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Research on noise and vibration reduction at DB to improve the environmental friendliness of railway traffic

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Abstract

One of the most prominent keywords relating to the environmental friendliness of railway traffic is noise reduction. Thus, the research and development programme "Low Noise Railway" of Deutsche Bahn (DB) is under way to treat the noise of the vehicles and infrastructure. The noise reduction of the trains and the rail/wheel system are being tackled within several projects.

The direct noise experienced by railway-lineside residents due to train movements on the track can be reduced by minimising the sound radiation directly at the source. This is the first-choice solution, as it proves to be the most effective countermeasure regarding a cost–benefit relation.

The limit values for the noise emission as specified in the technical specification for interoperability are an essential criterion to be confirmed during the procurement process of railway vehicles. A recently developed acoustical quality management scheme establishes systematic noise management to complete the vehicle procurement process in the phases of concept, design, construction and manufacturing.

In freight traffic quiet railway wheels for block brake operation will play an important role in the future to meet the goal of a low-noise railway system. A first attempt to realise successfully the low-noise potential of such optimised wheels was performed, even if with mixed results.

To show ways of reducing the noise of the cooling ventilation in locomotives, DB is a partner in a development project led by Siemens. A notable 8 dB(A) noise reduction was measured.

Concerning bridge noise, a project was started based on an effective and cost-efficient combination of experiments and simulations in order to develop specifications for the construction of generic low-noise bridges.

1. Introduction

To follow the EU requirements (see, for instance, Ref. [1]) and to strengthen the environmental friendliness of European railway traffic, the European Rail Research Advisory Council (ERRAC) has defined and now maintains the Strategic Rail Research Agenda (SRRA) also in the field of "environment" [2]. One of the most prominent keywords relating to the environmental friendliness of railway traffic is noise reduction. The

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strategies of the German government for the reduction of railway noise and their European context are described in Ref. [3].

Deutsche Bahn (DB) responded positively with the self-obligation to decrease the environmental impact of the railway traffic [4]. Among the seven central premises in the associated "Railway Agenda 21" of DB, it is stated that for sustainable mobility:

- the economically and ecologically successful railway creates the pre-conditions for the relocation of road and air traffic to rail;
- the quiet railway reduces the noise of rail traffic;
- the environmentally responsible railway protects nature and the countryside.

In 2002, an opinion poll of the Federal Environment Agency stated that 65% of the German population feels annoyed by road traffic noise, 37% by air traffic noise and 23% by railway noise (cited after Ref. [5]). This outcome stimulates DB to lower the noise impact of the residents by consequent noise prevention measures to be applied to new lines and by a special noise abatement programme for those affected by noise from existing sections of the rail network. The German government has made €51 million available annually for this programme. With the introduction of this scheme, it became financially feasible for the first time to realise noise protection measures along sections of railway track not undergoing significant modification. The implementation regulations are set out in the "Guidelines for promoting rail noise abatement measures" published by the Federal Ministry for Transport, Building and Housing [6].

DB is aware of the effects that noise emissions from rail traffic can have. This is the reason why a noise reduction programme was initiated when railway privatisation took place. The greatest efforts are being made to reduce noise at source, i.e. from the vehicle itself or from the wheel–rail interaction. Having optimised the acoustic characteristics of new vehicles used for local and long-distance passenger services, major reductions in noise emission levels from freight wagons are now feasible. The novel composite brake block (known as "K-blocks"), which has undergone years of extensive testing, has recently been approved for international use [7,8]. Up to now, wheel treads were roughened every time the cast-iron brake blocks were applied. With this new development, the treads remain smooth, a fact which will lead to a reduction of 8–10 dB(A) in rolling noise [9].

DB has established a special rail care programme called "Specially Monitored Track," in which noise radiation from the rail is regularly monitored by a custom-built sound-measuring car [10,11]. If the acoustic quality of the rail head surface is below a specified level, the short-pitch corrugations that occur on the rail head surface as a result of normal operations are removed by grinding the rail head along these specially monitored track sections using a special technique.

The four development activities reported in this article follow the above mentioned guiding principle to improve the noise reduction at source. Beyond the noise reduction by using K-block in freight wagon braking systems, a further improvement can be expected from a noise-optimised shaping of the railway wheels. The reduction potential is similar to that of the wheel dampers used in passenger coaches. Even railway stations with stationary locomotives can be noise "hot spots" for the passengers if the sound generation of the cooling-fan is too high. Therefore, investigating the reduction potential of the cooling fan noise is beneficial. Furthermore, bridges are very often noise "hot spots" for the residents for which thorough and consistent construction rules and specifications for low-noise bridges are still not available "off the shelf". Last but not the least, to take care of all noise aspects during the manufacturing process in a systemic manner, a continuous quality management scheme is essential.

2. Acoustical quality management linked to noise reduction at source

In the near future the fulfilment of the limit values for the noise emission of new trains as described, e.g. in the technical specification for interoperability (TSI) will be a mandatory homologation criterion. These values will be proofed and certified by "notified bodies" independent of the manufacturer and the ordering operator of the new trains. For the European high-speed trains, these limit values are specified in a TSI which was already ratified in 2002. The preparation of the TSI NOISE CRS (Conventional Rolling Stock) for the conventional interoperable rail vehicles with a maximum speed less than 190 km/h is almost finalised and will be ratified by the European Commission in due time. It is planned to put the limit values stated in this TSI into force for newly ordered railway vehicles at the end of 2005.

