OPERATIONAL TRANSFER PATH ANALYSIS FOR VALIDATION OF THE PREDICTION MODELS FOR HIGH-SPEED TRAINS

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An acoustical prediction at an early project stage revealed that the contribution of the pantograph at maximum speed will be decisive for the sound in the compartment. To determine the exact sound power radiated from the inner panels measurements were performed with the intensity measurement technique. To enhance the acoustical prediction model an operational transfer path analysis (OTPA) was performed as well to validate the contributions from each sound source and the panels separately at real running conditions. The latter is essential especially for aero-acoustic sound sources. Different reference signals were captured near the sound sources and on the interior panels to study the influence of different reference sets. The presented OTPA shows good agreement with the measurement results in the frequency range up to 1600 Hz. A study with different reference sets gives an insight into the sound transmission from the sound sources bogie and pantograph to the sides and proves that the turbulent layer excitation on the sides are still not dominating the contribution from the sides in the investigated speed range. Moreover, the usage of references on the inside panels only was checked. The OTPA results are compared with the results which were derived by means of intensity measurement technique. Thus it is demonstrated that the OTPA can also be used to separate and quantify the contributions from the inside areas/panels. Furthermore, the example demonstrates that the OTPA is also capable to cope with aero-acoustic sound sources. The derived speed-dependency of the contributions reveals the general noise generation and increases the understanding of the effects on the inside sound pressure levels. The contribution of the sound sources, the contribution of the inside panels to the interior sound pressure and the understanding of the energy-flow is useful to validate and detail the acoustical prediction model at real running conditions.

1. Introduction

The prediction of the interior noise levels is nowadays a standard tool in the railway industry for the development of new railway vehicles. For this purpose the railway industry uses tools which always combine several methods to hybrid approaches to deal with different kinds of transfer behaviour and frequency ranges\textsuperscript{1, 2, 3}. Some companies have developed appropriate tools in-house to perform the prediction from the early concept phases until the final design stage\textsuperscript{1, 3}. 
In the tender phase, where only rough designs and layouts of the railway vehicle are available, the acoustical prediction can provide the probable sound pressure levels to assess the vehicle concept concerning the acoustical regulations and the costumer’s requirement. During the development phase it is an essential tool, in order to assess the current vehicle design, for finding deviations from the noise requirements and for devising tailor-made sound packages for the required noise levels. The use of the prediction tools and the acoustic management in general is discussed in another paper.

Increasing requirements necessitate higher prediction accuracy. Beside the appropriate and advanced simulation method, a validated prediction model is crucial for the calculation of the estimated sound pressure levels with low variances. With the correct input parameters and source quantities a good agreement between prediction results and measurements can be often achieved. This shows that the applied method is appropriate. However, at the moment the validation is limited to the comparison of the total sound pressure levels and 3rd-octave band spectra at the relevant running condition. A validation of each source contribution, of the airborne and structure-borne noise or the contributions of the different areas in the vehicle is not possible.

The OTPA is a method to determine the sound contributions of different sound sources on the basis of operational data only. Compared with the classical TPA results are derived with much fewer experimental measurements and less effort. The measurements and analyses described in the following were performed with the data acquisition and analysis system PAK by Müller-BBM VAS.

2. The new high-speed train and experimental investigations

The investigation was performed for the development of new high-speed trains from Stadler Altenrhein AG with a maximum speed of up to 250 km/h. Early acoustical predictions based on the prediction model of the forerunner train with a maximum speed of 200 km/h revealed that the most challenging passenger area for noise reduction will be the compartment near the pantograph. Hence the exact sound power generated by the aero-dynamic of the pantograph was only roughly estimated in this phase, an experimental investigation was planned to determine the exact sound power radiated from the pantograph for different running directions and operation states of the pantograph.

