Road induced interior noise:

use of OTPA to determine tire contribution and vehicle sensitivity

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Abstract: Customers' expectations concerning noise and comfort inside a vehicle are getting higher, as an image of the quality of the vehicle. Because of optimization of engine noise during the past years, the contribution of road noise to interior noise has increased. The road noise performance is mainly due to the vibrations coming from the wheels and going inside the car through the frame. Thus, it depends on the good coupling between the tire and the vehicle, to avoid bad filtering or mode resonance.

The OTPA (Operational Transfer Path Analysis) is a powerful tool to investigate quickly the sound inside the cabin of the vehicle, and to determine the contributions of the main sources of it. Then it is possible to find the link between a disturbance inside the cabin and its origin.

One of the usage of this tool for Michelin is to investigate specific claims of customers concerning the interior noise of the car. For road noise, it makes it possible to find the wheel responsible for the disturbance, and to separate the input (wheel accelerations) from the path (car transmissibility). The cause of the sound can be determined: high source level from the wheel, or low filtering from the car on the specific disturbance. An example of study showing how the method is implemented in the case of road noise is presented.

Keywords: Road noise, Operational Transfer Path Analysis

1. Introduction

Interior noise is an important concern for car makers today. The level of expectation has increased in this domain and there is a strong necessity to be able to understand efficiently the origin of the noise phenomenon. Below 500Hz, where the noise level is the highest, an important part of it is *road noise*, due to vibrations generated in the tire/road contact patch and propagating into the car through its structure (we talk about structure-borne noise). Thus, the coupling between the tire and the vehicle is crucial as it may lead to bad filtering and mode resonance amplification. In order to improve the understanding of these phenomena and to find the appropriate solution to a specific noise issue, the tire manufacturer needs first to know for a specific noise peak if it is related to tire mode, vehicle mode or both. Then, it is useful to understand more precisely the principal contributors to noise. For example, identify if the noise in a specific frequency range is more linked to engine, or front axle, rear axle, and also the main vibration direction of this source.

Some methods of TPA analysis are already well known in the automotive industry, but OTPA method presents the advantages to be relatively quick to implement and to deliver information on the system in operational condition.

In this paper we will present the principle of the method and examples of application on road noise studies.

2. Why do we perform OTPA

In a physical system where several components are involved and interacting with each other, active components are typically considered as sources. These sources generate operational excitations into the system, leading to some response phenomena at some point(s) of interest, usually called receiver(s). If independent relationships between multiple sources and the receiver(s) exist, a direct measurement and analysis of the operational excitations, the transfer characteristics of the energy through the system and the operational contributions of each source to the receiver(s) are straight-forward. As described in Figure 1, independent relationships and operational data then allow to describe the system in its real operational conditions, to account for the amplitude and phase modifications induced during the energy transfer and analyze the excitation and contribution signals in the time domain with a broad variety of tools (ranking of contributions, frequency and order analysis, psychoacoustics, audio playback of individual contributions…).

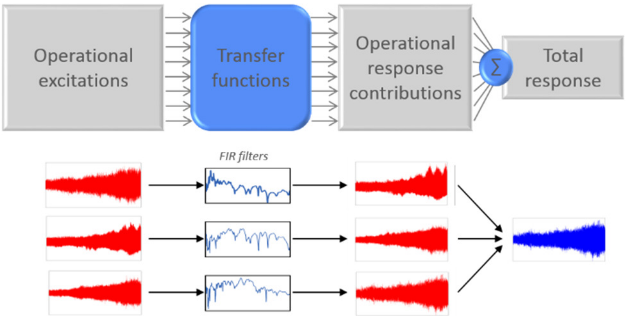

Figure 1: Independent relationships between multiple sources and receiver(s) in a simple system, allowing a direct measurement and analysis of each subcomponent independently

However, most of the physical systems are complex and the same applies to a vehicle (see Figure 2). Sources are known but often correlated, and the energy transfer is complex with a strong cross-coupling between the different paths. A direct measurement and analysis approach is not possible. Still, ranking the sources whose operational contributions are responsible for a particular phenomenon is of high interest. Identifying the paths used by the energy would also be very interesting. This is what Operational Transfer Path Analysis – OTPA - is all about.

