

Tire-Road Noise Analysis of On-Road Measurements under Dynamic Driving Conditions

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ABSTRACT

The powertrain noise of cars has been reduced in the last decades. Therefore in many cases, rolling tires have increasingly become the dominant sources of vehicles' interior noise. For sound design or a reduction of tire-road noise it is important to know the individual noise shares of the tires and their transfer paths. Authentic tire-road noise can only be measured on a real road, not on a roller dynamometer. So far measurements have been performed during a coast-down on the road with the engine switched off, avoiding the influence of engine noise.

Operational Transfer Path Analysis (OTPA) can be used to remove the uncorrelated wind noise, and to synthesize structure-borne and airborne tire-road noise based on input signals measured with microphones at the tires and a triaxial accelerometer at each wheel carrier. Simultaneously, the interior noise is recorded by an artificial head.

Acceleration, deceleration or other driving maneuvers with the engine running can lead to different tire noises. In this case the conventional method cannot be applied because the engine sound is measured at the source (tires) and receiver locations (cabin). This would lead to incorrect OTPA transfer functions and the tire-road noise synthesis would contain unwanted engine sound shares. Thus, a Cross-Talk Cancellation (CTC) must be carried out between the tire and engine sources.

In this paper a new approach is presented allowing for a tire-road noise analysis under dynamic driving conditions. The applied CTC requires additional input signals at the engine.

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INTRODUCTION

The tire-road noise dominates the interior noise of today's cars especially during constant speed with low load on country or urban roads because power train noise has been reduced in the last decades. Under other driving conditions the rolling tires are also an important noise source. Depending on the vehicle class, wind noise has a growing influence predominantly at higher speeds. For further reduction of the interior noise or for sound design the tire-road noise attains an increasing relevance. Therefore, the individual noise shares of the tires and their transfer paths are of major concern. Which axle causes an unpleasant or annoying sound pattern can give an acoustic engineer clues with respect to countermeasures, or it is helpful to know whether airborne or structure-borne sound is implicated.

Authentic tire-road noise cannot be measured on a roller dynamometer. After one revolution of the roll the tire contacts the identical surface. This periodic excitation sounds repetitive and artificial. In addition most acoustically-suited dynamometers are designed for engine tests and have a very

smooth surface which cannot be compared to a real road. For these reasons tire road noise should be measured on a real road. So far the engine has been switched off to avoid its influence during coast-down tests. The interior noise is recorded by an artificial head and source signals are measured with microphones at the tires and a triaxial accelerometer at each wheel carrier. With the measured data the Operational Transfer Path Analysis (OTPA) can be used to synthesize the tire-road noise without the uncorrelated wind noise. Furthermore, the noise shares of structure-borne and airborne sound or of the different tires can be determined.

In comparison to a coast-down, other driving maneuvers such as acceleration and deceleration with the engine running can lead to a different tire-road noise because of varying torque acting on the tires in comparison to a coast-down. In this case the conventional method cannot be applied because the engine sound is measured at the sources (tires) and as well at the receiver locations (cabin). This crosstalk between tire and engine sources needs to be cancelled. Otherwise OTPA transfer functions would be wrong and the tire-road

noise synthesis would contain unwanted engine sound shares. This paper presents a new approach for tire-road noise analysis under dynamic driving conditions with a Cross-Talk Cancellation (CTC). First, the necessary measurement setup and OTPA is described. Then CTC, which eliminates the influence of the engine, is explained. Examples show the need for CTC, and the results of dynamic driving conditions are compared to a coast-down.

OPERATIONAL TRANSFER PATH ANALYSIS

In general, transfer functions of a **Multiple-Input-Multiple-Output (MIMO)** model as shown in Figure 1 can be determined by Operational Transfer Path Analysis (OTPA) [1,2,3,4]. That means the transfer functions are not derived explicitly in additional measurements but are estimated from operational data of the simultaneously measured input signals $x_j(t)$ and output signals $y_i(t)$. In comparison to a conventional TPA this requires less time and effort, and is well suited to the synthesis of uncorrelated sources [1].

