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SOURCE SEPARATION METHODS FOR RAILWAY NOISE DEVELOPED IN THE TRANSIT PROJECT

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ABSTRACT

In the EU Shift2Rail project TRANSIT, methods have been developed and demonstrated for source characterization, source separation and interior sound control of railway noise. Source separation methods were investigated with different approaches: microphone arrays and PBA-based methods (Pass-by Analysis). Such methods are potentially useful in the context of standards and regulations for type testing and assessment of noise control of the track-vehicle system.

Microphone array methods were developed to enable a more detailed identification and quantification of sources, including their sound power and directivity. These methods enable the separation of aerodynamic, traction, and equipment noise sources. Additionally, they have the potential to identify the rail noise contribution from high-speed trains.

PBA-based methods were developed to separate overall contributions of other sources, averaged over the whole train pass-by or part of a pass-by. These methods require single trackside microphones and accelerometers on the track, originally developed to separate combined roughness from the vibroacoustic rolling noise transfer function.
The developed methods are presented together with some experimental results including a regional train and a high speed train upto 280 km/h.

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Keywords: *Railway noise, source separation methods, array measurement, pass-by measurement, PBA method.*

1. INTRODUCTION

In the EU Shift2Rail project TRANSIT methods have been developed and demonstrated for source separation of railway noise [1][2]. In this paper, methods are presented for separation of other sources from rolling noise. Although rolling noise is often dominant, both traction noise and aerodynamic noise are relevant, especially where rolling noise is low due to low wheel/rail roughness or at high speed for example. There is a need to be able to quantify the contributions of these sources from a viewpoint of noise control, but also in relation to type testing and environmental noise prediction.

In the TRANSIT project, different methods were investigated, including microphone array methods and PBA-based methods with a single trackside microphone and accelerometer underneath the rail.

2. MEASUREMENT CAMPAIGNS

Two measurement campaigns were performed in the TRANSIT project to validate the measurement methods, with specific test trains running at a series of speeds. The first, shown in Fig. 1, was at the Velim test loop in Czechia, where a regional train ran 34 pass-bys at various speeds. The second was on the high speed line Madrid-Zaragoza, at Ledanca, operating a high speed test train at night on a closed track, with 12 pass-bys including high speeds. Both array measurements and PBA measurements were performed simultaneously.

Figure 1. Regional train at Velim test ring.

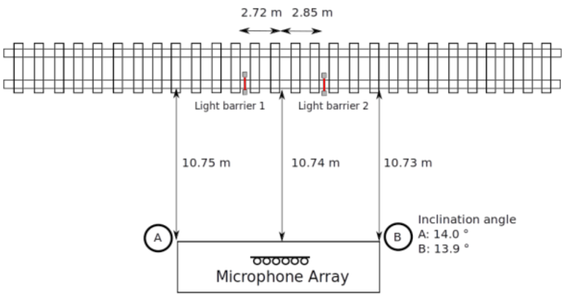


Figure 2. Array setup in the Velim campaign.

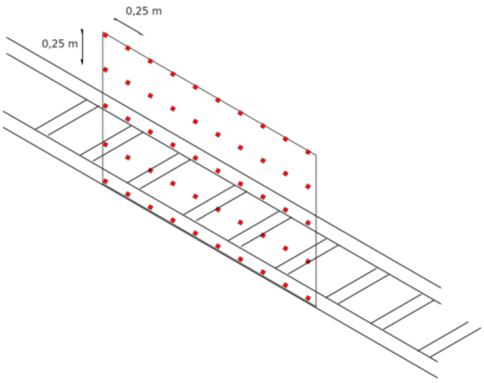


Figure 3. Grid to reconstruct the sound sources.

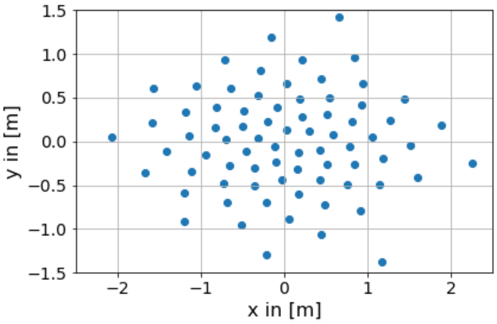


Figure 4. The used array geometry.

