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Identification, modelling and reduction potential of railway noise sources: a critical survey

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Abstract

Environmental requirements for railway operations will become tighter in the future. In particular, annoyance due to railway noise has to be taken carefully into account in the expansion of freight traffic as well as in new high speed line projects. Reduction of noise at source can be more attractive than the use of noise barriers but this requires a thorough understanding of the source mechanisms. This paper presents a critical survey of the identification and modelling of railway noise sources and summarizes the current knowledge of the physical source phenomena (mainly rolling and aerodynamic sources) as well as the potential for noise reduction. Future research perspectives are also given. These concern, in particular, improvements to source modelling, especially for aerodynamic noise, investigation of other sources and development of more advanced models for predicting railway noise in the environment. These should include a better description of the sources, obtained from modelling.

1. Introduction

A good knowledge of the nature and relative strengths of the various sources of noise is a fundamental requirement if railway noise is to be understood and, moreover, to be reduced.

Indeed, as soon as the noise level from a moving, or stationary, train is measured, two questions immediately arise:

- Where does the noise come from on the train and track?
- How could it be reduced?

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It is readily apparent that, as is often the case in acoustics, various sources may contribute to the overall noise level. Initially, therefore, the investigation is directed towards identifying each source individually, then towards understanding its generation mechanism in order, finally, to enable its reduction. The basic reason for investigating source mechanisms is that, in many cases, due to system considerations, simple shielding of the sources is not possible. Also, for reasons of efficiency in terms of reduction, the depth of knowledge necessary for each source has to be considered, with respect to the state of the art in the subject. Whereas reduction measures can be considered for some types of aerodynamic noise, progress is still needed in terms of modelling. On the other hand, reduction measures developed for rolling noise benefit from a deeper understanding of the physical processes involved.

The paper first reviews methods relevant to source identification, with a focus on the most promising advances and on areas where knowledge is still insufficient. The methods of modelling the main railway noise sources are then reviewed. Finally the potential for noise reductions is discussed.

2. Identification

For some time, source identification on trains has been more than simply measuring pass-by levels with a single microphone. More advanced methods have proved useful which involve either microphone arrays or a combination of different sensors. These are reviewed here.

2.1. Microphone arrays

The use of acoustic arrays for studying railway noise was introduced more than 20 years ago. More recently, for example, the German-French joint study for the identification of aerodynamic sources on high speed trains 'Deufrako' [1] developed the technique more effectively. It has also been used for the characterization of noise sources on upper parts of the Shinkansen vehicles in Japan [2] and for the identification of noise sources on the ACELA vehicles in the USA [3].

In relation to source localization on high speed trains, it is important to take account of:

- The effect of the high speed of the moving sources which induces a Doppler shift in frequency and a variation in the amplitude in the received signal.
- The turbulent boundary layer, which develops around the train, as well as the ground effect. These may modify the propagation and therefore are likely to affect the directivity of the sources. They may also influence the array behaviour.

Accurate measurements on a high speed train require the development of specific tools. The 'dedopplerisation' method is currently used to introduce corrections, due to the Doppler effect, into the signal recorded by the array. Specific configurations of arrays are necessary to localize railway sources with a good degree of resolution. The measuring station used by IABG and Akustik Data in Deufrako Annexes K and K2 [1] to obtain a map of turbulent boundary layer sources on the roof of a TR07 vehicle is illustrated in Fig. 1. Further studies have shown that a star shape can improve the array resolution by reducing the secondary lobes in the localization

Fig. 1. Turbulent boundary layer sources on the roof of a TR07 vehicle.