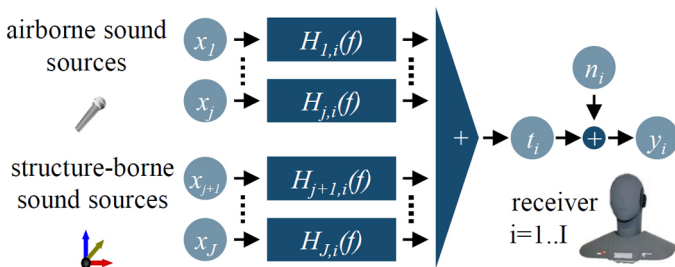


Figure 1. Multiple-Input-Multiple-Output (MIMO) model for Operational Transfer Path Analysis (OTPA)

The recorded time signals are divided into overlapping blocks, multiplied with an analysis window (typically a Hann window) and then transformed to $X_j(f,m)$, $j=1..J$, and $Y_i(f,m)$, $i=1..I$, using the **Fast Fourier Transform (FFT)** with frequency index f and block index $m=1..M$. The matrix notation allows a short and elegant description. For every frequency f the input quantities are combined to the matrix $\mathbf{X}(f)$ containing the values for all input sensors and all blocks.

$$\mathbf{X}(f) = \begin{pmatrix} X_1(f,1) & \cdots & X_1(f,M) \\ \vdots & \ddots & \vdots \\ X_J(f,1) & \cdots & X_J(f,M) \end{pmatrix} \quad (1)$$

For each receiver signal the values are arranged as a row vector.

$$\mathbf{Y}_i(f) = (Y_i(f,1) \quad \cdots \quad Y_i(f,M)) \quad (2)$$

The transfer functions $H_{j,i}(f)$ from input j to output i are also arranged as a row vector.

$$\mathbf{H}_i(f) = (H_{1,i}(f) \quad \cdots \quad H_{J,i}(f)) \quad (3)$$

The measured receiver signal consists of two parts: $t_i(t)$ is correlated and $n_i(t)$ is uncorrelated to the input signals. The first part is transmitted from the considered sources via their transfer paths to the receiver and the second part has its origin in other uncorrelated sources or disturbing noise.

$$\mathbf{Y}_i(f) = \mathbf{T}_i(f) + \mathbf{N}_i(f) \quad (4)$$

The part which is correlated to the input signals can be synthesized by the sum of the filtered input signals. Filtering with the impulse response is equivalent to a multiplication with the transfer function in the frequency domain. This can be expressed for every frequency by the following system of equations.

$$\mathbf{Y}_i(f) = \mathbf{H}_i(f) \cdot \mathbf{X}(f) + \mathbf{N}_i(f) \quad (5)$$

The number of blocks M needed to solve this system of equations is at least equal to the number of input signals. In the case of an over-determined system the solution is found using the pseudo-inverse [5].

$$\mathbf{H}_i(f) = \mathbf{Y}_i(f) \cdot \mathbf{X}(f)^+ \quad (6)$$

Eq. (6) is the best solution in the least-square sense

$$\min \|\mathbf{Y}_i(f) - \mathbf{H}_i(f) \cdot \mathbf{X}(f)\|_2 \quad (7)$$

OTPA determinates the transfer functions in such a way that the deviation between receiver measurement and synthesis is as small as possible (in the least-square sense). Because $x_j(t)$ and $n_i(t)$ are uncorrelated there is no linear dependence between $\mathbf{X}$ and $\mathbf{N}_i$. With a sufficient number of blocks the influence of $n_i(t)$ is reduced due to averaging. The sum of the filtered input signals is the synthesis

$$\hat{t}_i^{OPA}(t) = \sum_j h_{j,i}(t) * x_j(t), \quad (8)$$

where $h_{j,i}(t)$ is the corresponding impulse response to $H_{j,i}(f)$. The difference between the measured receiver signal and OTPA synthesis is the residual, which is the uncorrelated part in relation to the input signals.

$$\hat{n}_i^{OPA}(t) = y_i(t) - \hat{t}_i^{OPA}(t) \quad (9)$$

MEASUREMENT SETUP

The contact between the tires and the road is the cause of the tire-road noise. At these source positions the airborne sound radiation is measured with two or three microphones at each tire. Typically they are positioned at the in- and outlet of the tire; a third microphone can be mounted in the wheelhouse above the tire. For the structure-borne sound a three-dimensional acceleration sensor is applied at each wheel carrier. An artificial head is placed on the front passenger's seat recording the interior noise or the driver could wear a binaural headset. If the engine is switched off during a coast-down this setup is completed. Under dynamic driving conditions with engine running, additional signals are needed for CTC between engine and tire-road noise. Vibrations are measured on the engine close to the mounts, and microphones positioned at each side of the engine, exhaust and intake record its airborne sound radiation.