3. ARRAY METHODS

The method utilised in this study has been employed in previous works [1][2][3][5]. These are based on the application of the CLEANT method to moving sources, as demonstrated by Cousson [4]. During the TRANSIT project, the method was systematically demonstrated and evaluated for the first time. In this technique, microphone signals are temporally focused on a moving sub grid, and the sources are subsequently spatially deconvolved. The source maps obtained on the sub grid are spatially shifted, multiplied by a Hanning window, and superimposed to generate a source map for a train. Fig. 3 illustrates the overall grid employed in this context, which is modeled to be in the plane of the track nearest to the microphone array. The grid has a resolution of 0.25 m, and the sound pressure level at each point of the grid is extrapolated to a distance of one meter from that point. The method and data processing are implemented using the Acoular Python package [6].
The measurement setup is illustrated in Fig. 2, while the array geometry used is shown in Fig. 4. The sound pressure was recorded utilizing an array that was specifically designed for the TRANSIT project, comprising 75 microphones. Simultaneously, the train speeds were measured employing two light barriers. The array geometry used was a stretched Vogel geometry in the x-direction [7] located 10.74 m from the track, with an inclination angle of approximately 14 degrees. The track had a UIC60 rail profile and was damped by rail dampers. For the Ledanca campaign, a high-speed train was investigated with a measurement setup similar to the Velim campaign, except that the array was located 7.9 m from the track and had an inclination angle of 20 degrees. The rail profile was also UIC60, but without rail dampers and with softer railpads.

4. ARRAY RESULTS

In the current investigation, the source maps that were determined are analyzed. The source regions are identified, and their dependence on frequency, velocity, and angle is examined. For confidentiality reasons, the levels displayed are normalised levels that do not correspond to the actual values.

4.1 Source maps

A brief analysis of the source maps obtained for the one-third octave bands ranging from 125 Hz to 10 kHz is given here. Fig. 5 (top) displays two source maps for the Velim campaign, representing the train in the one-third octave band of 1250 Hz traveling at speeds of 80 km/h

Figure 5. Sound source maps for train pass-bys running right to left, in the 1250 Hz one-third octave band. Top: regional train in Velim at 80 km/h (upper) and 200 km/h (lower); Bottom: high speed train at Ledanca at 80 km/h (upper) and 280 km/h (lower).

and 200 km/h in the right-to-left direction. The dynamic range is 15 dB(A). At 80 km/h, the wheels of the train can be distinguished as one of the primary sources of noise. Notably, the first, fifth, sixth, and tenth bogies (counted from left to right) are driven, and differences from the other non-driven bogies are visible in the source map. At a speed of 200 km/h, aerodynamic sources such as the front cabin, the pantograph, and the gaps between the train wagons on the roof of the train can also be identified.

Fig. 5 (bottom) displays the sound maps obtained during the Ledanca campaign, depicting two pass-bys in the right-to-left direction of travel at speeds of 80 km/h and 280 km/h. The maps reveal that the areas of the rail and the ventilation grilles on the first and last wagons are significant sources of noise. At a speed of 280 km/h, all wheels are identified as sources, along with the pantograph situated on the roof of the last carriage.

The source maps were used to define spatial source sectors for both trains, as depicted by coloured rectangles in Fig. 6, with the corresponding colour legend given in Fig. 7.