These TSI limit values for noise emission will then be an essential criterion to be confirmed during the procurement process of railway vehicles and will be written down in the vehicle specifications. The sustainable fulfilment of these limit values is a sound challenge for the acoustical design methodology. From the very beginning, the acoustical requests have to be taken into account for the concept and design of the vehicles. The limit values will affect numerous details of the construction; therefore, later improvements of a non-noise-optimised construction will lead to economically difficult situations. This applies especially to locomotives and other vehicles with traction motors, as all the various supply devices are potential noise sources of different intensity.

The interaction of these noise sources and the variation of their intensity with the power output result in a complex acoustical design process of a railway vehicle. To balance the needs of the noise reduction with the other important demands like safety, reliability, low energy consumption, low diesel engine emissions, cost-effective construction, low operational costs, low life cycle costs and, last but not least, the outer design requirements is a demanding task.

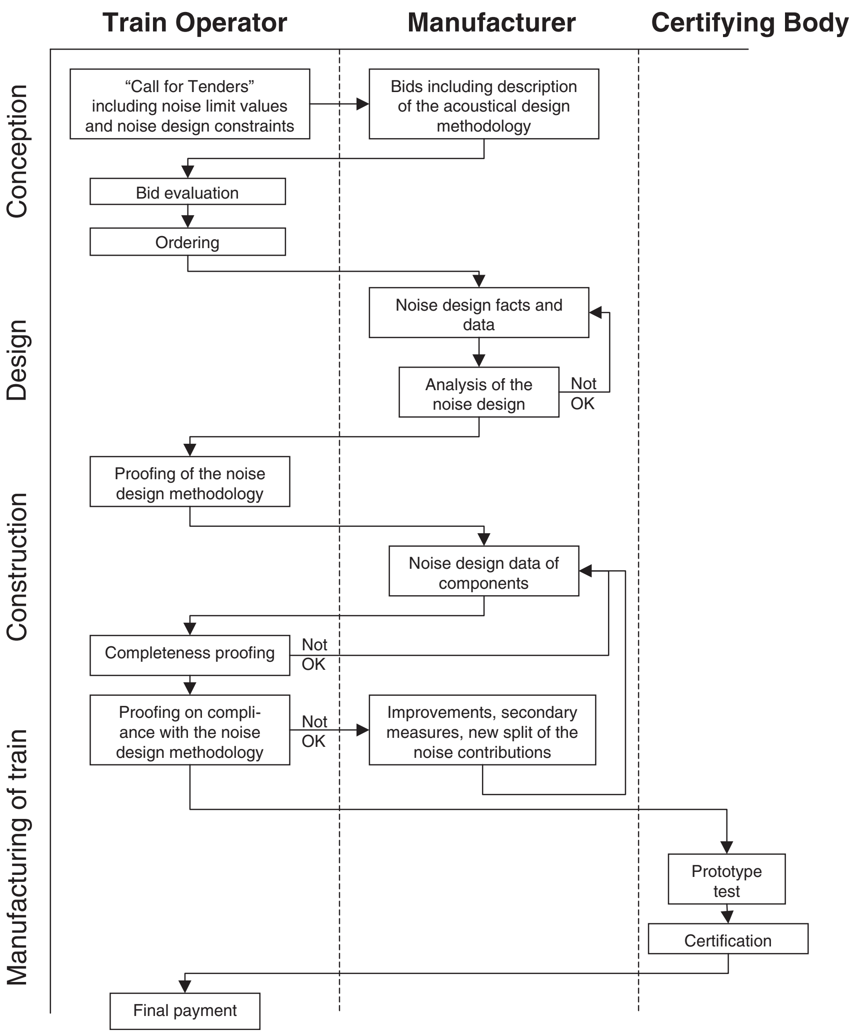


Fig. 1. Course of acoustical quality management as the joint action of train operator, train manufacturer and certifying body during the realisation process of a new train.

Together with several experts from railway-related technical and research institutions, from the railway industry and railway operators, DB has developed an "Acoustical Quality Management Scheme for Rail Vehicles" [12]. This project was performed and co-financed in the German Joint Research Programme "Leiser Verkehr" ("Quiet Traffic"). This acoustical quality management scheme establishes a systematic noise management regime to complete the vehicle procurement process in the phases of concept, design, construction and manufacturing, see Fig. 1.

The course of the acoustical quality management scheme is supported by a prediction tool for exterior noise and a database. The prediction tool is based on the assumption that the vehicle has an open superstructure, e.g. it is sufficient to describe the noise sources and the noise reflections at the inner absorbent structure (walls) of the vehicle and methods of room acoustics such as the ray tracing and mirror source technique. The database contains all mechanical dimensions and acoustical details of the vehicle, such as construction and superstructure, engine, type of brakes and wheels, auxiliary devices together with acoustical descriptions of track types, and grows together with the development status of the new railway vehicle.

To meet the goal to arrive at less overall noise emission of trains, the strength of the dominant noise sources has to be reduced step by step. Once a source is eliminated, another source with less intensity than the former one originally had will play the dominant role. During the development process of a train, it is important to recognise such phenomena early and to implement countermeasures in good time. From the manufacturers' point of view, the fulfilment of the TSI limit values is essential for the commercial success of new trains.