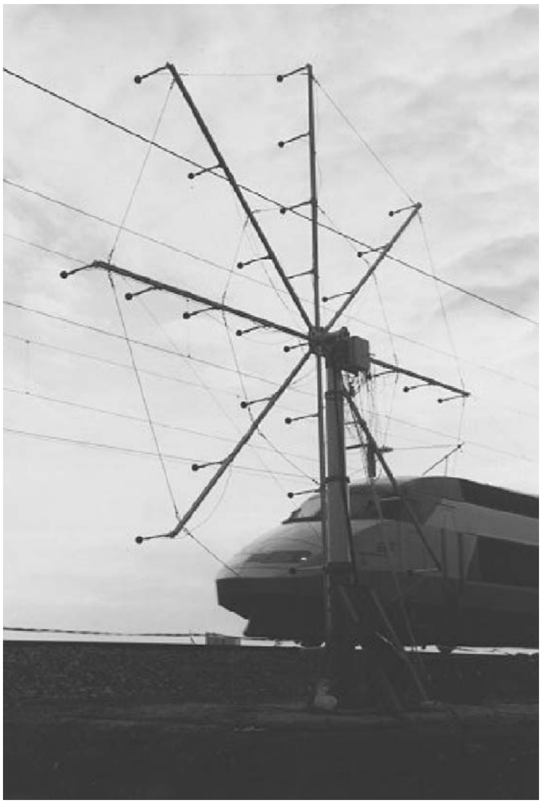

Fig. 2. The star array developed at SNCF.

Fig. 3. Spiral array developed at DB-AG.

images. The star array developed at SNCF, illustrated in Fig. 2, consisted of 29 microphones distributed along 8 branches of the star. DB-AG has also developed an array in a spiral shape as illustrated in Fig. 3 [4].

The analysis of the array signal in different frequency ranges enables classification of the different types of source. Moreover, different array configurations can be used to study different ranges of frequency.

Advanced methods to improve array measurements have been investigated in the last few years. One was carried out at the University of Le Mans and at SNCF, and used time–frequency and 'time-scale' tools [5]; a localization technique provides, for each source, the acoustic power, the position along the train, the height and the spectrum. The time–frequency analysis enables a refined analysis of the emitted signal. If it is localized in position and frequency, the directivity pattern of the source can be computed with this method [6].

Another method, called source density modelling (SDM), was investigated by Daimler Benz in Deufrako Annex K2 [1,7]. This method could be considered to be complementary to established data treatment methods, its main advantage being to give an estimate of the actual power of acoustic sources rather than only the emission level at several metres distance. When more accurate information is necessary on one particular source, the method is quite useful. However, the method is as yet limited to simple cases.

Whereas these methods were developed for identification of sources on high speed trains, source quantification and localization on freight trains were also performed through the EU Metarail sponsored research project by using a T-array with 48 microphones involving a swept focus technique [8].

2.2. Combination of different sensors

Techniques involving a combination of different sensors can provide further information in the identification of sources.

2.2.1. Combined noise and vibration measurements

Rolling noise is influenced by wheel and rail roughness, train speed and the particular combination of vehicle and track (see Section 3.1). One important issue for the future will be to define type-testing methods to characterize the vehicle noise in operating conditions. Previous international standards have lacked precision because no account was taken of the surface roughness. Roughness measurements will therefore be required as part of any new standards. Measurements directly on the wheel and rail surfaces require either a track possession or taking the vehicle out of service. An indirect technique was developed in Metarail, which provides an alternative to direct roughness measurements [8]. This consists of measuring rail-head vertical vibration during a train pass-by and using it to extract the total roughness. Additionally, information on the track dynamic properties can be obtained, such as the decay of vibration with distance.

Current developments in Europe mean that separating the noise contributions of the vehicles from that of the track is becoming necessary in order to identify the separate responsibilities of infrastructure authorities and train operators. Array techniques cannot have sufficient resolution to separate wheel and rail contributions, particularly at low frequencies. A measurement method was proposed in the Metarail project for separating track and vehicle noise using a quiet reference vehicle. Tests were performed in different countries [8]. Diagnostic techniques were also investigated which allow the noise contribution originating from the track to be separated from the total pass-by noise, by using multiple vibro-acoustic transfer functions and pass-by vibration responses.

This work is continuing through the EU sponsored STAIRRS research project, to provide methodologies to enable characterization of vehicles and track separately. Several advanced techniques are under investigation including measurements on the train and the track with different sensors and separate tests of vehicles and track. An objective is the assessment of a European classification of rolling stock and tracks.

2.2.2. COP techniques for aerodynamic sources

It has been seen that array measurements can be used to locate aerodynamic sources and classification of their frequency content. These can be complemented by on-board measurements to give a better characterization of the physical phenomena of aerodynamic sources. These can even be used to derive source models. In particular, a method called the 'causality technique' was developed by Ecole Centrale de Lyon (ECL) and Vibratec in the Deufrako Annex K2 [1] and used to characterize the aerodynamic sources in the bogie and inter-coach spacing areas of a TGV [9]. The causality technique or coherent output power (COP) uses 'phenomenological' sensors fixed near the sources and anti-turbulence sensors (Neise probes) which are expected to filter turbulence and to record mainly acoustic waves. These probes are shown later in Fig. 6 which is described in Section 3.