For this task intensity measurement technique was applied inside the train to determine the turbulent stochastic and periodic excitations by the pantograph in the airflow with high accuracy. In order to be able to perform a complete contribution analysis the intensities were also derived for the sides (upper sides, sides under the window and lower sidewall) and the floor (see Figure 1). A weak spots analysis could be performed, but only for 200 km/h and for the current design.
In parallel, an OTPA was performed with the aim to separate the contributions of the sound sources and to determine the amount of structure-borne and airborne sound. On this basis it should be possible to validate the prediction model of the forerunner train and to get detailed information about the real aero-dynamic excitations.

The investigation was carried out for the critical compartment.

2.1 Intensity measurements

For the intensity measurements all investigated areas (Figure 1) were scanned with the intensity probe (Brüel&Kjaer, type 2683). To suppress the reactive field, standing waves inside the compartment and the contributions of the other areas absorptive material was placed inside. To reduce the contributions of passenger areas nearby, these areas were also filled with absorptive material. The seats were removed to provide the accessibility for intensity measurements. A 50-mm-spacer was used with the intensity probe to capture the frequencies of interest below 1250 Hz. All areas were scanned at least 3 times. The left and right sides were scanned separately.

The measurements were performed over several days. To detect dramatic changes in the wind velocity a pitostatic tower was installed on a buffer of the head wagon. Luckily, the weather conditions did not change during the tests. Due to the careful preparation the pressure-intensity index was fairly low. Intensity values with a pressure-intensity index above 12 dB were rated as not valid, and were not considered in the analysis. The average pressure-intensity indexes for the valid values of the 1/3-octave bands are displayed in Table 1. Due to the fact, that the track and the environmental conditions were consistent during the measurement time, the contributions of all investigated inside panels/areas were comparable with high accuracy.

<table>
<thead>
<tr>
<th>Area</th>
<th>PI Index in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>roof</td>
<td>5 dB</td>
</tr>
<tr>
<td>upper side wall, left/right</td>
<td>5/6 dB</td>
</tr>
<tr>
<td>side under window, left/right</td>
<td>8/8 dB</td>
</tr>
<tr>
<td>lower side wall, left/right</td>
<td>8/7 dB</td>
</tr>
<tr>
<td>floor</td>
<td>9 dB</td>
</tr>
</tbody>
</table>

2.2 Calculation of the resulting sound pressure levels

By means of the acoustical prediction model the inside sound-pressure level was calculated from the measured intensities, respectively the sound powers.

3. Validation and detailing with operational data

3.1 OTPA

The basic idea of the transfer path analysis is the separation of the vibro-acoustic system into sources and transfer paths to the receiver (response), so that the transfer behaviour becomes comprehensible. The OTPA uses the vibro-acoustic quantities like acceleration (at the mounting points) and sound pressure (near the sound source) in contrast to force (and volume velocity) in case of the classical TPA to characterise the sound sources. The acceleration at one reference point always leads to acceleration at the other reference points. This phenomenon is called “cross-talk”. For the synthesis of the response signal \( p_{syn} \) with the reference signals \( x_{op,j} \)

\[
p_{syn} = \sum_j p_j = \sum_j H_j \cdot x_{op,j} = \sum_j \left[ \frac{P}{x} \right] \cdot x_{op,j}
\]  

(1)
the transfer functions $H_i$ without cross-talk are needed. The challenging at the OTPA approach is to derive the transfer functions between the response and the reference signals without the cross-talk. To overcome this issue the singular value decomposition (SVD) is applied. This method is combined with a principal component analysis (PCA) to reduce the effect of noise in the operational data. The combination of both methods is called cross-talk cancellation (CTC).

The transfer path synthesis (TPS) of the response signal is implemented in PAK by filtering the reference signals according the derived transfer functions in the time domain. By appropriate summation and arrangement of the signals the contribution of different sound sources in total and the proportion of the structure-borne and airborne sound can be analysed. A detailed description of the OTPA can be found in 5 and 6. The use of the OTPA for the acoustics of rail vehicles is described in 7 and 8.

The biggest advantage of the OTPA compared to the classic transfer path analysis is that the transfer functions can be derived directly from the operational data. In consequence no separate and time-consuming measurements of the transfer functions are necessary. Furthermore, the technique is capable to cope with structure-borne and airborne sound paths at the same time and the same framework.

