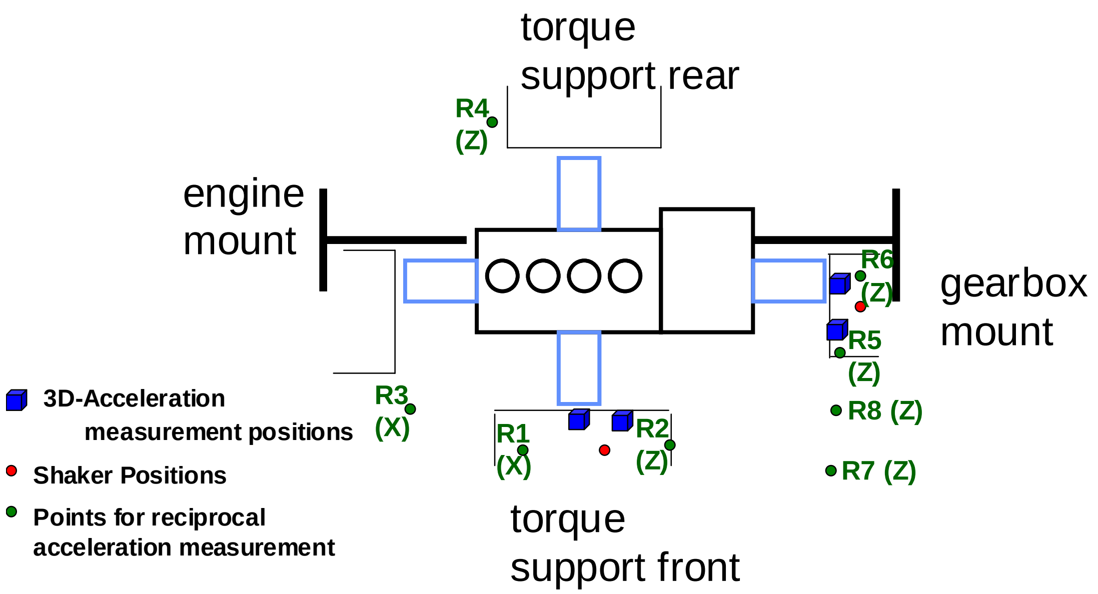

Figure 11: Additional response measurement points for the LMS software

4.2.6 Verification Method

For a detailed verification of the TPA FORM method following values have to be verified.

- Sensitivities calculated in Step 1
- Inertances calculated in Step 2
- Forces computed by inverting the inertance matrix that was calculated by TPA FORM

For verification of all values a block diagram showing the relations between sensitivities, inertances and (reciprocally measured) FRFs is given in Figure 12. This diagram was used to design appropriate verification procedures for all values computed in TPA FORM.

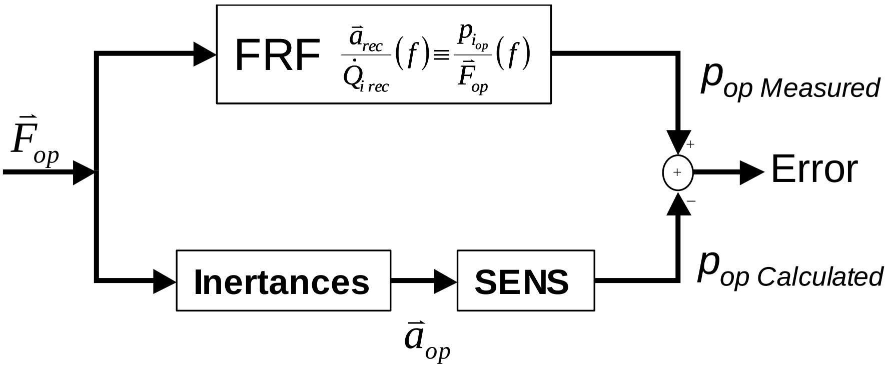

Figure 12: Block Diagram showing relations between sensitivities, inertances and FRFs.

4.2.7 Sensitivity Verification

In order to verify the sensitivities computed in Step 1.1 resp. Step 1.2 measured inertances and FRFs were used. As can be seen in Figure 12 a series connection of sensitivities and inertances equals the (reciprocally measured) FRF from source to target. For verification purpose the measured forces from the operational measurement can be used to determine sound resp. acceleration at the target position either by using the measured FRF or by using a multiplication of measured inertances and calculated sensitivities.