From the calculated correlation between the signal recorded by the phenomenological sensor and the signal received by an 'anti-turbulence' sensor, it is possible to determine whether the source radiates sound, and to estimate its spectrum. The main problem of this method is the choice of a good phenomenological sensor for which the received signal will be representative of the source, and to locate it near the source.

This type of approach is promising but must be improved; its application for modelling the bogie area sources will be discussed in Section 3.

2.3. Future

The main prospects for future work in source identification are as follows:

- A difficult subject, which has scarcely been addressed is the quantitative description of sources from array measurements. Further developments are required in array treatment to assess the actual power of acoustic sources.
- Separation methods for wheel/rail contributions involving combined noise and vibration measurements are among the most important issues for future source identification. This is due to the requirement to identify the separate responsibilities for noise emission of infrastructure authorities and train operators.
- It should be kept in mind that advanced methods in sound recording, such as 'Ambisonics', could, in addition to producing the impression of hearing a true three-dimensional sound image, give further information in source identification.

3. Modelling

In recent years, models have been developed for railway noise sources [10]. Three categories of model have been identified, both in terms of model complexity and potential use:

- Models for each individual source describe the physical processes associated with the source. They help to contribute to the understanding of the mechanism of noise production and allow prediction of the efficiency of different solution concepts. These models can be either numerical models or models developed from experimental databases, although only the former can be used reliably for predicting the effects of new solutions.
- Propagation models include advanced algorithms for the calculation of sound propagation (meteorological and ground effects, propagation paths). The sources can be described as point or line sources and trains are usually specified in terms of traffic types.
- Intermediate models could also be useful to help to assess the overall noise reduction potential. The description of sources is generally more detailed, and propagation algorithms less accurate, than for propagation models.

The following sections discuss the current status of modelling within these categories, with the first category being considered in most detail and being divided into separate sections on rolling noise and aerodynamic noise.

3.1. Rolling noise modelling

The noise generated by a wheel rolling on a rail was the subject of considerable research in the 1970s and 1980s, from which comprehensive theoretical models were developed, most notably the TWINS software [11]. These models have been validated by extensive field experiments [12]. It is, therefore, now well established that rolling noise is caused by structural vibrations of the wheel, rail and sleepers induced by the combined surface roughness of the wheel and rail running surfaces [13]. The main focus of research into rolling noise in recent years has, therefore, been the application of theoretical models to the design of low noise wheels and tracks, as will be described in Section 4.1.

Nevertheless, there have been a number of recent developments in rolling noise modelling. Several extensions of the TWINS model have been made, including, notably, the ability to model slab track, the addition of a module for bogie shields and low barriers based on statistical energy analysis [14], and consideration of vehicle superstructure noise, although the latter has been shown to be insignificant compared to the wheel and track for typical freight vehicles [15]. Improved models for wheel and rail radiation have been implemented [13] along with a more realistic model for the ground reflection. As a result, comparisons with experimental results show improved agreement and the validation of the models has also been extended through recent European projects [16].

In addition to this, studies have been carried out into a number of effects on track vibration and noise. Track support structures contain non-linear elements, rail pads and ballast. These stiffen under pre-load so that the track under a wheel load is stiffer than elsewhere. This has been shown to have significant effect on the point receptance of the track and the contact force, but its effect on the noise radiation has been found to be at most 3–4 dB [17]. The wheels themselves are also dynamic systems attached to the track and can cause reflections of waves in the rail. This leads to standing waves, particularly in the frequency range 600–1500 Hz [17]. The effect is strongest for soft rail pads. Interestingly, it leads to the cancellation of the peak at the pinned–pinned frequency when more than one wheel is present on the rail. A third effect that has been studied is the influence of random variations in sleeper spacings and pad and ballast stiffnesses [18]. This has been shown to have only small effects on the radiated noise. Wu and Thompson have also developed efficient models for the rail vibration that include the effects of cross-sectional deformation of the rail without the complication of finite element models [19,20].