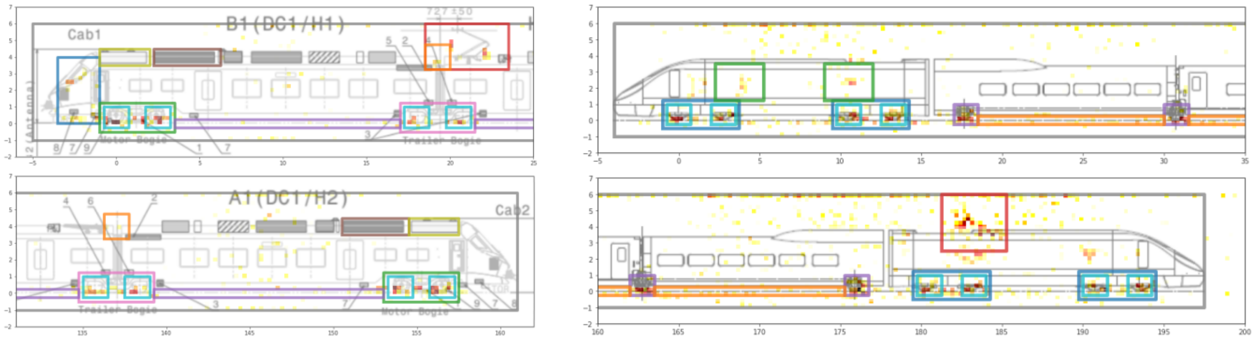


Figure 6. Defined integration sectors shown as coloured rectangles in the Velim campaign (left) and in the Ledanca campaign (right). The colour key per sector type is listed in Fig. 7.

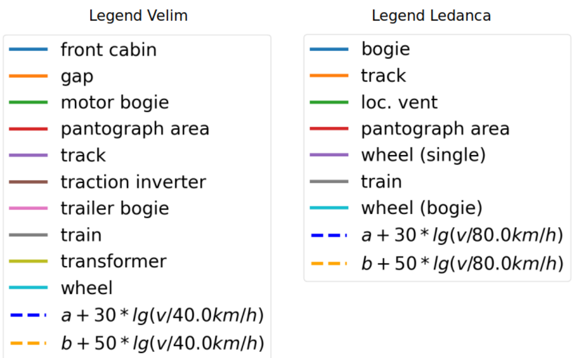


Figure 7. Colour legend for Velim campaign (left), Ledanca campaign (right).

The sectors are named after the train components located within them, as well as sources observed within the map. For example, in the Velim campaign, a source on the roof between individual wagons was observed at high speeds, which is referred to as the "gap" sector.

4.2 Spectra

The results of the integration across the defined sector types for the Velim campaign are presented in Fig. 8. The averaged sound pressure level per sector type is displayed in one-third octave bands for a pass-by direction right-to-left at 80 km/h.

The bogies are identified as the most dominant sound sources, with the powered bogies exhibiting the highest levels. Fig. 9 displays the average sound pressure level at 80 km/h and 200 km/h for the three sector types: "bogie", "front cabin", and "inverter".

The aerodynamic source "front cabin" exhibits a clear increase in level at 200 km/h and is the strongest source in the frequency range below 1000 Hz. In the other frequency ranges, the bogie dominates. The level of the inverter sector shows only small changes below 500 Hz at both speeds. Above this frequency, a clear increase in the level at 200 km/h can be observed.

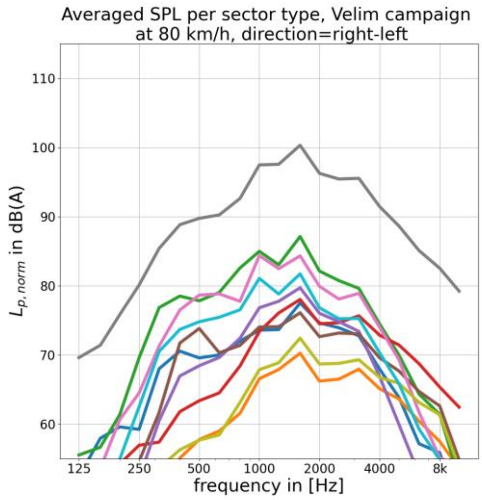


Figure 8. Averaged sound pressure level per sector type in third octave bands, normalized, for regional train at Velim at 80 km/h. See Fig. 7 for colour key per sector.

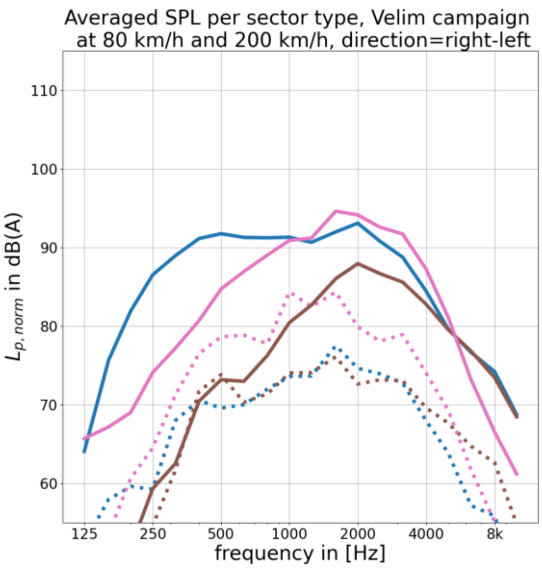


Figure 9. Averaged sound pressure level per sector type in different one-third octave bands. Results from the Velim campaign at 80 km/h (dotted line) and 200 km/h (solid line). See Fig. 7 for colour key for sector types.