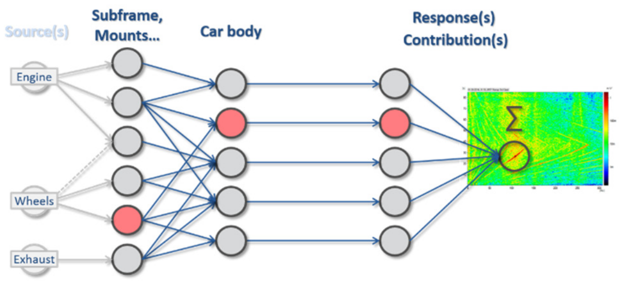

Figure 2: Complex relationships between multiple sources and receiver(s) in a real system such as a vehicle

3. The OTPA principle

Different Transfer Path Analysis approaches have been used in the car industry. The goal of this section is neither to give a complete overview of these approaches nor to compare them, as it has already been done in some papers, such as [1]. Instead we will introduce the main principle of OTPA and briefly relate to the complementary approach of the so-called conventional TPA.

Conventional TPA aims at measuring the forces [N] induced by the sources in the system and identifying the corresponding linear transfer functions [Pa/N]. A general framework is illustrated in Figure 3. Measuring the forces directly requires a high effort (when possible) therefore they are often estimated by indirect measurements, typically by inverting an accelerance matrix. The transfer functions (typically acoustical sensitivities) can be obtained by impact/shaker or reciprocal measurement. Despite the lean approach and the potentially good accuracy, the conventional TPA is often time consuming and does not look at the system in its real operating conditions. Furthermore, the approach considers the structure-borne contributions only, not the airborne contributions.

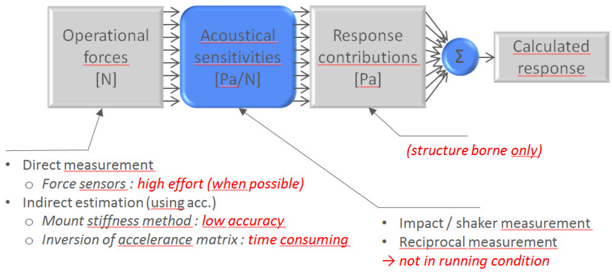

Figure 3: General framework of so-called conventional TPA

As an alternative, or complementary approach, the Operational Transfer Path Analysis – OPTA – uses directly the operational data to describe the sources behavior as well as to identify the so-called transmissibilities of the system. Forces are disregarded while physical quantities such as Sound Pressure, Acceleration, Pressure etc. are preferred and easily acquired by placing sensors close to the sources involved. The signals measured serve both to describe the sources in operation and estimate the transmissibilities.

While conventional TPA uses a matrix inversion to estimate the transfer functions, the OTPA uses a statistical approach to estimate the transmissibilities. A general framework of the Operational TPA is presented in Figure 4. A Singular Value Decomposition – SVD - is applied (Pseudo-Inverse using Principle Component Analysis - PCA) on operational data of all sources acquired synchronously. The observation of many excitations (statistical variations through RunUps, Coastdowns…) allows to quickly extract principle components in the behavior of the system and recompose a set of complex linear transmissibilities (amplitude and phase), later used as FIR filters to compute operation contributions in the time domain. Many papers have described more into details the concept and theory of OTPA such as [1] and [2]. This approach has also been applied to tire noise in [3].

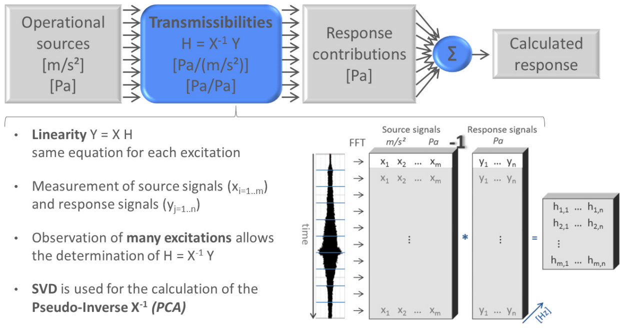

Figure 4: General framework of Operational TPA

The OTPA is based on the strong assumption (similar to many approaches on complex systems) that the system behaves linearly during the operating conditions of interest. At least small variations are smoothed by the SVD yielding to a more precise description of the system, instead of considering a static system standing still and not constrained. Still, it is interesting to notice that a similar set of impact data processed by SVD and matrix inversion give similar results, as shown in [4]. However, the SVD allows in addition (even requires) to overdetermine the matrix to be decomposed through statistic variations, naturally leading to consider the variations observed in operation (see [5]).