Although the non-linearities within the track structure can be dealt with using a linear model with pre-load dependent stiffnesses, non-linearities at the wheel/rail contact zone have been the subject of recent studies. The contact spring is non-linear and its approximation by a linearized spring is required if a frequency-domain model is to be used. It has been shown, using a time-domain model, that for normal roughness amplitudes and wheel loads, a linear model is acceptable, but that for larger amplitudes or smaller wheel loads non-linear effects can become significant [21]. This is associated with loss of contact. This has now been extended to include wheel flats and rail joints and models have been produced for the noise radiation due to these events [22,23].

Within the STAIRRS project, an alternative modelling approach is being pursued based on a database of experimental and/or predicted functions [24]. Various levels of detail are identified depending on the extent to which the vehicle and track contributions are to be separated. At the most detailed level, the wheel and rail roughnesses are identified along with transfer functions describing the vehicle and track sound radiation for a unit roughness input. If it can be assumed that the vehicle and track designs do not affect the transfer function of the other, these functions can be obtained from one location and used at another. However, this assumption is not always valid and the more rigorous theoretical models are required to assist in the 'translation' process.

3.2. Aerodynamic noise modelling

3.2.1. Numerical simulations

Aeroacoustics is a recent subject of research and even more recently of numerical modelling. Different approaches can be found to tackle aeroacoustics using numerical tools. A first approach involving the resolution of the turbulent viscous flow surrounding a three-dimensional train shape, with a '$k-\varepsilon$ code', was carried out through co-operation between SNCF and ALSTOM Transport (ATREBAT project) [25]. This approach cannot be considered as a real aeroacoustic simulation (CAA: computational aeroacoustics), but instead is an acoustic interpretation of aerodynamic simulations (CFD: computational fluid dynamics). Reynolds Averaged Navier–Stokes (RANS) calculations have thus been carried out with the code StarCD on an inter-coach gap of a TGV including the complex bogie geometry. The idea was to identify the turbulence-producing areas and to classify the different sources according to their extent and level. It must be kept in mind that this type of calculation can only give information on steady sources due to the fact that the equations are averaged, and the description of turbulence is statistical. Nevertheless, this approach can be sufficient to classify different solution concepts and to select the most efficient, which can be tested later in a wind tunnel.

CAA is being developed into a practical tool and two approaches can be identified as having potential for future industrial applications.

The first approach consists of a direct solution of compressible and unsteady Navier–Stokes equations, providing with in the same calculation both aerodynamic and acoustic fields. Specific algorithms have been developed recently and simple cases can be computed at the moment [26]. The limitation of the method is mainly due to the computing effort required.

The second approach consists of a separated calculation of aerodynamic and acoustic fields. One such method was tested some years ago by SNCF in co-operation with Ecole Centrale de Lyon and Framatome (SAMBA project). The idea was to use Lighthill's theory for aeroacoustic calculation of simple geometries (jets, steps, cavities, wakes). Source models were built from CFD data. Each model, which was two-dimensional, was derived from different specific theories (Ribner and Goldstein models for jets, Howe diffraction models for cavities, Blake formulations for wakes, etc.) and compared to experiments in a wind tunnel. For example, a simple cavity with the same aspect ratio as a pantograph cavity [27] and a wake with a TGV section shape were studied. An intrinsic limitation of this method for industrial applications is that each case must be modelled analytically.

'Large Eddy Simulation' could be a good alternative, falling between RANS and direct simulations. This method consists of separating the different scales of turbulence:

- Large scales of turbulence, which produce most of the energy and are thus mostly responsible for noise generation, are explicitly resolved.
- An appropriate model (sub-grid scale model) is used for the action of turbulent eddies, smaller than the size of the computational mesh, and must correspond to the dissipative scales.

The source term is calculated from the LES results and then implemented in the linearized Euler's equations for the acoustic propagation [28]. SNCF has recently chosen to test this method in co-operation with PSA, EDF and ECL for a forward–backward facing step. Fig. 4 shows the vorticity field obtained at one iteration of the LES calculation (using an EDF program) and Fig. 5 illustrates the interpolation of the source term on the mesh used for the acoustic calculation. Results from numerical models have been compared with experiments [29] and the agreement is encouraging. Numerical tools in CAA are promising but are still limited to simple cases. Further developments are therefore still required.