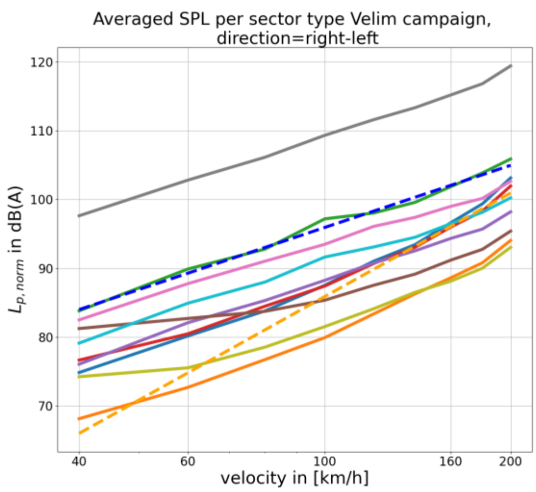


Figure 10. Averaged sound pressure level per sector type, shown as a function of speed in the Velim campaign. The colour key for sector types is given in Fig. 7.

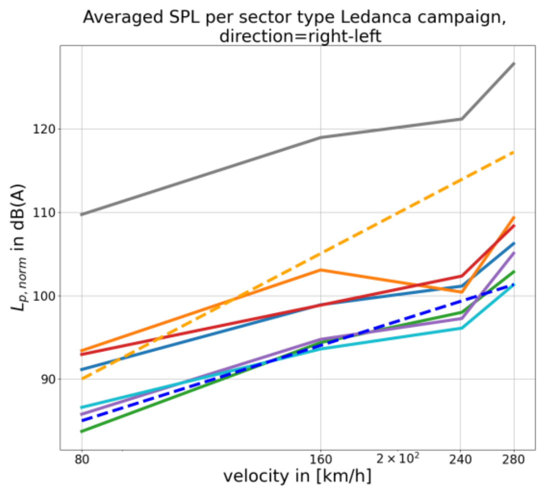


Figure 11. Averaged sound pressure level per sector type, shown as a function of the train speed in the Ledanca campaign. The colour key for individual sector types is given in Fig. 7.

4.3 Speed dependency analysis

In a further analysis, the sound pressure level values obtained from sector integration are presented as a function of train speed. The sound pressure level in the frequency band from 125 Hz to 10 kHz, averaged per sector type and speed, is examined. Fig. 10 shows this for the Velim campaign and Fig. 11 for the Ledanca campaign. In addition, the speed laws listed in Fig. 7 are represented by blue and yellow dashed lines.

The analysis reveals that the level values of sectors such as the bogies and wheels follow the equation a + 30 lg(v/40 km/h), while sectors such as the pantograph, front cabin, or intermediate space follow the equation b + 50 lg(v/40 km/h). Sectors such as the transformer or inverter exhibit a considerably lower increase in sound pressure level for speeds below 100 km/h. In the results from the Ledanca campaign, this correlation is less pronounced. Thus, the characteristics of the bogie and wheel sectors are similar to the equation a + 30 lg(v/80 km/h), and the equation b + 50 lg(v/80 km/h) shows agreement only in the characteristics from 240 km/h onwards. All sectors show a stronger increase in sound pressure level in the range from 240 km/h to 280 km/h. A local maximum is observed in the dominant level curve of the track sector at 160 km/h.

The microphone array method described for identifying and characterizing noise sources of a moving train was applied successfully to data from two measurement campaigns. One campaign demonstrated the influence of the rail (on softer railpads), but as the method is designed for evaluating acoustic sources moving at the speed of the train, caution should be exercised in interpreting the results. In the Velim campaign, many different source types were identified, and their source strength showed a presumed speed dependence. Rolling noise sources showed a different speed dependence than aerodynamic sources as expected. Directivity was also investigated by analysing angle dependent data, set out in detail in the TRANSIT report [2].