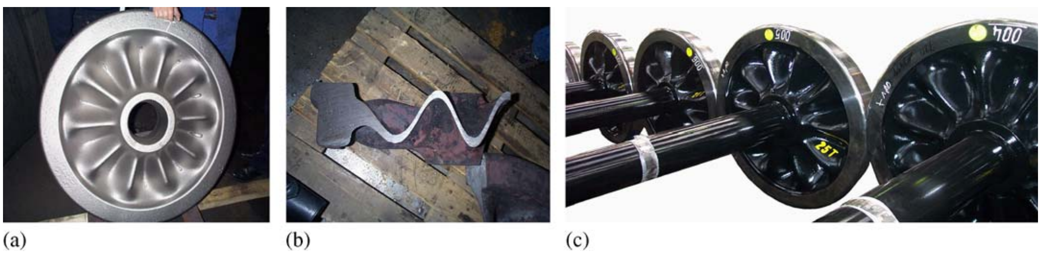
3. Enhanced noise reduction at source

3.1. Recent developments in reducing noise generation of freight train wheels

Reducing sound radiation at the source is the first-choice solution, as it proves to be the most effective countermeasure in terms of an indicator relating noise reduction to investment costs.

Railway coaches and wagons are equipped with up to eight wheels, and the discs and rims of these wheels are excited by the wheel/rail interaction and dominate the overall sound radiation up to medium velocities. Since in freight traffic this large radiating area per unit train length cannot be reduced because of axle load limitations, quiet railway wheels for use with block brakes will play an important role in future to meet the goal of a low-noise railway system. Basic studies concerning the optimum shape with respect to the acoustic requirements of 5 dB(A) noise reduction have already been reported in Refs. [10,13]. The sound field around the wheel was simulated with the commercial Boundary Element code SYSNOISE. The variation in noise emission of the different wheel shapes was compared with the standard wheel BA 04. Systematic analysis with the commercial finite element code ANSYS led to the low-noise wheel shape. In Fig. 2 the geometry and dimension of the low-noise prototype freight wagon wheel for block-braked operation is shown.

The noise optimisation approach was different from attempts in the Silent Freight project [14]. Contrary to a stationary wheel, the work of the excitation force of a rolling wheel is only non-zero for a wheel resonance where the wheel vibration mode is identical with a harmonic of the stimulation roughness of wheel and rail running surface. Moreover, vibration amplitudes of axial wheel modes are significantly larger than radial and tangential vibration modes. These two concepts were used in the optimisation of the wheel shape. This leads to



(a) (b) (c)

Fig. 2. Low-noise prototype freight wagon wheel for block-braked operation ((a) side view and (b) horizontal cut through the wheel and (c) full wheel set ready for assembly).

the result that the axial modes had to be shifted into a frequency area where no excitation is possible. In fact the most disturbing mode was shifted from 1717 Hz (normal wheel BA 14) to 3454 Hz by stiffening the wheel structure in the axial and radial directions by a specific tangential and radial "waviness" of the wheel disc [15]. For load measurements and the operational tests, 26 such low-noise wheels were produced from the standard R 7 wheel material.

Besides DB as a freight wagon operator, the wheel manufacturer Gute-Hoffnungs-Hütte Radsatz GmbH, Dresden Technical University and wheel and brake engineers are involved in the project to clarify questions of the casting process and of brake and running safety [16].

The acoustical shape optimisation tackled the range of the excitation frequency between 550 and 1100 Hz. This corresponds to the wavelength of the rail surface corrugation, between 3 and 6 cm, at a typical freight train speed of 120 km/h. However, in this frequency range the predicted noise reduction effect could not be verified. The reasons are probably the following:

- A vibration mode of the wheelset may be coupled to the bending mode of the wheelset axle, which was noticed to be acoustically relevant.
- The sound radiation of the rail itself in the regarded frequency range may mask the wheel noise.

On ground and corrugated rail surfaces, a reduction of the rolling noise between 1.6 and 2.4 dB(A) was measured, and an average value of 2 dB(A) could be confirmed. Compared to the estimated potential, the acoustical field measurements show that the wheel shape is still not at an optimum and also that the noise reduction potential of freight train wheels and wheelsets is not easy to realise.

Fig. 3 shows the one-third-octave spectra of the sound pressure level (SPL) considering both corrugated and non-corrugated rail surfaces. On the corrugated tracks the quality of the rail surfaces dominates the excitation. Corrugation with an amplitude 15 dB (re 1 μm) at a wavelength of 3.15 cm is the maximum. At a train speed below 100 km/h, this wavelength is responsible for excitation frequencies below 1 kHz. Below this frequency no real reduction was measured for the low noise wheel, see, e.g., the one-third-octave mean frequencies at 800 Hz ($v = 100$ km/h) and 630 Hz ($v = 80$ km/h). The reason is that on corrugated rails with a strong excitation at approximately 870 Hz a vibration mode of the wheelset's vibration modes is excited (upper dotted curve in Fig. 3). This peak vanishes on non-corrugated rail because it is not excited (lower dotted curve in Fig. 3).

The field measurements for the confirmation of the noise reduction properties led to several new insights concerning the relationship between the shape dynamics of the wheel and the noise emission. The measured noise reduction of 2 dB(A) is a promising value although the forecast was not met. On the one hand, it must be taken into account that most noise reduction technologies act in the low single-figure range of dB(A). On the other hand, it is found that there is a potential for noise reduction by wheel shape optimisation.