3.2.2. Semi-empirical modelling

DB-AG has developed a semi-empirical simulation tool for pantograph noise optimization. This calculates the sound levels according to the well-known expression for the sound pressure emitted by slender cylindrical bodies under different flow conditions [30]. The software uses a link to a database which contains experimentally obtained values of Strouhal number, unsteady lift value and correlation length as a function of Reynolds number and structure dimensions. The sound level radiated from each cylindrical structure can be calculated, as well as the peak frequency. The overall sound emission can be obtained by a summation of the levels of each structure. In addition to the geometry of the structure, some other properties such as the turbulence of the flow, the end parameter of the structure (open end, rounded end) and the roughness of the surface can be taken into account.

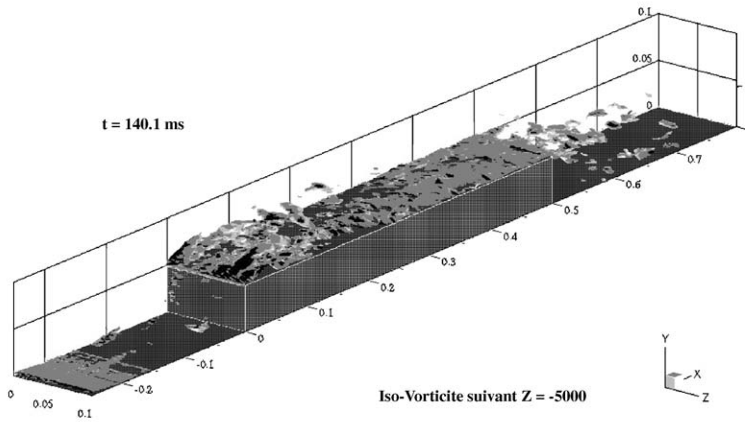

Fig. 4. One iteration vorticity field.

3.2.3. Modelling from experimental data

Another way of modelling aeroacoustic sources uses data from on-line measurements carried out with the COP technique described previously, and illustrated in Fig. 6. Analysis of these measurements showed that this region can be considered as a sum of uncorrelated sources, with three main sources identified. For each point source, a spectrum can be extracted from the measurements and can be used to build source models for overall modelling.

The purpose of modelling was to build a spectrum in one-third octave bands along with some relevant peaks to represent the experimental spectrum [31]. Fig. 7 shows the final spectrum compared to the measured spectrum.

3.3. Propagation models

Outdoor sound propagation is an area which cannot be completely described analytically. This is due to the complexity of the phenomena and the large number of parameters involved in the description of the physics from the emission to the reception of sound (absorption, meteorological conditions, ground effects, screening and diffraction of barriers, reflection and screening effects in built-up areas, vegetation screening, three-dimensional topography).

Models use point or line sources and the long-term behaviour of the sources must also be well defined. For railway traffic noise, the description of sources is obtained by extrapolation of measurements carried out at a rather short distance from the track and for a representative range of rolling stock and track types. Models to predict environmental railway noise, such as 'Mithrafer' in France, 'Schall 03' in Germany, the Dutch 'Standaard Rekenmethode' or 'Calculation of Railway Noise' in the UK, predict noise from railway traffic for a given series of various trains types and traffic schedules, over a range of distances, at least over a 24 h period, and incorporating different meteorological conditions.

When compared with noise measurements, models such as Mithrafer have shown an ability to predict daytime L_{Aeq} up to 400–500 m within 2–3 dB accuracy.

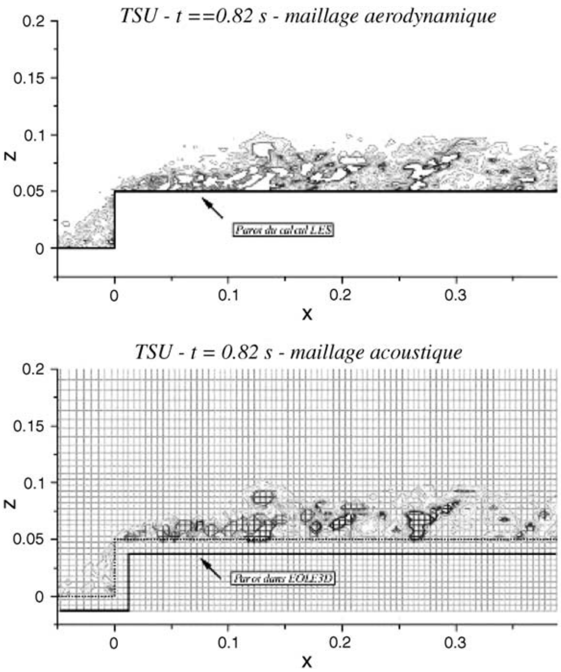

Fig. 5. Interpolated source term from LES calculation.