The source quantities, which are measured as field quantities like acceleration and sound pressure, are in the following called references, while the receiver inside the train is called response.

### 3.2 Measurement setup for OTPA

In order to derive the contributions of each sound source and to separate the structure-borne contributions from the airborne ones, acceleration sensors were placed at the mounting points of the sound sources at the car body. The airborne sound of the sound sources was measured with standard microphones with wind screens. The used measurement equipment and the represented sound sources are listed in Table 2. A second reference level was chosen to separate the contributions from the inside panels (see Table 3). Always, the response signal was the sound pressure inside the investigated train section.

#### Table 2. Reference sensors outside and near the sound sources and at the mounting points.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sound source</th>
<th>Sensor and position</th>
<th>Type</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>bogie, structure-borne contributions</td>
<td>triaxial acceleration sensors at all mounting points</td>
<td>PCB 356A15</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>bogie, airborne contributions and subfloor turbulences (sft)</td>
<td>microphones in the vicinity of the bogie and the gangway</td>
<td>PCB 378B02</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>pantograph, structure-borne contributions</td>
<td>triaxial acceleration sensors, at all mounting points</td>
<td>PCB 356A15</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>pantograph, airborne contributions</td>
<td>microphones at the roof</td>
<td>PCB 378B02</td>
<td>4</td>
</tr>
</tbody>
</table>

#### Table 3. Reference sensors on the inside areas/panels.

<table>
<thead>
<tr>
<th>No.</th>
<th>Inside panels/areas</th>
<th>Sensor and position</th>
<th>Type</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>floor</td>
<td>mono-axial acceleration sensor</td>
<td>Endevco 27A12</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>upper side wall/windows</td>
<td>mono-axial acceleration sensor</td>
<td>Endevco 27A12</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>side wall under the window</td>
<td>mono-axial acceleration sensor</td>
<td>Endevco 27A12</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>lower sidewall</td>
<td>mono-axial acceleration sensor</td>
<td>Endevco 27A12</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>roof</td>
<td>mono-axial acceleration sensor</td>
<td>Endevco 27A12</td>
<td>4</td>
</tr>
</tbody>
</table>
The measurements were performed with the compartment in production configuration without seats. Absorptive material was placed in the passenger areas nearby to suppress the contributions of these areas.

### 3.3 Analysis

By means of CTC the transfer function responses by references were calculated using the operational data only. The high variation of the running conditions is beneficial for obtaining reliable transfer functions. Therefore, various running conditions (speed variation between 120 km/h and 200 km/h, different running directions, various points, different track sections, curves) were captured and used for the determination of the transfer functions.

Three different reference sets were studied:

- Set 1 comprises the references of the sound sources in Table 2 only.
- Set 2 comprises the references of the inside panels/areas of Table 3.
- Set 3 combines the reference sensors of the sound sources with the reference sensors on the sides (no 6, 7, 8 of Table 3).

Due to the different reference sets, different contribution analyses can be performed. So, reference set 1 is for the analysis of the contribution of the sound sources bogie (and subfloor turbulences) and pantograph. Reference set 2 should give a good picture of the contributions of the train’s inside areas. References set 3 is something in between the two other reference sets.

For each reference set the transfer functions were calculated. The transfer functions were used for a synthesis of the sound pressure level inside the compartment by means of the transfer path synthesis (TPS).

### 3.4 Effect of the different reference sets

A comparison of the OTPA results and the measured sound pressure level inside the train as well as the contributions of the sound sources of the three different reference sets are comprehensively displayed in Figure 2.

![Figure 2. A-weighted SPL inside the compartment and the contributions for the reference sets 1, 2, 3 in dB, SW: side wall, sft: subfloor turbulence, 10 – 1600 Hz.](image)

All reference sets are capable to synthesise the overall sound pressure level inside the compartment with an accuracy of 0 - 1 dB. Set 1 matches best, set 2 worst. Set 2 uses only the acceler-
tions on the inside panels as reference signals. The 3\textsuperscript{rd}-octave band spectra reveal that the divergence of set 2 is caused by a frequency-depending underprediction above 400 Hz. This is very likely caused by the fairly coarse sensor grid on the inner panels. The increasing divergence for higher frequencies also occurs for the reference sets 1 and 3 even though they are only around 2 dB. Smaller turbulent vortexes on the outer shell could also be a reason for that divergence.