As mentioned previously, the sources involved must be known and measured synchronously altogether. The question and the case come if/when a source has not been measured. 3 cases can be faced:

- The source missed has not been measured by any of the sensors: the other transmissibilities are still correct, as well as the contributions calculated. The sum of the individual contributions obtained differs naturally from the original signal measured at the receiver. In other words, the OTPA does not simply divide the total signal in as many parts as there are sources considered. Instead it accurately estimates each individual contribution independently.
- The source missed has been measured by another sensor and has a low contribution: it is easily disregarded by tuning the number of Principle Components used while recomposing of the transmissibilities.
- The source missed has been measured by another sensor describing a second source and has a significant contribution: the contribution estimated for the second source actually accounts for the both sources. For a consistent analysis this case must be carefully considered.

4. OTPA applied to the tire

The purpose of OTPA is to identify the transfer between vibration sources and a response; therefore it is fundamental to define correctly the measurement channels. In our case, the response channels are usually microphones in the vehicle cabin, close to the driver's ear for example. In some cases it can also be an accelerometer at the driver seat to describe the vibration felt by the driver instead of noise. The sources are less obvious to select. The goal is to capture the input of all the sources of noise in the car, while separating them as much as possible. OTPA is not a source identification tool, so we need first to identify relevant sources, usually: the four wheels, the engine, the exhaust system, sometimes the rear drive axle... Each of those sources is recorded with a triaxial accelerometer or in some cases a microphone. We know that we are missing some sources, either because they are not significant, or because they are too complicated to capture properly, as the aerodynamic noise for example, we will come back to this topic later in the document.

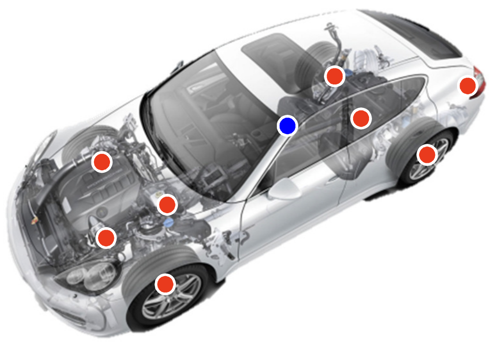

Figure 5: Example of OTPA instrumentation, with in blue a response channel, microphone at driver's ear, and in red the sources, 8 accelerometers for the hubs, engine, gear box and rear drive axle

Concerning the wheels, we can either consider the wheel as one source and use only one sensor per hub, or try to identify the vibration path and put sensors on each link from the hub to the frame. However, it is necessary to be very careful when defining those sensors positions, because if we miss one of the links, the result will be inaccurate (one source will be missing) and if we measure twice the same source (for example one accelerometer on the hub and one on each of the links), the recomposition will be fine but we won't be able to analyse properly the contribution of each link.

Concerning the solicitations, since we drive in some analytic conditions (constant speed and coast down on uniform asphalt), it is necessary to have the spectrum we want to analyse. But we also need some variation in the excitation in order to identify correctly the influence of the different sources and build the transmissibilities. For this reason, we also drive in more normal condition, with acceleration, braking, turn, etc.

5. Example of study analysis

In the first example, we show the impact on the analysis of missing some sources. As we have measured only structure-borne sources, above 400-500Hz when the airborne noise becomes predominant, the recomposed noise signal becomes much lower than the measured noise signal (see Figure 6). This is a positive result because it shows that when we miss a source, the analysis we preform does not simply assign its contribution to the other sources in order to rebuild the complete signal.

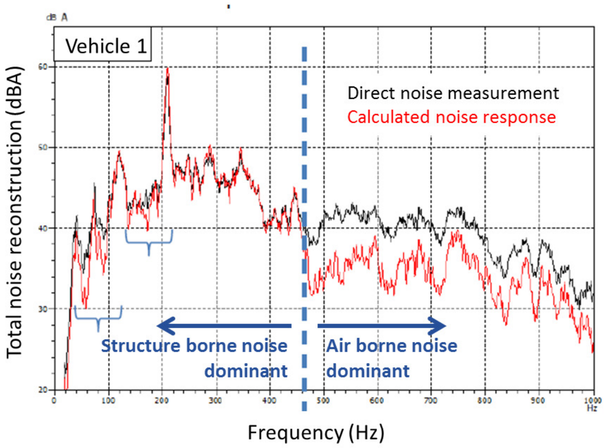

Figure 6: Comparison between measured noise and recalculated noise with OTPA method

In the second example, we use the OTPA to identify the main contributors to noise for each frequency range. This analysis can be very useful for understanding the mechanisms. On the Figure 7, we can see the contribution to the global noise level of the two axles and the rest of the channels (engine, exhaust system…). For the axles contributions we have detailed the X, Y and Z contributions. We can see for example that the first peak is a strong contribution of the engine/exhaust, or that the 200-220Hz resonances are due to front axle only, in X and Z directions, or also that between 300 and 450Hz, the front and rear axle in Z direction are the main contributors.

