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45 Efficient Transfer Path Analysis for Vehicle Sound Engineering*

Werner BIERMAYER (1), Franz BRANDL (1), Robert HOELDRICH (2), Alois SONTACCHI (2),
Stephan BRANDL (3), Hans Herwig PRIEBSCH (3)

ABSTRACT

An interior vehicle noise quality optimization can only be performed in optimizing the NVH of the different vehicle noise sources with the knowledge and / or modification of the chassis transmission paths. The necessary NVH and sound optimization of the different vehicle noise sources is quite straight forward, however the exact evaluation of the chassis airborne and structure vibration transfer characteristics is much more complex.

Most of the benefits and drawbacks of current available transfer path analysis (TPA) procedures have been reported and discussed last year at JSAE (20075399). Based on further findings and the results published in 20075399, in this publication some TPA optimization strategies will be presented, to increase the accuracy and efficiency of TPA procedures.

Key Words: Passenger car, chassis, acoustic, research

1. CURRENT TPA PROCEDURES

As current commercial TPA software tools apply different approaches, it is not obvious which method yields the most precise results [1]. Additionally the exact procedure of crosstalk recognition within some of the systems is more or less unknown. Beside force based TPA methods acceleration based methodologies are also used [2].

For the calculation of sound source contributions on the interior target microphones, TPA methods depend on measured data as well as on mathematical analyzing techniques. Therefore inaccuracies in TPA can be related to one of these two categories – see Figure 1.

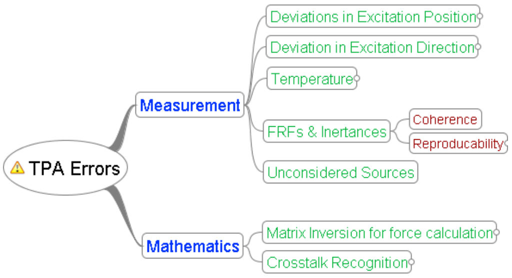

Figure 1: Overview of possible inaccuracies occurring in TPA procedures

2. EXPERIMENTAL INACCURACIES IN CURRENT TPA PROCEDURES

Depending on the applied methodology **errors from excitation position** caused by measured data can mainly originate from the definition of excitation positions, deviations in excitation direction and different chassis temperatures.

To analyze the effects of deviations in excitation position a substantial sensitivity analysis was performed. As one example two Force Response Functions (FRFs) from adjacent excitation positions (distance 35 mm) at one engine mount to the same target microphone are plotted in Figure 2.

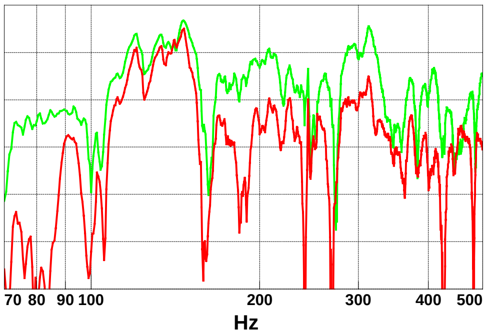

Figure 2: Comparison of FRFs measured in 35 mm distance at one engine mount

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1) AVL List GmbH, Hans-List-Platz 1, 8020 Graz, Austria

2) IEM Institute of Electronic Music and Acoustics, Inffeldgasse 10/3, 8010 Graz, Austria

3) ACC Acoustic Competence Centre, Inffeldgasse 25, 8010 Graz, Austria

It can be seen that for this example errors up to 10 dB can be caused by small deviations in excitation position.

Beside deviations in excitation positions **errors from excitation directions** of up to 10 dB are also based on variances in excitation direction as reported in [1].

Errors from different temperatures are due to the fact that, 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 FRFs and inertance measurements on the one hand and the operational measurements on the other hand will occur. In Figure 3 a comparison for one measured FRF in cold (20°C, blue line) and warm (60°C, red line) condition is displayed. It can be seen that discrepancies up to 5 dB between the warm and cold FRF can occur.