The description of the sources is one of the main issues to be resolved for good prediction of environmental noise; the long-term behaviour of the sources, their position and a full description, including their directivity, are required. There will also be a need to provide separate information on the vehicle- and track-related source aspects (see Section 2.2.1).

3.4. Intermediate models

Intermediate models could also be useful in helping to assess overall noise reduction potential. The description of sources is generally more detailed, and propagation algorithms less accurate, than in propagation models. An example of such a model was the ProHV program or ADPRO developed more recently by Barsikow. The MAT2S software, developed by SNCF in the Deufrako project [1] is another intermediate model. An interesting feature of this software is that any train set can be modelled as a combination of vehicles, which are themselves defined as a collection of source models located in space and with acoustical characteristics, spectral information (one-third octave bands with the possible addition of discrete frequency peaks), and a directivity and a speed exponent. The source models have been obtained either from calculations (for example, the rolling noise obtained from TWINS), or from experiments (for example, the aerodynamic noise of the bogie based on models derived from the COP technique described in Section 2).

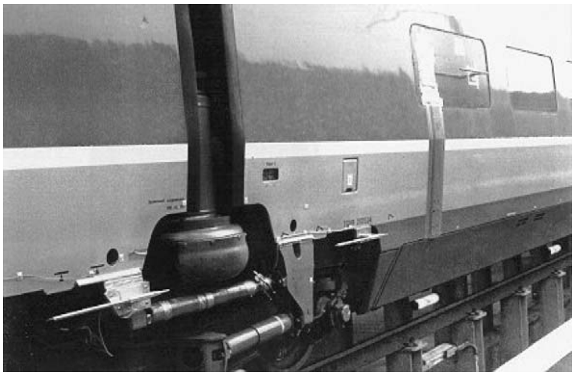

Fig. 6. Experimental arrangement for using COP technique.

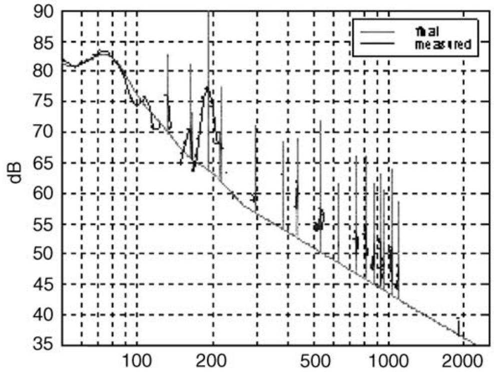

Fig. 7. The spectrum obtained.

The main interest of such a model is to observe the effects of simple parameter variations, and even design modifications of the train itself (by modifying the source models), on the overall noise radiated by a high speed train.

3.5. Future

Source modelling for rolling noise is well established and can be used fairly reliably for predicting the effects of low noise solutions. By contrast, the modelling of aerodynamic noise is still in its infancy and considerable developments can be envisaged. Other sources of railway noise have seen much less model development and are at present mainly characterized empirically. Intermediate models could help improve understanding of the contribution of the most relevant parameters to be used in propagation calculations. Coupling a better source description with advanced propagation methods is one of the main issues to be addressed for improving the modelling of environmental railway noise.

The development of tools to allow the audible effects of source modifications to be assessed could also be an interesting issue for the future.

4. Current knowledge of sources and potential for noise reduction

4.1. Rolling noise

In this section an overview is given of the potential scope for reducing rolling noise. A good overview of this topic is given in Ref. [32] so the discussion here concentrates on results obtained recently. A recent discussion of the means of controlling rolling noise is also given in Ref. [33].

4.1.1. Projects

Several large national and international projects have been completed recently to demonstrate the potential for reducing rolling noise. These include the EU-funded projects Silent Freight and Silent Track [34] and Eurosabot [35], as well as their predecessor OFWHAT [36,37]. In France, projects have demonstrated rolling noise reduction on high-speed trains [38]. Elsewhere, the emphasis has been on freight trains, with the Low Noise Train project in Germany and the Dutch Quiet Train Traffic (STV) project. Much use has been made of theoretical models, for example TWINS, and in each case it has been recognized that significant overall reductions in rolling noise require a suitable combination of measures applied to the wheel, track and roughness, possibly complemented by local shielding measures.