In a special test bench with a block-brake device and mounted *K*-blocks of the Becorit company, the mechanical and thermo-mechanical properties were examined with the following results:

- The criteria for the wheel disc deformation under cold and hot conditions were fulfilled.
- Even before the tests the treated wheel rim showed a significant level of internal stresses. In the residual stress tests according to UIC 510-5 rules, the requirements for the thermo-mechanical performance were not fulfilled. After the tests, unacceptably high strain occurred on the wheel tread.
- The subsequent destructive test to confirm that the thermo-mechanical dimensioning of the wheels is sufficient was not passed.
- In the bending tests according to UIC 510-5 rules (10^7 load changes with 140 MPa load), the requirements for mechanical dimensioning were met. The higher DB requirements (160 MPa load) were not met; instead, a crack-like state was noticed. The quality of the geometrically complex outer wheel surface appears not to be suitable for the high stresses which develop in real train operation.

Also, the improved treatment of the wheel rim to bring the residual stress to negative values did not lead to sufficient thermo-mechanical properties.

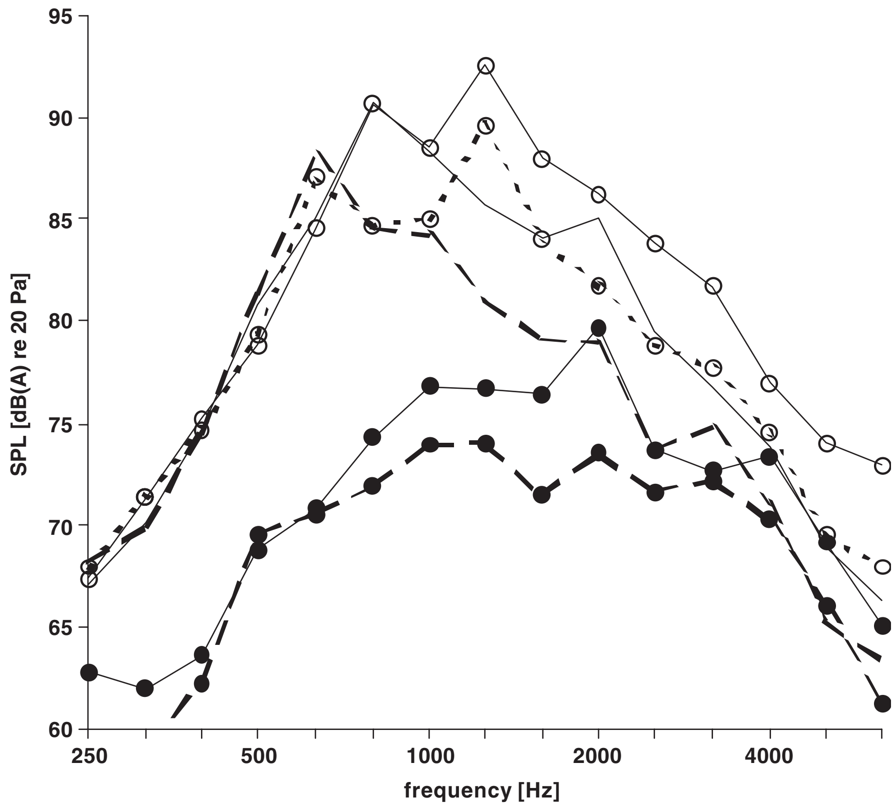


Fig. 3. One-third-octave spectra of the *A*-weighted SPL on the corrugated (bold as well as broken line w/o black dots) and non-corrugated (bold as well as broken line with the black dots) rail surface of the noise-optimised wheel and reference wheel BA 04 on corrugated rail surface (bold as well as broken line w/o white dots) at measuring point 7.5 m from the track at a height of 1.2 m, freight train velocity $v = 80$ km/h (broken line) and 100 km/h (bold line).

Since not all safety-relevant limit values for the wheel's mechanical integrity were fulfilled, the work group is currently concentrating on these issues by improving the whole manufacturing process, while maintaining the acoustical properties.

3.2. Recent developments in reducing noise generation of train cooling fans

The TSIs fix noise limit values not only for trains in motion but also for stationary trains, for example, in stations when the cooling ventilator noise is the only sound source. To show ways of reducing the noise of the cooling ventilation in locomotives, DB is a partner in a development project led by Siemens. Several other partners from industry and scientific institutions complement the expertise and skill of the project group. This project was performed and co-financed in the German Joint Research Programme "Leiser Verkehr".

After detailed investigations of the flow path of the cooling air and the related sound radiation contribution, the first prototype of an acoustically improved ventilation path with unaltered cooling performance was tested on a type 182 locomotive, see Fig. 4. For low-noise operation, the original cooling tower was modified as follows:

- exchange of the radial fan by a radial–axial ventilator with the same performance and speed but fewer blades;
- sound-absorbing surface layer inside the ventilator housing and in the air inlet region;
- assembly of a silencer behind the heat exchanger.

