Methods for Transfer Path Analysis

Stichling, Thomas[1], Quickert, Martin[1], Foken, Wolfgang[2]
[1] *Fraunhofer Institute for Machine Tools and Forming Technology IWU, 01187 Dresden, Germany, Email: thomas.stichling@iwu.fraunhofer.de, martin.quickert@iwu.fraunhofer.de*
[2] *West Saxon University of Applied Sciences, 08056 Zwickau, Germany, Email: wolfgang.foken@fh-zwickau.de*

Abstract

Transfer path analysis (TPA) is a well known technique to evaluate and to separate the different transfer paths describing how noise gets from the sources into the compartment of a passenger car, i.e. to the driver's ear. It is not only a measurement technique but a prediction method as well. Based on previous measurements and assumptions TPA provides the opportunity to predict the interior sound for a virtual prototype. Due to the progress in computational technology and measurement techniques, TPA is being seen as an important tool in automotive acoustic design. The paper gives a brief survey of the mathematical background of different TPA methods like the complex stiffness method or the inertance matrix method. With the help of a 3:1 scaled simplified car model differences between the methods of calculation are verified and discussed. In conclusion the paper presents the measurement setup for a real car with a dominating transfer path of the structure borne engine noise into the passenger compartment.

Introduction

A research project was launched in joint efforts between the Fraunhofer Institute for Machine Tools and Forming Technology and the West Saxon University of Applied Sciences to compare common methods of transfer path analysis. The first step in this project was to carry out tests on a clearly structured model and the second step was making measurements on a real car. This was initially limited to the methods of one commercial manufacturer.

Methods of Transfer Path Analysis

Since transfer path analysis was developed, a whole series of methods have emerged to meet the various measuring tasks carrying out TPA. In classical cases, these tasks can be divided up into measuring frequency response functions and calculating the forces [3]. Unfortunately, it is not always possible to divide them up in this fashion with a series of more recent methods such as operational TPA

Force often has to be measured indirectly since it is not always possible to directly measure force in real-life situations. The foremost methods are the complex stiffness method and inertance matrix method. Both of these methods take advantage of indicators such as acceleration or displacements to draw conclusions on the forces exerted.

The complex stiffness method makes it possible to calculate the bearing force by multiplying the bearing's deformation with its stiffness (1). The first prerequisite here is the existence of flexible bearings in the transfer paths [1] and a knowledge of its stiffness. If the force is known, the stiffness can be calculated in the simplest case by measuring the deformation path of the bearings and normalize it to the force applied.

$$F = k \cdot (x_{act} - x_{pas}) \qquad (1)$$

This is a problem in real-life situations since stiffness has to be calculated in all translational degrees of freedom which requires a relative extensive test stand. Furthermore, it is necessary to replicate the pretension of the bearings on the test stand. This is made possible with additional weights for static cases, although this is very difficult to create for dynamic tension (such as with changes in torque).

A second method of calculating operating forces is the inertance matrix method (or matrix inversion method) which is premised upon calculating the force exerted on the bearing by multiplying the apparent mass of the car body by the acceleration in operation (2).

$$\begin{bmatrix} F_{op,1} \\ \vdots \\ F_{op,m} \end{bmatrix} = \begin{bmatrix} \dfrac{a_{art,1}}{F_{art,1}} & \cdots & \dfrac{a_{art,1}}{F_{art,m}} \\ \vdots & \ddots & \vdots \\ \dfrac{a_{art,n}}{F_{art,1}} & \cdots & \dfrac{a_{art,n}}{F_{art,m}} \end{bmatrix}^{-1} \cdot \begin{bmatrix} a_{op,1} \\ \vdots \\ a_{op,n} \end{bmatrix} \qquad (2)$$

The difficulty with this method is the calculation of the apparent mass. This is done by measuring the initial inertance of the car body and inverting the matrix it produces. This is the difficulty with this method since the quality of the results greatly depends on the fault intensification of the inverted matrix [4]. This is also why the available software applications apply the common methods of numerical mathematics (overdetermination, singular value decomposition and principal component analysis) to lower the condition of the matrix.

A defined force has to be brought into the structure to be examined to directly determine the transfer functions from the force application points to the recipient. This is normally done with an impulse hammer or shaker where the key factor for the quality of the measurement is the direction and position of the force applied. There is a dispute as to whether it is necessary to remove the engine for this test to prevent crosstalk from other coupled points.

Another option for determining FRF is inverse measurement where a volume velocity source is set up at the recipient point and the resulting acceleration is measured at the force application points. The transfer functions measured in this fashion should be identical with those directly measured if the object under investigation is a linear system. Since all transfer functions can be calculated with one single measurement, this method is much more efficient than the direct method in terms of time.

Description of the Model

An object of study was needed that was as simple and clearly structured as possible to be able to observe these methods under practical conditions. The West Saxon University of Applied Sciences in Zwickau joined forces with the Fraunhofer Institute for Machine Tools and Forming Technology to design the demonstration model shown in Figure 1 because it has the design elements typical of TPA, including an electrical motor and a flyweight for replicating the mass forces of an internal combustion engine, flexible engine bearings and a closed space for replicating the passenger compartment. The model's geometry follows that of a car on an approximate scale of 1:3.