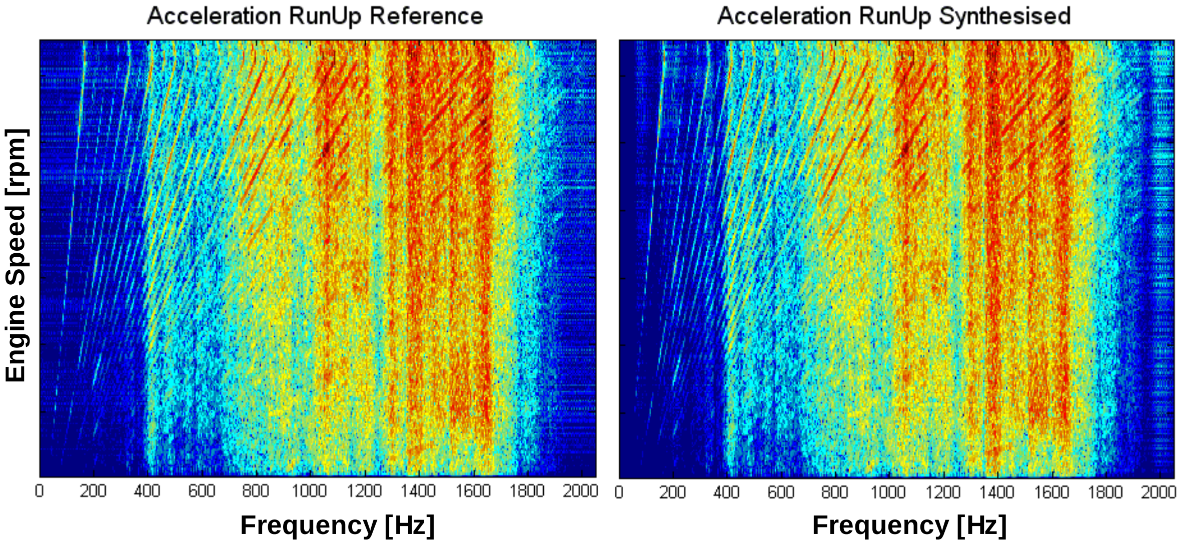

Figure 13: Comparison between measured accelerations at target position and acceleration at target position calculated from computed sensitivities and measured inertances.

To verify the calculated sensitivities Campbell plots of acceleration at target values for the operational data (WOT 3rd gear run-up) are used. In Figure 13 the left plot shows the Campbell diagram computed by using a measured FRF. The right plot contains the acceleration at target position computed by using measured inertances and calculated sensitivities. As both plots are nearly identical the calculated sensitivities are verified.

4.2.8 Inertance Verification

Verification of the inertances computed by TPA FORM is done by comparing them to conventionally measured inertances. For the conventional inertance measurement it is crucial that the error made in inertance measurement is minimal. Therefore the excitation direction of the inertance measurement has to be equal to the direction of the accelerometer that has been used in TPA FORM. Additionally the location of the excitation position for the conventional inertance measurement has to be as close as possible to the real excitation position of the shaker. Finally the temperature in operational condition has to be equal to the temperature when the conventional inertance measurement is performed.

In case of the verification measurement setup the conventional determination of inertances should fulfil all requirements. Therefore the error in measured inertance is assumed to be neglectible. Figure 14 shows a comparison between conventionally measured inertances (full) and inertances that were calculated using TPA FORM. Beside a numerical problem at about 350 Hz measured and calculated inertances fit very well.