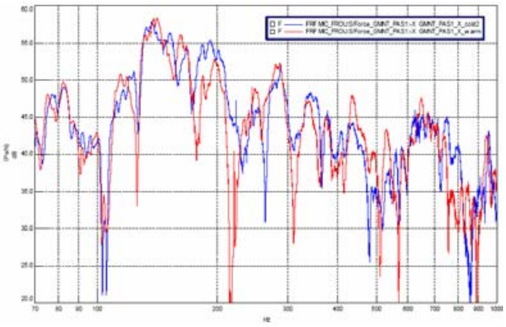

Figure 3: Comparison of FRFs in cold (20°C, blue line) and warm (60°C, red line) condition

Concluding from the presented results deviations in excitation position, excitation direction and differences in temperature can cause substantial deviations in the simulated TPA result. Therefore a development of new methods which avoid or reduce the mentioned deviations caused by measurements would directly improve the quality of TPA results.

3. NUMERIC TPA INACCURACIES

Beside errors caused by deviations within measurement procedures, numerical procedures contribute additional discrepancies between the actual measured and via TPA simulated interior noise.

Two main reasons can be identified for numerical problems. Firstly the recognition of crosstalk between the defined excitations has to be adequately considered otherwise errors of up to 10 dB can occur [1]. Beside the crosstalk recognition an error amplification based on mathematical operations has to be considered. On main problem is the amplification at antiresonances by the inversion of the inertance matrix to obtain the apparent mass matrix. This amplification based on matrix inversion can be at least limited through a condition number [3] of the inertance matrix.

4. IMPROVED TPA METHODOLOGIES

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

In this paper two advancements in TPA are introduced. Firstly the so called mount wise calculation. This is a force based calculation methodology which reduces error amplification while considering essential crosstalk. Secondly the TPA FORM **(F**rom **O**perational and **R**eciprocal **M**easurement) approach. This is a newly developed procedure for determining inertances from operational measurements, using additional reciprocally measured FRFs [4].

Making computed forces and contributions audible was also our prerequisite for an improved TPA. Due to matrix 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 [3] is applied in our approach. For this regularization a white noise signal is utilized, which is dependent on the original signal but some dB lower and shows a smoother spectrum.

Mountwise TPA approach

The more inertances are used for the apparent mass calculation to increase crosstalk recognition, the higher becomes the 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 it is proposed for this approach that only inertances within one mount are used for apparent mass calculation. It can be shown from benchmark data that crosstalk within one mount is in most cases noticeably higher than crosstalk between mounts. As the condition number constraints the error amplification, this decrease in condition number leads to a decrease of error amplification – as can be seen in Fig. 4.

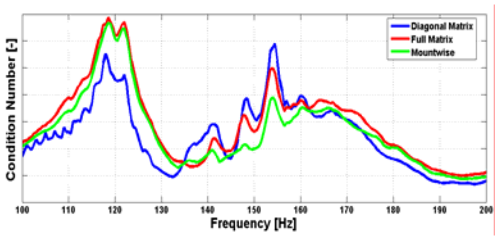

Figure 4. Condition number for diagonal (blue), full (red) and mountwise (green) inertance matrix

TPA From Operational and Reciprocal Measurements → TPA-FORM

Aim of this newly developed method is a fast and more accurate computation of forces and contributions in operational condition without initial inertance determination by shaker or hammer excitation.

As shown before, one of the most time consuming and error-prone tasks is the measurement of inertances and source to target FRFs by artificial excitation [1]. Therefore this new method computes inertances from a measurement in operational condition and reciprocally measured FRFs. [4]

These calculated inertances are then used to determine applied forces in operational conditions. Using finally these forces allows a more precise evaluation and identification of the contributions of corresponding sources on the target microphones. While the time saving aspect of this new method is obvious, the increase in result quality has to be described in detail.

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 as to use a shaker or an impact hammer to excite at these positions. Furthermore the error based on temperature differences will be drastically reduced by the reciprocal measurement if it is accomplished directly after the operational measurement.

Beyond other acceleration based methodologies this computation of forces and their contributions is able to consider crosstalk phenomena which seems not to be provided by currently available commercial acceleration based TPA tools.

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

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 ptot at the target microphones. Therefore in the further description only structureborne sound pressure p_{SB} will be used.

$$p_{tot} = p_{SB} + p_{AB} \qquad \textbf{Equation 1}$$

p_{tot} …Total sound pressure
p_{SB} …Structureborne contribution on total sound pressure
p_{AB} …Airborne contributionon 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 Equation 2.