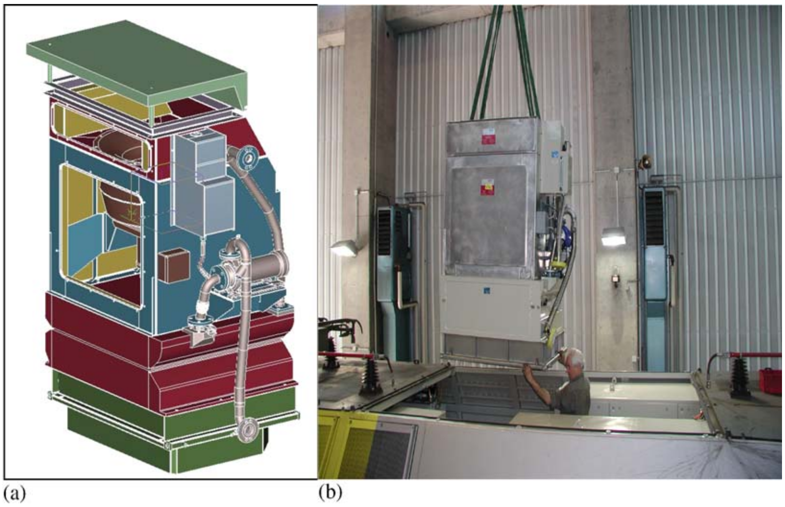


Fig. 4. Application of a modified oil cooling tower in the type 182 locomotive to investigate the noise reduction potential by optimised ventilation ((a) design sketch of the cooling tower and (b) assembly in the locomotive).

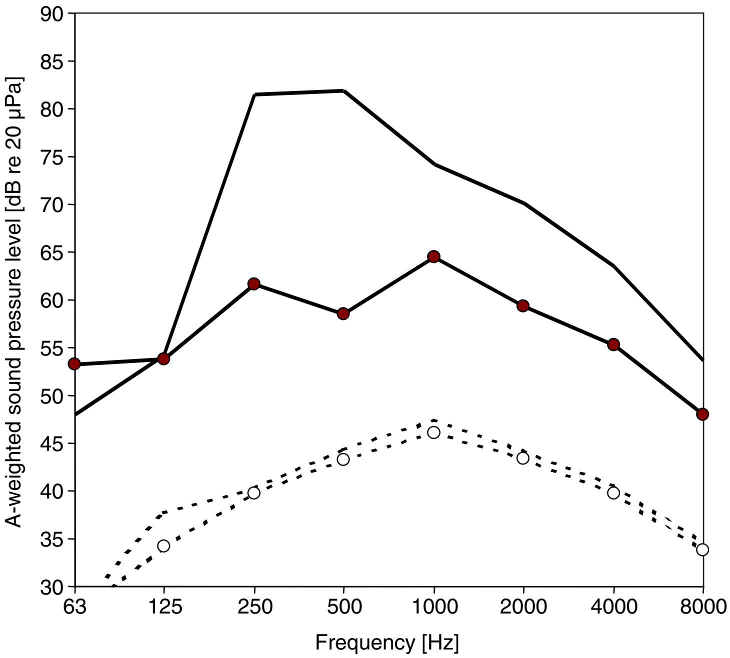


Fig. 5. *A*-weighted octave spectra of the SPL at the position of measured maximum values around the locomotive at a distance of 7.5 m (cooling fan at nominal rev/min). Bold line, original cooling tower at measurement position 9; bold line with ●-dots, modified cooling tower at position 10; broken line with/without o-dots, background noise at measurement position 9/10. For measurement positions, see Fig. 6 left part.

The SPL was measured at 12 positions around the train circumference at heights of 1.2 and 3.5 m and at a distance of 7.5 m. Comparison of the measured maximum values for the original and the modified cooling tower showed for the maximum fan speed a remarkable 15 dB(A) reduction, on average 12 dB(A) less noise was achieved (see Figs. 5 and 6) [17,18].

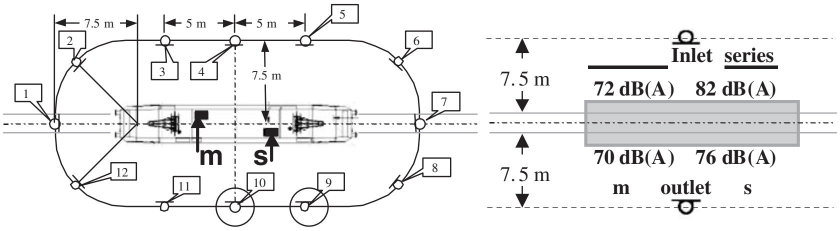
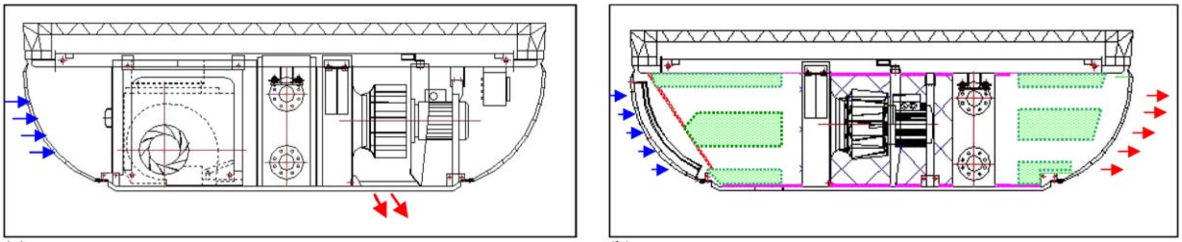


Fig. 6. Scheme of microphone measurements points (mp)–cooling modified (m) and series (s). Left: cooling tower—positions m and s. SPL at mp 10 for m: 70 dB(A) and at mp 9 for s: 85 dB(A), each at a height of 3.5 m. Right: transformer cooling. Microphone positions the same for s and m. SPL inlet s/m 82 dB(A)/72dB(A) and outlet s/m 76 dB(A)/70 dB(A).