Carrying out the Test and Findings

A triaxial accelerometer was mounted on the active and passive sides of each bearing point to be able to capture the measuring data needed for the test. A ½" microphone in the passenger compartment was used as the recipient point.

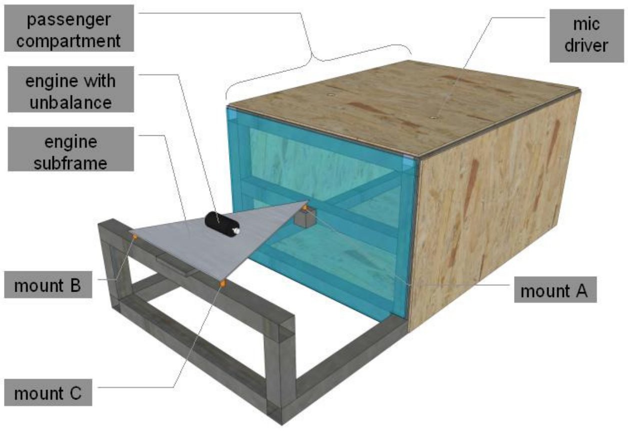

Figure 1: *The graph of the model's simulation*

A controlled power supply unit and optical tacho-sensor make it possible to carry out a run-up providing the speed information. The space situation in the model makes it possible to measure transfer functions directly.

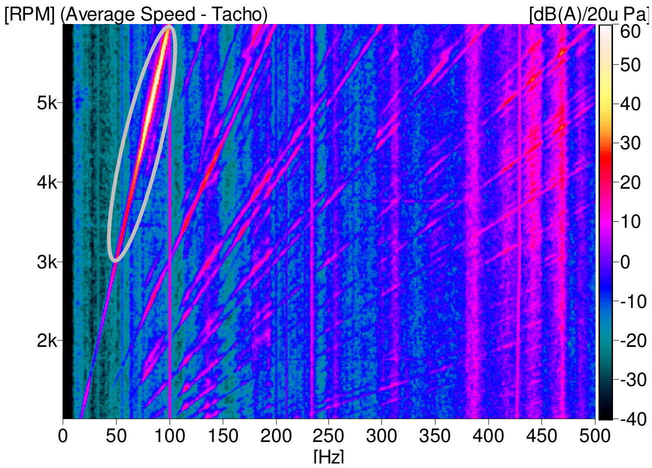

Figure 2: *The range of inside noise*

The forces caused by the unbalanced state appear dominantly in the contour plot as the engine's first order (Figure 2). This is the reason why the subsequent tests will be restricted to the first-order.

Figure 3 shows the first-order synthesized sound pressure for various methods of calculating force in comparison to the sound pressure measured. A significant deviation becomes apparent using the complex stiffness method because it was only possible to calculate the bearing stiffness for one coordinate direction. Simultaneously, this shows how important the other directions are. An operation deflecting shape test on the model indicated that there is not only strong excitation in the z-direction, but also in the x-direction. In contrast, the findings of the inertance matrix method map a good approximation of the actual noise.

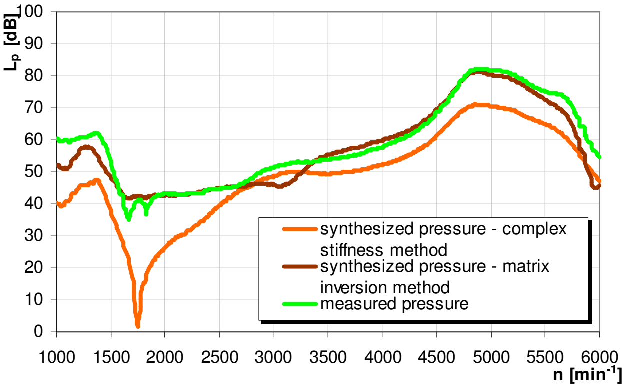

Figure 3: *Synthesized acoustic pressure in the passenger compartment using different methods to calculate forces as a first-order intersection.*

The number of inertances included in the inversion has a crucial impact on the precision of findings with the inertance matrix method. Figure 4 indicates that the synthesis is better the more inertances are included in the inversion. However, this normally also increases the condition number of the matrix because especially cross inertances between the various bearings are usually very small making the signal-to-noise ratio small as well.

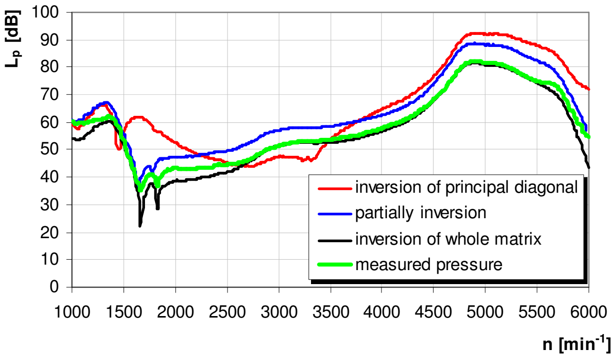

Figure 4: *Synthesized acoustic pressure in the passenger compartment using a wide range of different elements in matrix inversion and as a first-order intersection*

As previously mentioned, the decision whether the engine should stay installed for the measurement or whether it should be removed has an impact of the precision of findings. We tried both for the demonstration model test and the findings are shown in Figure 5.