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


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

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

i…Target microphone position
f…Considered frequency
$t_1 \ldots t_m$…Considered timeslots **Equation 2**
$a_1 \ldots a_n$…Considered accelerations
$S(i,j,f)$…Acceleration to pressure sensitivity for target microphone i and acceleration j for frequency f

For a defined number of timeslots during engine run up sound pressure and acceleration spectra are calculated from time data. FRFs and inertances are assumed to be constant for different operation 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 (FRFs from operational measurement) - step 1.

Based on the reciprocity principle, reciprocally measured FRFs and FRFs in operational condition are equal. For determination of the inertances - step 2 - reciprocally measured FRFs are compared to FRFs computed from the operational measurement.

$$\frac{a_{rec}}{Q_{i\,rec}}(f) \equiv \frac{p_{i_{op}}}{a_{op}}(f) \cdot \frac{a_{op}}{F_{op}}(f) \qquad \textbf{Equation 3}$$

a_{rec} … Acceleration in reciprocal measurement in direction of F_{op}
$Q_{i\,rec}$ … Volume acceleration in reciprocal measurement at target microphone i
$p_{i_{op}}$ … SPL at microphone i in operational condition
a_{op} … Acceleration in operational condition
F_{op} … Vector of applied forces in operational measurement

As described above the FRFs in operational condition can be computed by utilizing the acceleration to sound pressure sensitivities determined in step 1. As the inertances are the only unknown in this system of equations, they can be computed by utilizing appropriate mathematical methods. [4]

Having determined the inertances from operational measurements and from reciprocally measured FRFs, the required forces and source ontributions which yield the overall interior noise level in operational condition can be obtained. To obtain here also the actual forces with an acceleration based method is another big benefit of our approach.

5. TPA - FORM VERIFICATION

In order to proof the theoretical concept of TPA FORM a verification result is here presented. To design a model allowing a theoretical verification of the method, care has to been taken in eliminating measurement based errors. Therefore measured inertances and reciprocally measured FRFs of a passenger car have been taken and were used to compute synthetic "operational" data. Needed accelerations and sound pressures in operational condition are computed by applying artificial forces on the given inertances and FRFs.

To verify the TPA FORM method these computed accelerations and sound pressures in "operational" condition as well as the given FRFs were used as input data. Benefit of this procedure is the exact knowledge of the result, namely the inertances used to compute the "operational" data. This approach therefore allows a verification of the theoretical framework of TPA FORM. Such a result is shown in Figure 5.

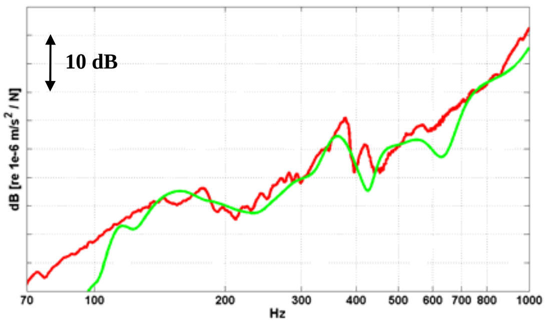

Figure 5. Comparison of pre-defined (red), and calculated (green) inertances

As can be seen, the differences between calculated and pre-defined inertances are smaller than 5 dB which proves that the theoretical framework of TPA FORM can be used for the set up of an efficient and accurate vehicle TPA procedure.

6. CONCLUSIONS

It has been shown, that a number of inaccuracies can occur by applying a TPA. Additionally it has been shown that these numerical as well as measurement based deviations can cause differences between simulated and measured source contributions to interior noise of more than 10 dB. Therefore, two further optimized methods have been developed in order to open new ways for more accurate and time saving analysis procedures. Especially the TPA FORM approach has high potential to fulfil these requirements.

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8. REFERENCES

[1] W. Biermayer, F. Brandl, R. Höldrich, A. Sontacci, S. Brandl, W. Fliesser: Sound Engineering based on Source Contributions and Transfer Path Results. JSAE Paper 318 / 20075399, 2007

[2] Kousuke Noumura, Junji Yoshida; "Method of Transfer Path Analysis for Interior Vehicle Sound by Actual Measurement"; 2006

[3] H. R. Schwarz; „Numerische Mathematik“; Teubner-Verlag, 2004

[4] AVL Patentapplication: No. 55625 ”TPA FORM“