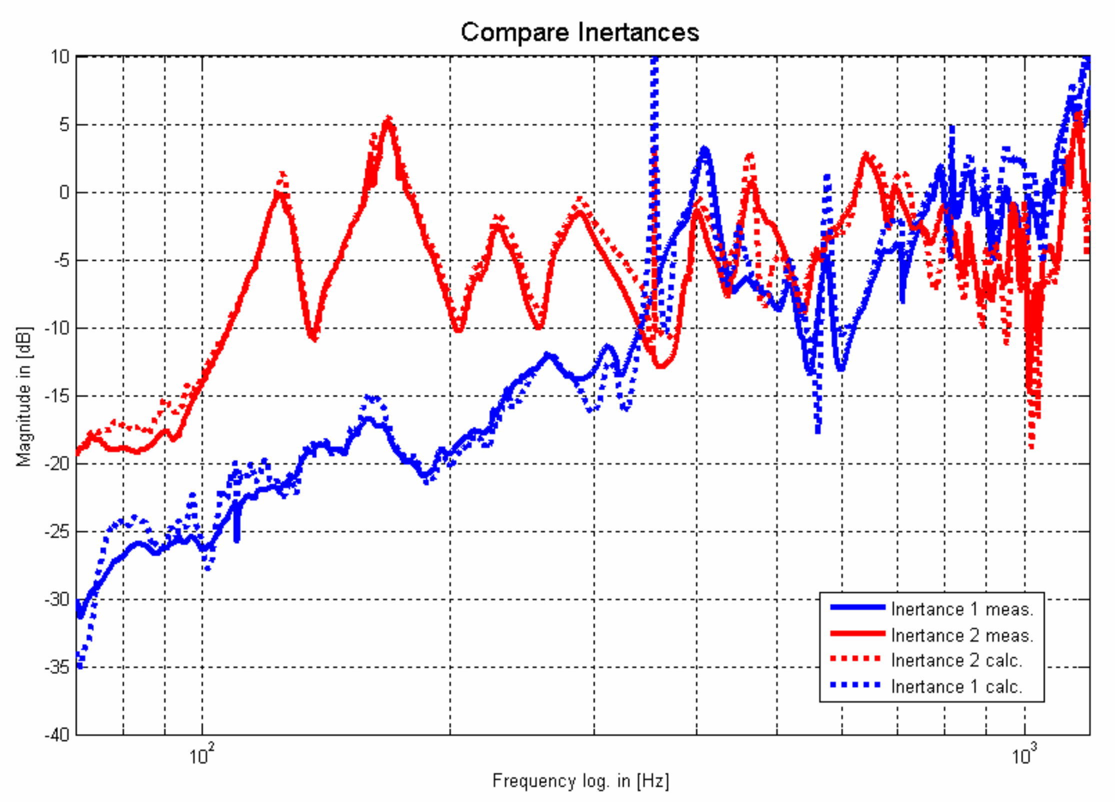

Figure 14: Comparison between measured and calculated inertances.

4.2.9 Force Verification

In order to quantify the overall influence of deviations between measured and calculated inertances on force calculation, the full inertance matrix method was used to compute forces induced by the shakers in operational condition.

For verification Campbell plots of the force measured in operational condition and the force computed by a full matrix TPA using inertances calculated by TPA FORM are compared in Figure 15. As can be seen, both diagrams show a very good agreement.

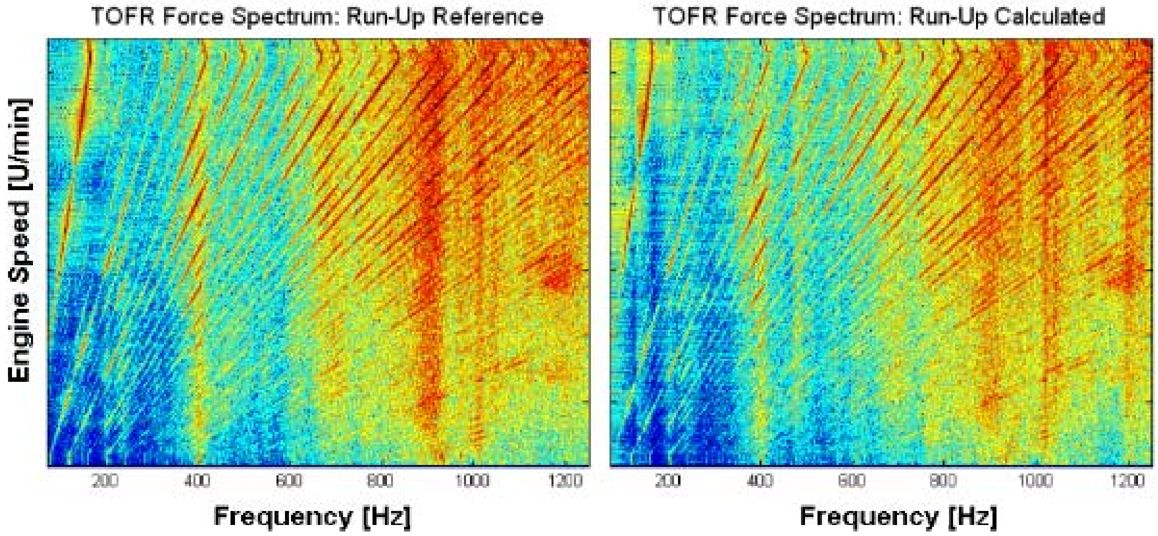

Figure 15: Comparison between measured forces and forces computing by using a full matrix method holding inertances calculated by TPA FORM.

5 Summary

In this paper errors of commercially available TPA tools have been presented. In a detailed analysis containing a verification measurement possible sources of errors in TPA computations have been categorized and investigated. Additionally the new TPA FORM approach to acquire needed inertances and FRFs was introduced.

The aim of TPA FORM to deliver a fast and accurate computation of forces and contributions in operational condition in the scope of Transfer Path Analysis (TPA) has been achieved. During the verification process it has been shown that TPA FORM are able to reduce the problems in conventional inertance measurement. Therefore the time consuming and error-prone measurement of inertances can be omitted which substantially reduces the effort for accomplishing a TPA.

6 Acknowledgements

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