5. PBA-BASED METHODS

PBA stands for Pass-by Analysis and was developed by TNO between 2000-2006. The methodology was formalised in CEN TR16891:2016 [8]. It has several applications including assessment of wheel/rail roughness and separation of roughness from sound transmission, for train pass-by data. The methods entail a basic setup of a single trackside microphone and one or more accelerometers attached vertically to the rail. The acceleration signals are used to derive combined effective roughness of the wheel and rail during a pass-by. Together with the sound pressure level a transfer function can be obtained, which in the case of dominant rolling noise represents a rolling noise transfer function for the track and vehicle together. This transfer function is typically speed independent.

The vertical rail acceleration signal is used to derive the vertical track decay rate D(f), and combined roughness $L_R(\lambda)$ or $L_R(f,v)$ as set out in CEN TR16891:2016. The transfer function $L_{HpR,nl}(f)$ is determined from

$$L_{HpR,nl}(f) = L_{peq,Tp}(f,v) - L_R(f,v) - 10\lg(N_{ax}/\ell) \qquad (1)$$

where $L_{peq,Tp}(f)$ is the pass-by sound pressure level, and all levels are in third octave bands, with f=band centre frequency [Hz], v= train speed [m/s] and λ = wavelength [m].

The application for separation of other sources was first published in IWRN 2010 [9] applied to in-service high speed trains. In the TRANSIT project, measurement campaigns allowed for demonstration and a more detailed analysis on datasets with multiple speeds of the same train.

If other sources are prevalent above rolling noise, this is seen in the transfer function as a level increase above the typical trend, indicating the relative strength of those sources compared with rolling noise. This is shown in Fig. 12. In this way, the contribution from other sources relative to rolling noise can be derived, if measurements at multiple speeds are available. A rolling noise transfer function $L_{HpR,nl,roll}(f)$, shown in Fig. 13, can be derived from the minimum of the measured functions, which in principle should be independent from train speed and includes both the track and wheel contributions. The combined effective wheel/rail roughness (including the contact filter) shown in Fig. 14 is derived from the vertical rail acceleration during pass-by and the vertical track decay rate.

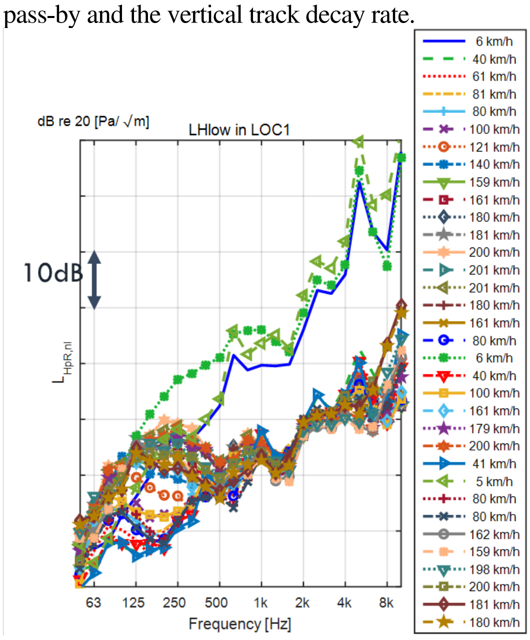


Figure 12. Measured transfer functions $L_{HpR,nl}(f)$ for multiple pass-bys of the regional train at Velim at different speeds, inner position.