4.1.2. Wheel design

Optimized wheel designs using theoretical models have been considered for some time. One design, involving a reduced diameter and thick, straight web, was predicted to reduce the wheel component of noise by 11 dB compared to a Corail wheel, but it was not built [39]. In the OFWHAT project an optimized wheel shape was designed and implemented that had a thick web and diameter of 860 mm. This was predicted to reduce the wheel component by 4 dB although in field tests only 1 dB reduction was measured. The design was, in any case, unsuitable for application in tread-braked vehicles [37]. In Silent Freight, optimized wheel shapes were again studied. In this case, the thermo-mechanical requirements of tread braking had to be taken into account, which imposed a further constraint. Two 860 mm diameter wheels were produced, each predicted to reduce the wheel noise by 3 dB; experimental results showed modest reductions [40]. For a disc-braked wheel, the potential of shape optimization is much greater than for a tread-braked wheel. Wheel shape optimization was attempted on a TGV in France, producing 4–5 dB less noise in the frequency range above 1.6 kHz where the wheel is expected to dominate [41]. A small (640 mm diameter) straight-webbed design has been shown to produce as much as 18 dB reduction in wheel noise compared with a conventional wheel, although the track component of noise can increase slightly due to a shift in the contact filter effect [37].

The other main area in which wheel noise reductions are sought is in added damping. Constrained layer damping has been applied to railway wheels in the UK since 1988 to counteract curve squeal. More recently such damping treatments have also been used in attempts to reduce rolling noise. Jones and Thompson [42] predicted reductions of 3–4 dB in the wheel component of noise. In recent tests on the ETR500 a constrained layer damping treatment was found to reduce the overall noise by 4–5 dBA between 200 and 300 km/h [43]. As with all wheel damping treatments, it is important that sufficient damping is added to overcome the 'rolling damping' [42].

It is also important to realize that damping treatments can be most effective on wheel designs that are initially relatively noisy.

An alternative method of adding damping is a tuned absorber system. Absorbers of various designs have been used on railway wheels for many years in Germany with success [44]. Applications elsewhere have been less successful [45]. Simple tuned absorbers were used in the OFWHAT project and achieved a 4 dB reduction [37], while in the Silent Freight project reductions of up to 7 dB were found in combination with optimized wheels [34,46]. A wheel cover, which shielded the wheel web, was also studied in Silent Freight. This, in combination with the optimized wheel design, also reduced the wheel noise by about 8 dB [34]. Table 1 summarizes the main results obtained in the combined final tests of the Silent Freight and Silent Track projects. The first column of results indicates the reduction in the wheel component of noise compared to the reference wheel and the first row similarly the reduction in track component of noise. The remaining figures are reductions in overall noise due to the various combinations of measures.

4.1.3. Track design

One of the most influential parameters of the track for noise radiation is the stiffness of the rail pad. In OFWHAT, a reduction of 4–5 dB was found by optimizing the pad stiffness relative to a reference track. Although increasing the damping loss factor of the pad should also reduce noise this was found to be impracticable [37].

Another means of reducing the radiating length of the rail is to add damping in the form of tuned absorbers, i.e. damped mass–spring systems added to the rail. In OFWHAT, an absorber clamped to the end of the rail foot was used but this was only tested in conjunction with the optimized pad, which gave an additional reduction of 2 dB [37]. In Silent Track, a new absorber has been designed that is attached to the rail at the base of the web and on the top of the foot. This gave reductions of 6 dBA in tests on track with relatively soft rail pads [47] (see Table 1 and Fig. 8).

By reducing the size of a rail section, its radiation efficiency and radiating area can be reduced. A low-height rail reduces the noise from lateral vibration while a narrow rail reduces the noise from vertical vibration [33], as shown in Fig. 9. In Silent Track a narrow foot rail was tested that was expected to reduce the rail noise by about 4 dB. This was tested in combination with a new rail support system and measurements showed a reduction of 3 dB [34].