Set 1 provides only the contributions of the sound sources (and subfloor turbulences) and pantograph. Because this analysis includes the sound transmission overall, the contributions of the sound sources are the highest. Including the sides as a separate transfer path, in case of set 3, leads to lower contributions of the sound sources. Consequently, the sound contributions from the sides are no separate sound sources, driven by the turbulent boundary layer, but rather flanking paths for the sound sources bogie and pantograph.

Although the contributions from the sides differ between the sets, the ranking between the inside panels/areas is always similar.

### 3.5 Conclusions from the different reference sets

Set 1 leads to a good agreement with the measurement results. Consequently, the chosen reference set is sufficient for the transfer analysis and the turbulent boundary layer on the sides still is not relevant for the total sound pressure level inside the train at the investigated speed.

### 3.6 Comparison with intensity measurement results

The comparison between the measured sound contributions (by means of the intensity probe and the prediction model) of the different areas with the OTPA results is displayed in Figure 3. Since the reference set 1 only serves for analysing the contributions from the sound sources, it was not included in the comparison.

Both reference set 2 and 3 are in good agreement with the measurement results of the intensity probe. The deviations of OTPA results and intensity probe measurements are around 0 – 2.5 dB for most of the investigated areas. For the side wall under the window and the floor is the deviation up to 6 dB.

All in all reference set 3, which includes reference signals at the sound sources and reference signals on the panels, leads to the best accordance with the measured contributions.

![Figure 3](image-url)

**Figure 3.** Comparison of the sound pressure contributions derived with the different methods.
3.7 Speed-dependency of the sound sources

The investigation was performed with the forerunner train with a maximum speed of 200 km/h. Since 250 km/h is the maximum speed for the new train, the speed-dependency of the sound contribution is needed for an appropriate modelling of the sound source. For extracting the speed-dependency of the sound sources, the contribution of the reference set 3 was plotted between 120 km/h and 200 km/h and then calculated by means of linear regression (Figure 4).

The pantograph changes with $56\log_{10}(v/v_0)$. This is an indication for this source being driven by aero-acoustic excitation. The bogie noise changes by about $30\log_{10}(v/v_0)$. The structure-borne noise contribution changes by $20\log_{10}(v/v_0)$, but airborne sound changes are around $49\log_{10}(v/v_0)$. This indicates that the driving sound source is not the bogie, but the subfloor turbulences.

Due to the fact that the sound contribution of the sides is generated by the bogie and the pantograph, the speed dependence of the sides is in between of these sources.

![Speed-dependency of the A-weighted sound pressure level contributions.](image)

**Figure 4.** Speed-dependency of the A-weighted sound pressure level contributions.

4. Conclusions

The presented OTPA shows good agreement with the measurement results up to the frequency range of 1600 Hz. This is due to an appropriate measurement setup and some preparations in the vehicle. Furthermore, the example demonstrates that the OTPA is also capable to cope with aero-acoustic sound sources.

A study with different reference sets gives an insight into the sound transmission from the sound sources bogie and pantograph to the sides, and prove that the turbulent layer excitation on the sides are still not dominating the contributions from the sides in the investigated speed range.

Using only the reference signals of the inside panels of the compartment shows very similar results with the OTPA with sensors on the sound sources.

Parallel measurements with the intensity measurement technique show very similar results. This demonstrates that the OTPA can also be used to separate and quantify the contributions of the inside areas/panels.

The derived speed-dependency of the contributions reveals the general noise source and provides the necessary understanding of the effects to the inside sound pressure level.

The contribution of the sound sources, the contribution of the inside areas/panels to the inside sound pressure and the understanding of the energy-flow is useful for a validation and for detailing the acoustical prediction model at real running conditions.
REFERENCES


