Benefits of operational transfer path analysis for sound engineering of rail-bound vehicles

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ABSTRACT
The operational transfer path analysis is used when the quantitative ranking of contributions from different sources and transfer paths to sound or vibration response needs to be known. Depending on the positions of the reference sensors a source contribution analysis, link/interface contribution analysis or panel contribution analysis can be performed. Based on the investigation of the noise inside a high-speed train during tunnel passage on slab track the possibilities are explained and illustrated. The performed analysis clearly shows that the increase of the interior noise in tunnels is caused by higher contributions from the upper sides and the roof. Based on these results a target-orientated optimization process can be initiated.

Keywords: OTPA, sound transmission, high-speed train

1. INTRODUCTION
Target-orientated sound engineering requires a detailed understanding of the sound transmission from the sound sources into the vehicle interior. From a sound engineering perspective it is not only the contributions of each sound source that are of interest but also the contributions of each link to the car-body and, moreover, the contribution of each panel inside the train. Especially the latter is of high interest for the car manufacturer due to the fact that the implementation of design changes is much easier for these components than it would be for other components with their variety of crucial requirements.

The operational transfer path analysis is used when the quantitative ranking of contributions from different sources and transfer paths to sound or vibration response needs to be known. It is mainly used in the automotive industry (1, 2, 3). As for this technique only operational data of the complete product is necessary, it is a very convenient technique for rail-bound vehicles (4, 5, 6), because tests can only be performed on normal tracks or, at best, on a railway test circuit, where – due to safety reasons – no mechanical alternations of the vehicle are possible.

Depending on the positions of the reference sensors different analyses can be performed by means of the operational transfer path analysis. The possibilities will be explained and illustrated with an example at a high-speed train in tunnels on slab track.

2. Operational transfer path analysis (OTPA) as a multidimensional tool

2.1 Background
The basic idea of the traditional TPA is the separation of the vibro-acoustic system into sources and transfer paths. In the traditional TPA the operational force is chosen to quantify the sources.

The approach of the OTPA uses the vibro-acoustic quantities \( x \) like acceleration (at the mounting points) and sound pressure (near the sound source) in contrast to force (and volume velocity) to characterize the sound sources. The sound pressure synthesis \( p_{\text{syn}} \) is the sum of all contributions \( j \):

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The challenge of this approach lies in the fact that the acceleration at one (reference) point is not only generated by the force acting at this reference point, but also by other reference points nearby. This phenomenon is called “cross-talk”. Therefore, the transfer functions $H_j$ cannot be calculated directly on the basis of the measured sound pressure and accelerations. To overcome this issue a cross-talk-cancellation (CTC) technique based on the singular value decomposition was developed. To reduce the effect of noise in the measurement data, the CTC is combined with a principal component analysis. A detailed description of the method can be found in (3, 7).

The biggest advantage of the CTC technique is that the transfer functions can be derived directly from the operational data and in consequence no separate and time-consuming measurements of the transfer functions are needed. This approach is therefore called Operational Transfer Path Analysis (OTPA). Furthermore, the technique is capable to cope with both structure-borne and airborne sound paths at the same time.

### 2.2 OTPA as a multidimensional tool

The operational transfer path analysis is a suitable method for contribution analyses, which can be applied in many different ways. Traditionally it will be used to identify the strength of the noise-generating equipment like motors, gears, traction converter etc. to the response signal, which, in most cases, is the sound pressure inside the compartment. In that case we are normally calling it source contribution analysis. This kind of analysis will be performed when detailed information on the equipment is available or when the equipment is completely unknown. Due to the fact that the equipment is not a core competence of the train manufacturer, this kind of analysis is not often performed.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Positions of the reference sensors</th>
<th>Results of OTPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>source contribution analysis</td>
<td>acceleration sensors and microphones on /near all sound sources</td>
<td>separation of the contributions of each source and separation of airborne and structure-borne contributions</td>
</tr>
<tr>
<td>link/interface contribution analysis</td>
<td>acceleration sensors on the coupling points of the bogie to the car-body and microphones near the surface of the car-body contributions</td>
<td>separation of the structure-borne contributions of each link and airborne contributions via the surface areas of the car-body</td>
</tr>
<tr>
<td>panel contribution analysis</td>
<td>acceleration sensors of the inside panels</td>
<td>separation of the contributions of each inside surface area</td>
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</table>

The train manufacturer’s fields begin at the attaching points of the equipment to the car-body and all other interface between the equipment and the car-body. The difference to the source contribution analysis can be illustrated by the example of the bogie: The sound sources of a bogie are the wheels, which are interacting with the rails, and the motor-gear units. For a source contribution analysis reference sensors will be placed on the motor-gear units on the wheel bearings and near the wheel-rail interaction point. The outcome of this analysis will show the contributions of the wheels in comparison to the motor-gear units. From the perspective of a train manufacturer this information is only interesting in terms of noise management. The field of noise engineering of a train manufacturer starts with the interfaces between the equipment and the car-body, which, in case of the bogie, are the attaching points of the dampers, the springs, the lateral connections and the whole car-body structure, which is excited by the airborne sound of the motor-gear unit and the rolling noise of the bogie. For analyzing the contributions of the interfaces, which are the attaching points for the structure-borne
excitation and the whole surface areas of the car-body structure for the airborne excitation, reference sensors will be placed at these. This, then, is not a source contribution analysis any more, but rather an interface or a link contribution analysis. The used techniques for the determination of the transfer functions are the same as above.