(a) (b)

Fig. 7. Sketch of transformer cooling of the ICE-T tilting train: (a) original and (b) modified arrangement for low-noise operation.

With some further optimisation and fine-tuning, this concept can be applied to new locomotives as well as to retrofitted existing locomotives.

For EMU trains the situation is different [18,19]. The traction is distributed along the train and so is the related electrical equipment such as transformers. The transformer-cooling device which was modified for low-noise operation is shown in Fig 7. The modifications were:

- changes of the cooler–fan-arrangement and the cooling air path;
- replacement of the radial fan by a radial–axial ventilator with the same performance and speed;
- sound-absorbing covering inside the housing;
- assembly of silencers and optimisation of the dust filter at the air inlet.

SPL was measured on the air inlet and outlet sides at a distance of 7.5 m and at a height of 1.2 m (Fig. 6), the fan was operated with the nominal number of revolutions. The octave spectra of the SPL are shown in Fig. 8. Comparison of the measured maximum values for the original and the modified transformer cooling showed a remarkable 9 dB(A) reduction on the inlet side and 6 dB(A) on the air outlet side. With some further optimisation and fine-tuning, this concept can be applied to new trains as well as retrofitted to existing EMUs.

3.3. Recent developments in reducing noise generation of bridges

In the following, the effect of bridge noise and the first results of the DB-internal project ‘‘Leise Brücke’’ (‘‘Quiet Bridge’’) will be described, which focuses on the optimisation of measures to reduce bridge noise.

The acoustic problems associated with railway bridges are well known. When a train passes over a bridge, noise can be heard beside and under the bridge. This effect arises from the vibrations generated at the wheel–rail contact point, which are transmitted into the bridge structure. Vibrations are incited in the components of the bridge and consequently noise is emitted. This so-called ‘‘secondary air-borne noise’’ is particularly distinct at low frequencies. To assess the annoyance of residents caused by the bridge noise, unweighted sound–pressure levels instead of *A*-weighted levels are used in Germany. Fig. 9 shows typical

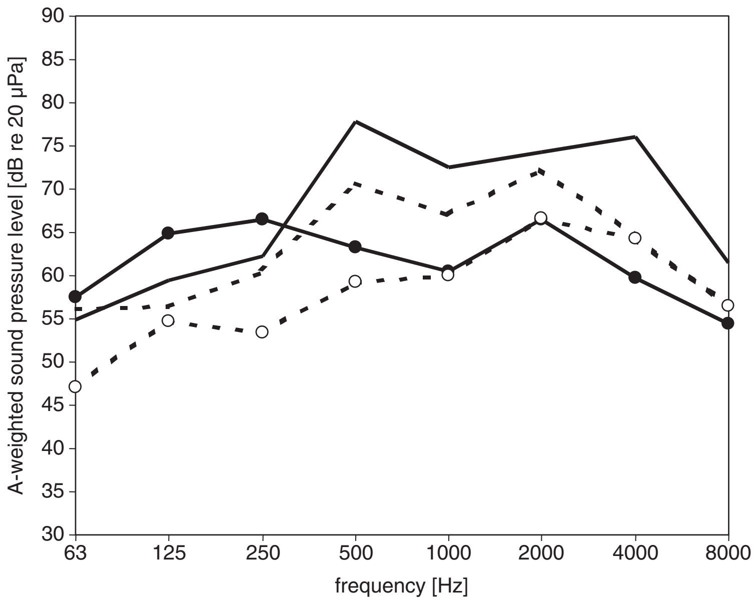


Fig. 8. *A*-weighted octave sound pressure level original vs. modified transformer cooling unit measurement positions at a distance of 7.5 m and at a height of 1.2 m (cooling fan at nominal rev/min). Bold line, with/without ●-dots, measured at the air inlet side of the modified/original transformer cooler. Broken line with/without o-dots, measured at the air outlet side of the modified/original cooler. For measurement positions, see Fig. 6 right part.

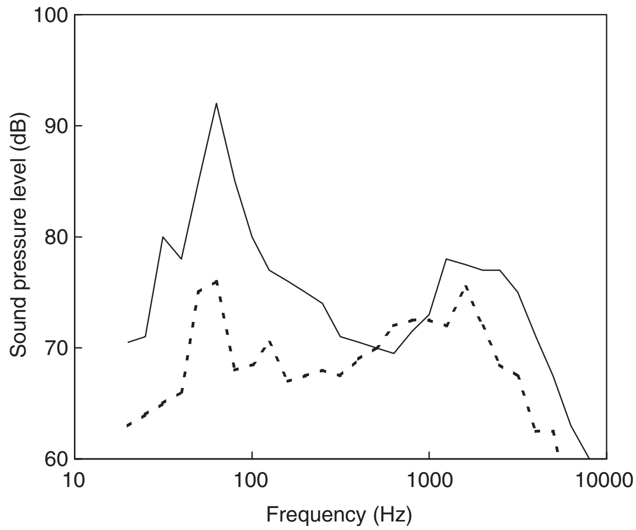


Fig. 9. Typical SPL for hollow box bridges made of steel (bold line) and concrete (dotted line) measured at a distance of 25 m during the pass-by of passenger trains at a velocity of 130 km/h.

spectra measured during the pass-by of a train for a steel and a concrete bridge. As could be seen, the noise level emitted by a typical concrete bridge is much lower than the noise level emitted by a typical steel bridge.