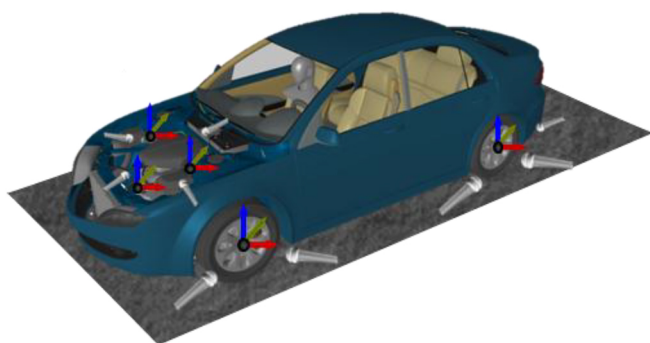


Figure 2. Measurement setup for tire-road noise analysis under dynamic driving conditions

TIRE-ROAD NOISE ANALYSIS OF A COAST-DOWN

Operational Transfer Path Analysis is well suited for tire-road noise analysis of a coast-down without engine running [4, 6, 7]. The aforementioned sensors at the tires measure the input signals and the artificial head the output signals of the OTPA model in Figure 1. The transfer functions are estimated from the coast-down and the tire noise can be synthesized with Eq. 8. In this case the residual in Eq. 9 is the wind noise which is uncorrelated to the tire-road noise because of the different mechanism of generation. Therefore, this approach separates the interior noise into tire-road and wind noise. Furthermore, it is possible to calculate structure-borne or airborne sound shares by filtering and summing only the acceleration and the microphone signals respectively. The contribution of front or rear axle or of each tire can be synthesized by considering only the related transfer paths. Details can be found in [4].

CROSS-TALK CANCELLATION

If the tire-road noise should be analyzed under dynamic driving maneuvers like acceleration under full load, the engine is inevitably a further source of the interior noise. In principle, it does not matter that there is an additional source besides the air flow around the car, as long as it is uncorrelated to the tire-road excitations. It is obvious that this is valid for the engine and in this case $n_i(t)$ in Eq. 9 would consist of both wind and engine noise. Nonetheless, the tire-road noise could still be calculated. The problem is that the engine affects not only the receiver but also the input signals. The engine running causes vibrations at the wheel carriers, and its airborne sound radiation is also measured with the tire microphones. Then it is no longer possible to measure “pure” input signals consisting only of tire-road excitations. There is crosstalk between the sources engine and tires. This leads to incorrect OTPA transfer functions and the tire-road noise synthesis would contain parts of the engine sound because the filtered input signals contain engine noise shares. This is unavoidable even if a second vehicle is pulling the car. This would lead to different load conditions and the noise of the additional car would disturb input and receiver signals. Hence, a CTC must be carried out to remove the influence of the engine on the tire input signals and on the receiver (Figure 3). The second step is an OTPA based on these new input and output signals. Then the tire-road noise can be calculated equivalent to the case of a coast-down without running engine as mentioned before, but correctly including important tire noise behavior due to tire torque loads from the powertrain, etc.

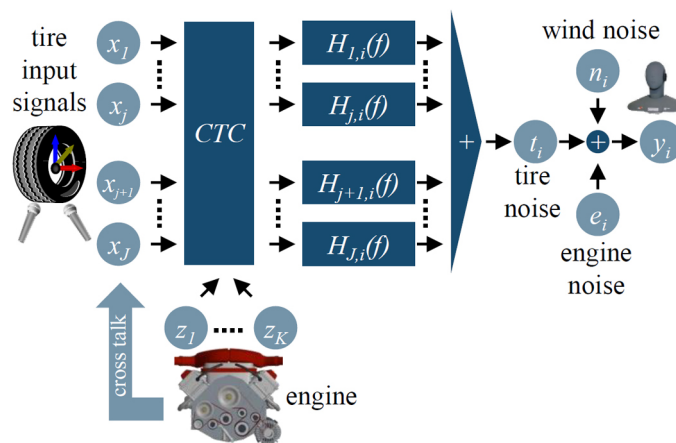


Figure 3. Model of tire-road noise analysis with Cross-Talk Cancellation (CTC) of engine noise under dynamic driving maneuvers

Although it is impossible to measure tire-road excitations alone, signals characterizing the engine can be recorded separately. In opposition to the engine microphones, the accelerations found on the engine are not significantly affected by tire-road contact due to the isolation of soft