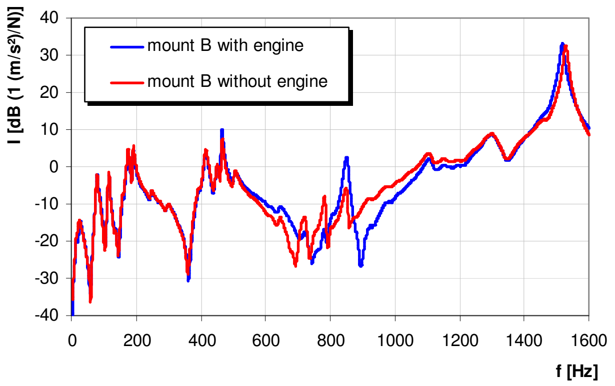

Figure 5: *Inertance on bearing point B in the z-direction with the engine installed and removed*

Other Phases of This Project

The second step of this project extended measuring the test object to a car using a Wartburg 311 from the historical car collection at the West Saxon University of Applied Sciences. We used the inertance matrix method to calculate operating forces because it was not possible to remove the engine from this historical automobile to measure the engine bearings. The inertances and transfer functions were simultaneously measured. Then, the operating measurements needed were made on a dynamometer of the West Saxon University of Applied Sciences.

Figure 6 shows the transfer paths measured with this car while Figure 7 shows the contributions made by the specific transfer paths to the third-order total synthesized noise. The dominant influence of the rear exhaust bearing can be clearly seen which is due to a special type of design for this car. The Wartburg does not have a self-supporting car body. Instead, it has a ladder frame with coupling elements for linking both to the drive train and the car body. That means that there are two flexible bearings in each transfer path (with the exception of the path over the rear exhaust bearing) which is fastened directly to the sheet-metal of the floor of the trunk. The tests shown in [2] also arrive at these findings on this car.

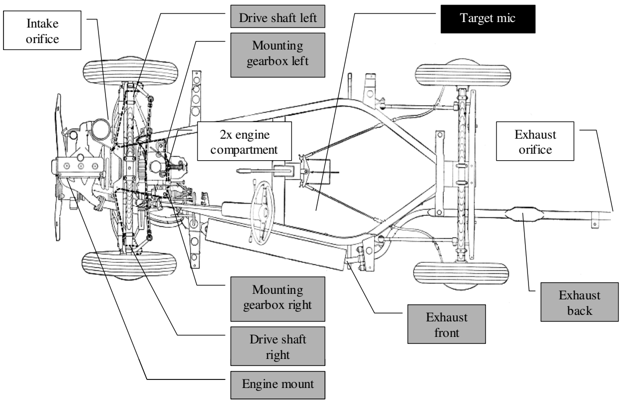

Figure 6: *The measured transfer paths on the Wartburg 311*

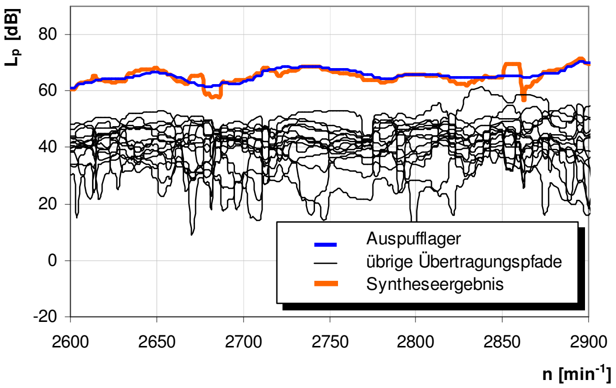

Figure 7: *Components of the paths of the third-order total noise*

This comparative study will be extended beyond measuring the car and this project is supported by various manufacturers of commercial TPA solutions. It will also be continued in two phases: first of all, measuring the model and then the actual car. This will require some revisions to the model for improving the applicability of methods for characterizing airborne noise and allowing studies on the findings of methods on the disturbance from other sources adding a number of other sources to the model.

A shaker was applied to the frame structure as one of the new sources. It can be operated with as many excitation signals as desired, which means that it is a source of structure-borne noise independent the engine. The idea is to show how reliably the components of the engine's structure-borne noise are identified if there are other sources of disturbances from structure-borne noise. This is a major benefit of the demonstration model since it is not possible to make one measurement of structure-borne noise on the actual object under study. The second of the two new sources is a loudspeaker that works in correlation to the engine's structure-borne noise. The loudspeaker's range has spread a wide ordering fan that contains the whole-number engine orders.

Summary

The demonstration model developed for this project features a wide range of possibilities for applying the various methods in real-life practice so that it is useful for studying basic questions and carrying out comparative analyses between the specific methods. This will be high on the agenda of further project application and proven in a second project phase with measuring cars for detecting various forces.

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