The effect has been investigated at DB during the last 30 years [20]. Up to now, the noise problems associated with railway bridges have been dealt with primarily empirically and experimentally. Despite the expenditure that has been made in recent years, the known noise-reducing measures are still not sufficient in many cases and there are hardly any specifications for the construction of low-noise bridge structures. Particularly in view of the large variety of bridge designs, the approach adopted by the DB project "Leise

Brücke'' is an effective and cost-efficient combination of experimental investigations with simulations to produce low-noise bridges [21,22].

Today, the main means used to reduce bridge noise is to introduce resilient elements in the track structure. Typical measures on the track–bed structure are resilient rail fastenings, under-sleeper pads and ballast mats. As constructional measures for new bridges, stiffening of the deck plate, stiffening of radiating bridge parts and improved construction rules are to be applied. Because of the large number of influence parameters, the efficiency of the measures can only be predicted by using simulations.

For the optimisation of measures, the prediction of noise radiated by any bridge type is needed. Based on the finite element method (FEM) and statistical energy analysis (SEA), different simulation concepts to predict bridge noise have been proposed in the past, which are mainly focussed on particular frequency bands [23–25]. Because the assessment of bridge noise in Germany is based on the unweighted SPLs, the whole frequency region has to be considered. Therefore, an extended simulation concept based on both simulation methods, FEM and SEA, will be developed and applied in the project. The development process of this simulation tool covers a cost–benefit analysis, an assessment of data and models, experimental investigations, development and validation of a simulation concept, as well as its application.

The cost–benefit analysis has been performed in order to identify problematic bridge types and measures which should be optimised. Important input parameters for the analysis are the distribution of bridge types, typical sound radiation of the bridge types without measures and the efficiency and costs for the noise-reduction measures. As a result of this investigation, it was found that a distinction has to be made between direct and retrofit measures and between steel and concrete bridges. Construction measures are reasonable for newly built steel bridges, under-sleeper pads for steel and concrete bridges, ballast mats for steel and concrete bridges, and elastic rail fastenings for old steel bridges without ballast.

The development and validation of the simulation tool focuses on an effective prediction of the sound radiation of any bridge type. An impedance model such as that integrated in the program RIM, which has been developed and validated for the DB [26], is used for the rolling noise and the vibration transmission into the bridge structure. The sound radiation at low frequencies is calculated by a commercial FEM code to model the bridge construction in detail. To compute the sound radiation at high frequencies, SEA is used as an efficient and reliable analysis method. Main aspects for the development of the simulation concept are the interface for the data transfer between the simulation tools and the determination of the correct simulation parameters for the bridge, the track and the trains considered. The simulation concept will be validated by using vibration and SPLs measured during the pass-by of trains at three different bridge types.

As an example for the simulation of the vibration generation, Fig. 10 shows simulations of the insertion loss of a ballast mat and an under-sleeper pad as a function of the input impedance. The input impedances have

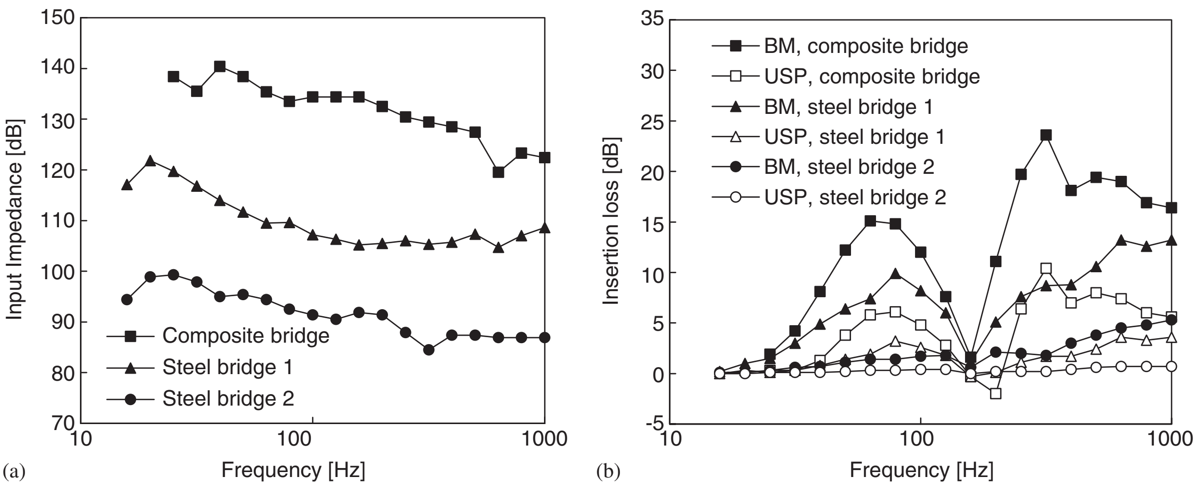


Fig. 10. (a) shows the input impedance for three different bridges, which are used for the simulations of the insertion loss as shown in (b). Using the program RIM, the insertion loss was calculated for a ballast mat (BM) and an under-sleeper pad (USM).

been measured at different bridge types in Germany. It is shown that the insertion loss is highest for the concrete bridge and lowest for the very soft steel bridge. These results are supported by published measurement results [20]. From these simulations, it can be concluded that the measures have to be optimised in order to obtain a reasonable insertion loss for the application to steel bridges.

The project "Leise Brücke" will be completed at the end of 2006. At that time, the validated simulation concept will be available.