The pass-by rolling noise sound pressure spectrum $L_{p,roll}(f)$ can now be derived for any speed using formula (1). The contribution from other sources is estimated from

$$dL_H(f) = L_{HpR,nl}(f) - L_{HpR,nl,roll}(f) \qquad (2)$$

$$L_{p,other}(f) = L_{p,total}(f) \text{ for } dL_H(f) \geq 7 \text{ dB} \qquad (3)$$

and otherwise for $dL_H(f) < 7$ dB

$$L_{p,other}(f) = 10\lg\left(10^{L_{p,total}(f)/10} - 10^{L_{p,roll}(f)/10}\right) \qquad (4)$$

with the additional requirement that the energy sum of the parts should also equal the total pass-by sound level:

$$L_{p,total}(f) = 10 \lg \left(10^{L_{p,other}(f)/10} + 10^{L_{p,roll}(f)/10}\right) \quad (5)$$

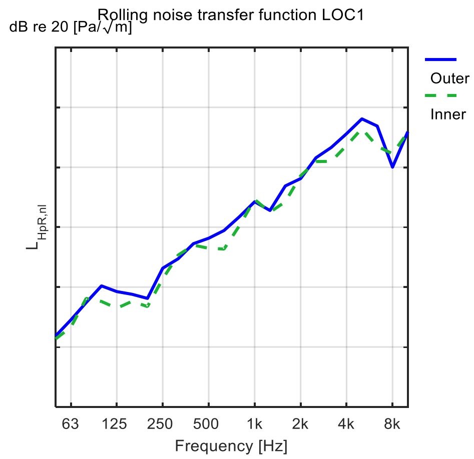


Figure 13. Derived transfer function $L_{HpR,nl,roll}(f)$ for rolling noise, for either side of the track, regional train at Velim (10 dB scale steps).

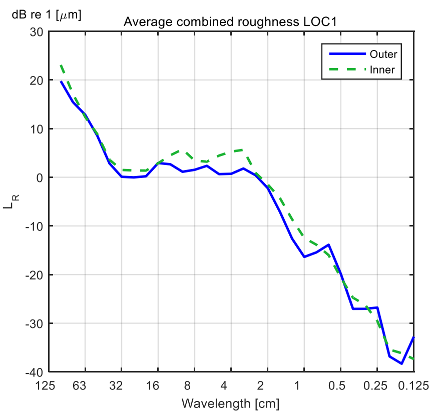


Figure 14. Combined effective roughness averaged over all train speeds for both rails, regional train.

For small dL_H, the uncertainty in the contribution of other sources increases significantly, which is the case if these fall more than about 2 dB below the rolling noise. This can be avoided by analysing only part of a train where sources are present.
Methods were also applied to determine sound power from the pass-by sound pressure level in line with the new draft standard for Railway noise source terms, prEN 17936 (2022) [10]. In addition, methods to derive directivity of sources from the spectrogram of the pass-by noise were developed and applied, described in TRANSIT reports [1][2].

Separation results are shown in the following.
The overall unweighted separated sound levels for other sources and rolling noise are shown as a function of speed in Fig. 15, for the regional train at Velim. The 25 lg v trend line for rolling noise differs from 30 lg v due to the unweighted sound pressure level. The separation would be less visible for A-weighted levels. Data is normalised.

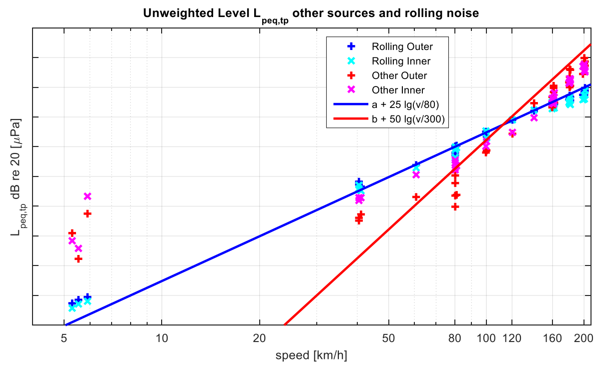
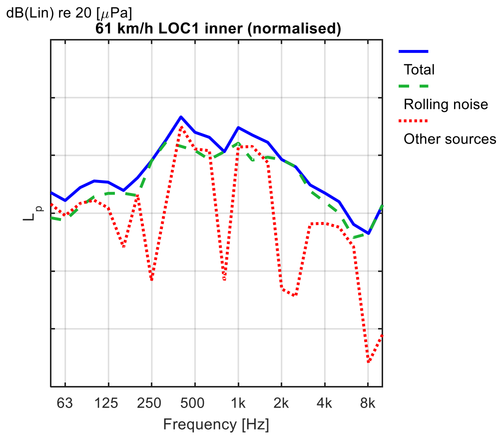


Figure 15. Unweighted pass-by sound pressure levels of the regional speed train at different speeds with contributions of rolling noise and other sources (5 dB scale steps, normalised data).