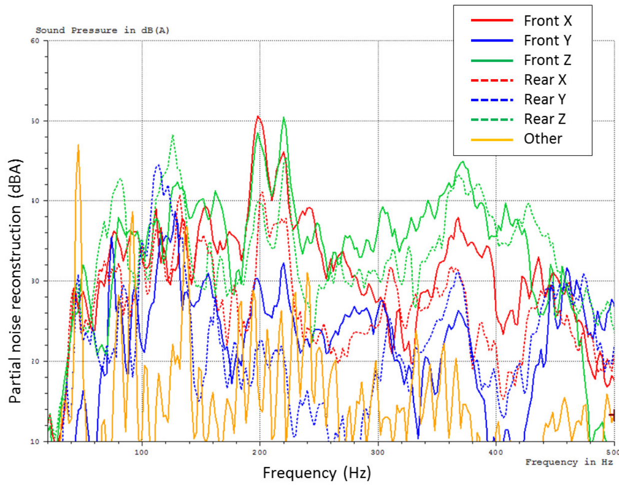

Figure 7: Noise contributions of several channels calculated with OTPA method

Finally, we present how the OTPA method can help identify a vehicle influence for a specific noise issue. In that case, there is a strong noise peak around 150Hz that is not very impacted by tire design effects (Figure 8).

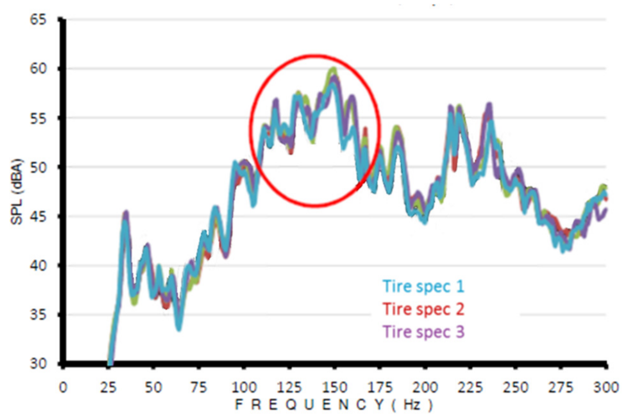

Figure 8: Noise measurement with different tire specifications

We perform OTPA analysis and analyse the results in a driving condition that reveals the 150Hz issue. First we identify looking at noise contributions (Figure 9) that the sources from front axle in Y direction are clearly the main contributors and explain this noise peak.

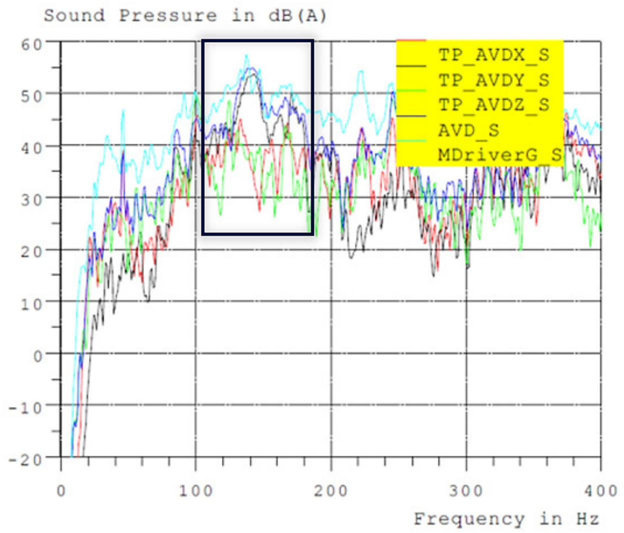

Figure 9: Front axle contributions compared to the global noise level (cyan curve)

Then, looking at the sources level (the accelerations measured at the hub, Figure 10), we observe no specific resonance in the frequency range of interest. But looking at the transmissibility of the front axle (Figure 11), we can see a strong peak around 150Hz, in particular for the Y direction.