4. Conclusions

As one of the major railway undertakings in Europe, DB performs continuous research to respond to public demand for railway traffic with low environmental impact. The aspects of the reduction in the generation of noise are being tackled in several projects together with experts from manufacturers. Joint research projects provide a common basis of knowledge and strongly support the harmonisation of existing national rules and guidelines for train design and operation.

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References

[1] CALM Research Network, Research for a Quieter Europe, European Commission Research Directorate-General, www.calm-network.com, July 2002.
[2] European Rail Research Advisory Council (ERRAC), Strategic Rail Research Agenda (SRRA), September 2002. www.unife.org
[3] M. Jaecker, Strategies of the German Government for the Reduction of Railway Noise and their European Context, *INTERNOISE* 2000, Nice, France, 27–30 August, 2002.
[4] Deutsche Bahn AG, Umweltbericht 2000, Berlin, 2000.
[5] Deutsche Bahn AG, Umweltbericht 2002, Berlin, 2002.
[6] Bundesministerium für Verkehr, Wohnungs- und Bauwesen. http://www.bmvbw.de
[7] P.H. de Vos, M. Bergendorff, M. Brennan, F. van der Zijpp, Implementing the Retrofitting Plan for the European rail freight fleet, *Journal of Sound and Vibration*, this issue (doi:10.1016/j.jsv.2005.08.054).
[8] Deutsche Bahn AG, *Key Environmental Data 2003*, Berlin, Germany, 2005. www.db.de/environment
[9] L. Willenbrink, A. Martens, A. Zakel, M. Beier, Nachhaltigkeit der akustischen Auswirkung von K-Sohlen, DB Systemtechnik, Internal Reports 101.1-PR-012-01, 2001 and 101.1-PR0061-03-02, 2003.
[10] B. Schulte-Werning, M. Beier, H.-P. Grütz, K. Jäger, G. Kock, J. Onnich, R. Strube, Headed for the low-noise railway: the DB noise reduction research programme, *World Congress on Railway Research WCRR 2001*, Cologne, Germany, 25–29 November, 2001.
[11] B. Schulte-Werning, K. Jäger, R. Strube, L. Willenbrink, Recent developments in noise research at Deutsche Bahn (Noise assessment, noise source localisation and specially monitored track), *Journal of Sound and Vibration* 267 (2003) 689–699.
[12] M. Staiger, Akustisches Qualitätsmanagement für Schienenfahrzeuge*, Abschlussbericht BMBF-Forschungsverbund "Leiser Verkehr" AP 4210*, April 2004.
[13] W. Behr, L. Willenbrink, K. Degen, M. Beier, C. Katzenschwanz and D. Stüwing, Modelling of wheel sound emission by computer-simulation, *World Congress on Railway Research WCRR 2001*, Cologne, Germany, 25–29 November, 2001.
[14] B. Hemsworth, R.R.K. Jones, Silent Freight Project—Final Report, ERRI, Utrecht, September 2000.
[15] D. Stüwing, Schalltechnische Strukturoptimierung eines Vollrades für Reisezugwagen, Institut für theoretische Grundlagen der Fahrzeugtechnik, Technische Universität Dresden, Dresden, 2002.
[16] M. Beier, D. Müller, D. Stüwing, T. Gerlach, K-Sohlen geeignetes Eisenbahnrad für Güterzüge im Geschwindigkeitsbereich bis v = 120 km/h mit um 5 dB(A) geringerer Schallabstrahlung, DB Systemtechnik, Internal Report 101-Be-0026-03, 2003.
[17] K. Bay, P. Brandstätt, R. Rambausek, Mitigation of the ventilation noises at the electric locomotive BR 182, DAGA & SFA 22.-25.03.2004, Straßburg.
[18] M. Beier, C. Gerbig, DB-interner Abschlussbericht zum Arbeitspaket Minderung der Lüftungsgeräusche angetriebener Schienenfahrzeuge, DB Systemtechnik, Internal Report 012-BE-0003-04, 2003.
[19] G. Reiß, Minderung der Lüftungsgeräusche von Schienenfahrzeugen, *Status-Seminar zum BMBF-Forschungsverbund "Leiser Verkehr", Bundesministerium für Bildung und Forschung,* Bonn, 17–18. June 2003.
[20] G. Müller, M. Möser, *Taschenbuch der Technischen Akustik*, Springer, Berlin, 2003.
[21] D. Stiebel, W. Behr, W. Brandl, K.G. Degen, Silent Railway Bridges, DAGA & SFA 22.–25.03.2004, Straßburg.

[22] D. Stiebel, W. Behr, W. Brandl, K. G. Degen, Maßnahmen zur Reduzierung des Brückendröhnens, DAGA 05, München.

[23] M.H.A. Janssens, D.J. Thompson, A calculation model for the noise from steel railway bridges, *Journal of Sound and Vibration* 193 (1996) 295–305.

[24] J.G. Walker, N.S. Ferguson, M.G. Smith, An investigation of noise from trains on bridges, *Journal of Sound and Vibration* 193 (1) (1996) 307–314.

[25] F. Poisson, Noise of railway steel bridges: a complete study, *Proceedings of WCRR 2003 (on CD-ROM)*, Noise and Vibration Session 21.6, Edinburgh, 2003.

[26] R. Diehl, G. Hölzl, Prediction of wheel/rail noise and vibration—validation of RIM, *Proceedings of EURONOISE 98*, München, 1998, pp. 271–276.