Another field of the train manufacturer’s sound engineering starts on the inside panels and covers. Therefore, the OPTA technique can also be used to perform a panel contribution analysis by placing the reference sensors on the inside surface areas and panels.

3. Sound transmission of a high-speed train

3.1 Interior noise of a high-speed train on ballasted track and slab track in tunnels

Slab track generates higher exterior and interior noise than ballasted track due to the lower damping of the rail and track and the lower absorptive properties of the track ground. The negative effect of the latter can nowadays be reduced by absorptive material. According to (8) the inside sound pressure level (SPL) still increases by several dB – especially in tunnels – which highly correlates with increased vibration levels of the rail.

Figure 1 – Impact of slab track on the inside and outside noise (8) in comparison with the investigated high-speed train at 300 km/h

3.2 Test object, test set-up and captured test-runs

Similar effects were observed at the investigated high-speed train. To gain a deeper understanding of the causes and the driving transmission paths the OTPA technique was applied with different reference sets in order to perform a link/interface contribution analysis and a panel contribution analysis. The measurements were performed with the measurement and analysis Software PAK and the MKII Hardware by Müller-BBM VAS on a train section above a Jacobs bogie. All measurements were performed simultaneously using 133 channels. For gaining reliable results with the OTPA technique as many operation conditions as possible were captured: run-ups and run-downs (80 – 300 – 80 km/h), different runs at constant speed, different track section, free-field and inside tunnels and several runs through switch points.

Table 2 – Reference sensors for the different analysis

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Acceleration sensors</th>
<th>Microphones</th>
</tr>
</thead>
<tbody>
<tr>
<td>link/interface contribution</td>
<td>tri-axle sensors at all links (13)</td>
<td>microphones in the vicinity of the bogie, outside the gangway (icg) and on the roof (15)</td>
</tr>
<tr>
<td>contribution analysis (reference set 1)</td>
<td>single axle sensors on the inside panels (50)</td>
<td></td>
</tr>
<tr>
<td>panel contribution analysis</td>
<td>single axle sensors on the outside shell and windows (20)</td>
<td></td>
</tr>
<tr>
<td>(reference set 2)</td>
<td></td>
<td></td>
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<tr>
<td>panel contribution analysis from outside</td>
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</tbody>
</table>
3.3 Analysis

The following steps were performed for each analysis:

1. Calculation of the vibro-acoustic transfer functions by means of cross-talk-cancellation technique (CTC) and principal component analysis
2. Synthesis of the single contributions by filtering the reference signals (source signals) according to the determined transfer functions and adding up these single contributions to common contributions by means for transfer path synthesis (TPS)
3. Appropriate display of the results

3.4 Reference set 1: contribution of structure-borne and airborne noise

The result of the OTPA reference set 1 is displayed in Figure 2, which compares the measured SPL (‘aisle_measurement’) with the synthesized SPL (‘total_aisle’) and shows the estimated contribution of the structure-borne (‘sbn_aisle’) sound and airborne (‘abn_aisle’) sound. Over a broad range of speed and different track conditions the synthesized SPL is very close to the measured SPL. Only for the tunnel section the deviation between the OTPA analysis and the measured SPL becomes significant so that the level increase is not adequately represented. This is mainly caused by the fact that the measurement set-up did not include microphones on the sides of the outer shell of the train section of interest. On the other hand, this flaw in the analysis shows that the OTPA technique can provide reliable results even for an incomplete measurement set-up. Furthermore, the analysis shows that the structure-borne sound does not change and that the airborne sound gets more dominant in the tunnel.

![Figure 2 – Link/interface contribution analysis by using reference set 1](image)

3.5 Reference set 2: panel contribution analysis

The results of the OTPA reference set 2 is displayed in Figure 3, which compares the measured SPL (‘aisle_measurement’) with the synthesized SPL (‘total_aisle’) and shows the estimated contributions from each inside surface area. The reference set 2 gives a good prediction of the SPL inside the train running at different speeds, track conditions outside and inside of tunnels. The noise increase in tunnel is well predicted. The difference between synthesis and measurement is only about 1.5 dB. At low speeds the contributions via the floor and the upper sides are dominating. At higher speeds the contributions of the lower sides and the roof are getting more important, although the speed dependency is small. In the tunnel the contributions of the lower sides, the windows and the roof are getting much more important and are at the same levels as the contribution via the floor, which stays on the same level as outside the tunnel. The upper sides are responsible for the highest noise contributions.
4. CONCLUSIONS

The first OTPA analysis (reference set 1) shows that the increase of the interior SPL in tunnels is not caused by structure-borne sound. The second OTPA in form of a panel contribution analysis (reference set 2) shows that the increase of the interior noise in tunnels is caused by higher contributions from the upper sides and the roof. These can only be generated by higher airborne noise excitation outside the train, due to the reverberant properties of the tunnel or higher aero-acoustic excitations, since the structure-borne sound contributions are unaffected in the tunnel.

Based on these results a target-orientated optimization process can be initiated, including an assessment of the current design of the upper sides and the roof and the calculative/experimental optimization of potential alternatives.

The determined panel contributions enable to estimate the effect of certain mitigation measures on the overall sound pressure level inside the train.

REFERENCES