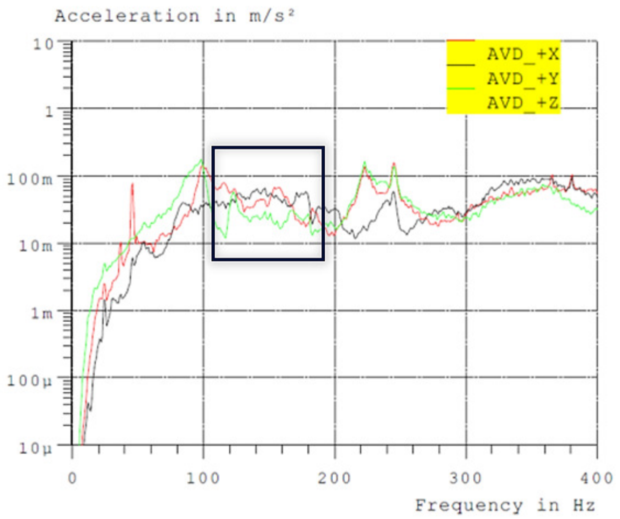

Figure 10: Acceleration measured at the front right hub (X : red curve, Y : black curve, Z : green curve)

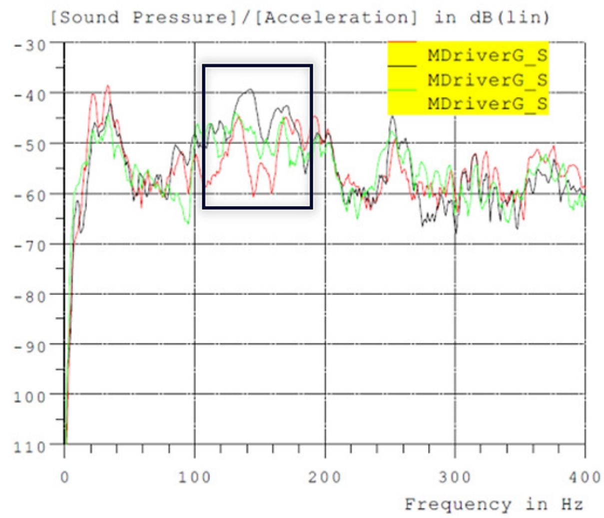

Figure 11: Transmissibilities for front right hub (X : red curve, Y : black curve, Z : green curve)

It seems then that this 150Hz noise is more due to vehicle sensitivity than a tire mode resonance. It explains why the tire modifications brought no change on this noise peak.

6. Conclusion

Operational TPA is a quick approach to draw the vibroacoustic picture of a complex system, including its sensitivities to the sources involved and their contributions in the time domain. Thanks to the SVD, it allows to separate structure borne and airborne contributions, even for (highly) correlated sources. It is particularly appropriate to describe the system in operation, provided all paths of interest are measured simultaneously and energy-to-noise ratio tends to be significant enough. However, the forces and pure transfer functions normalized to the excitation forces are disregarded.

Applied to the vehicle for road induced interior noise concerns, the OTPA allows to perform a quick diagnostic of the origin of noise peaks, it gives interesting information for the understanding of phenomena and to help solving issues. We are able to separate the different sources and even to reveal when we are missing sources as the airborne contribution for example. The main drawbacks are the impossibility to have access to the effort, and also, because of the evaluation in operational condition, the transmissibilities may be sensitive to the tire-wheel assembly. We have seen in particular an effect on transmissibilities if we modify significantly the mass and size of the tire-wheel assembly.

Accuracy could be improved by applying more sensors and/or combining sensors to include the wheel torque as an additional descriptor for each wheel. In the examples of case study analyses, the airborne contributions were not of interest and therefore not taken into account. To enlarge the frequency range, a further step of investigations would be to include the airborne contributions as well. For practical reasons this would most probably be done on a chassis dyno.

7. Acknowledgement

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8. References

[1] Maarten V. van der Seijs, Dennis de Klerk, Daniel J. Rixen: *"General framework for transfer path analysis: History, theory and classification of techniques",* Mechanical Systems and Signal Processing 68-69, August 2015.

[2] Dennis de Klerk, Martin Lohrmann, Martin Quickert, Wolfgang Foken: *"Application of Operational Transfer Path Analysis on a Classic Car",* DAGA, 2009.

[3] D. de Klerk, A. Ossipov: "*Operational transfer path analysis: Theory, guidelines and tire noise application*", Mechanical Systems and Signal Processing 24, October 2010.

[4] Martin Lohrmann, Dr. Thomas Hohenberger: "*Methodenvergleich zur Ermittlung von Übertragungskoeffizienten: Liner/kraftbasiert und mittels Hauptkomponentenanalyse*", DAGA, 2008.

[5] N.B. Roozen, Q. Leclère: "*On the use of artificial excitation in operational transfer path analysis*", Applied Acoustics 74, 2013.

8. Glossary

TPA: Transfer Path Analysis
OTPA: Operational Transfer Path Analysis
SVD: Singular Value Decomposition
PCA: Principle Component Analysis
FIR: Finite Impulse Response