Separation spectra are shown for speeds 61 and 200 km/h for the regional train in Fig. 16, and for 280 km/h for the high speed train in Fig. 17. As expected, aero-dynamic noise arises especially in the frequency range below 1 kHz and at higher speeds. For the high speed train, the rail roughness contained a grinding peak, which together with the softer railpads, resulted in a strong rolling noise contribution around 2 kHz. Without this, aerodynamic noise would be dominant at high speed.

6. CONCLUSIONS

Improved methods for source separation have been developed and validated in the TRANSIT project, including array methods that allow detailed identification and quantifying of railway noise sources. Also PBA methods were developed and shown to be capable of separating overall contributions of other sources from rolling noise. These are now available for the railway noise source terms standard prEN 17936 and others.



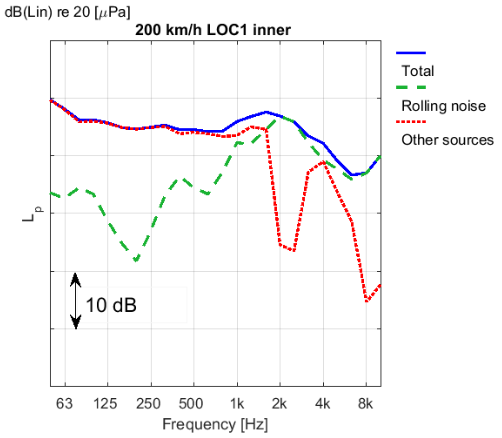


Figure 16. Pass-by sound pressure spectra of regional train at 61 km/h (top) and 200 km/h (bottom) with contributions of rolling noise and other sources.

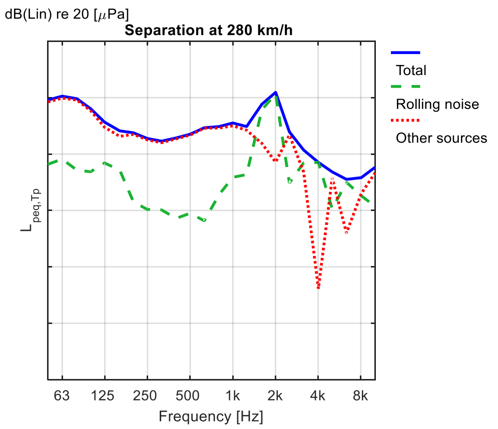


Figure 17. Pass-by sound pressure spectra of a high speed train at 280 km/h with contributions of rolling noise and other sources (10 dB scale steps).

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Innovative separation techniques: theoretical description and validation testing campaign proposal, Deliverable D2.2, TRANSIT Consortium 2022.

[2] Analysis of pass-by source separation results and uncertainty analysis; Innovative separation techniques: validation test results, Deliverable D2.4, TRANSIT Consortium 2023.

[3] M. Czuchaj, A. Kujawski, and E. Sarradj. Erweiterung der CLEANT-Methode zur Entfaltung bei Mikrofonarray-Messungen an Hochgeschwindigkeitszügen, *Proc. DAGA* 2021.

[4] R. Cousson, Q. et al. A time domain clean approach for the identification of acoustic moving sources. *Journal of Sound and Vibration*, 443, 47-62, 2019.

[5] A. Kujawski and E. Sarradj. Application of the CLEANT method for high speed railway train measurements, *BeBec* 2020.

[6] E. Sarradj and G. Herold. A Python framework for microphone array data processing, *Applied Acoustics*, 116, 50-58, 2017.

[7] H. Vogel. A better way to construct the sunflowerhead, *Mathematical Biosciences*, 44, 179-189, 1979.

[8] CEN TR16891:2016 Indirect measurement of Track Decay Rates, Combined roughness and Transfer functions.

[9] H.W. Jansen, M.G. Dittrich: Separation of rolling noise and aerodynamic noise by in-service measurement of combined roughness and transfer functions on a high speed slab track, *Proceedings 10th IWRN*, Nagahama, Japan, 2010.

[10] prEN 17936 Railway applications - Acoustics - Measurement of source terms for environmental noise calculations (2022).