In the Dutch STV project, a new form of slab track was tested with an embedded rail of a small section supported on a stiff foundation [48,49]. Using vibro-acoustic transfer function

Table 1
Measured noise reduction obtained for various wheel and track treatments in Silent Freight and Silent Track projects to nearest whole dB [34]

	Wheel noise reduction	Stiffer pads	Reference track + absorbers	Stiffer pads + absorbers	New track	New track + absorbers
Track noise reduction	—	2	6	5	3	7
Perforated wheel with ring damper	4	2	6	4	2	6
Optimized wheel with shields	8	3	7	5	4	8
Optimized wheel with tuned absorbers	7	3	7	6	4	8

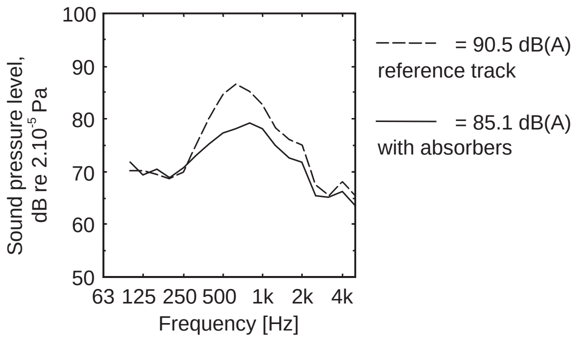

Fig. 8. Measured noise from reference track and the same track fitted with Silent Track rail absorbers, in both cases at 100 km/h using a vehicle fitted with a noise-reducing wheel. Average from three microphones at 3 m from near rail [47].

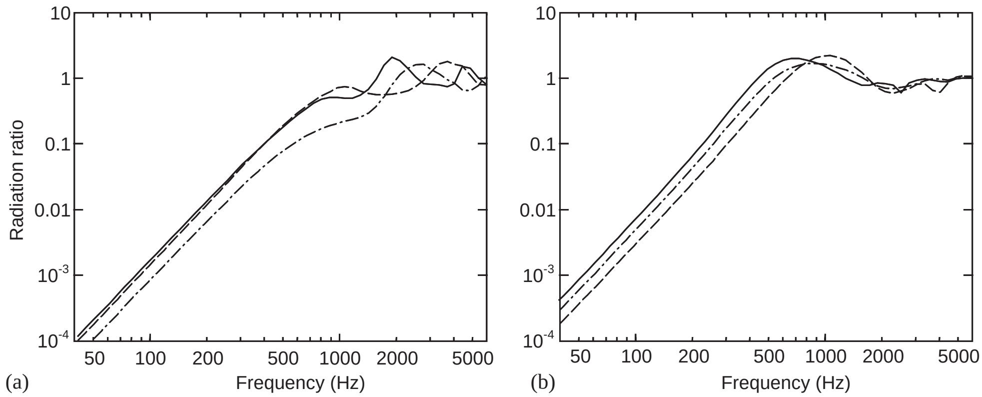

Fig. 9. Radiation ratio of rails of various dimensions, calculated using boundary elements. (a) Uniform vertical motion, (b) uniform lateral motion. —— UIC60 rail (172 mm high, foot width 150 mm), – – – low height rail (107 mm high, foot width 150 mm), – · – · 'bullhead' rail (172 mm high, 'foot' width 70 mm).

measurements, the track noise was found to be reduced by 9 dBA compared with ballasted track and 12 dBA compared with a slab track with normal embedded rails [48].

4.1.4. Braking system

The changes to wheel and track design discussed above reduce noise by affecting the vehicle and track transfer functions from roughness to noise. The surface roughness forms the input to the system so a reduction in the roughness can give additional effects on the noise. The widespread introduction of disc brakes replacing cast-iron tread brakes for passenger vehicles has given significant reductions, typically up to 10 dB. For freight vehicles in Europe cast-iron brake blocks are still widely used. Their replacement by disc brakes is considered both uneconomic and difficult due to the organization of the international traffic in Europe. However, a recent initiative by the UIC has set out to replace cast-iron blocks by a composite material [50]. These do not roughen the wheels and therefore the rolling noise is reduced. If this can be done by retrofitting vehicles, there need be no additional costs. The Eurosabot project set out to develop such brake blocks but results were rather disappointing [35] and suitable materials for retrofitting are not yet available.

4.1.5. Local shielding

A third possibility for noise reduction is to add local shielding measures in the form of bogie-mounted shields and low trackside barriers. Tests in the UK demonstrated that this concept can achieve a reduction of 8–10 dB [51]. Within the Silent Freight and Silent Track projects, a system was developed within international gauging constraints. Consequently a gap of 118 mm had to be left between the top of the barrier and the bottom of the shield. The reduction of noise was therefore limited to about 3 dB(A) [52].

4.2. Aerodynamic noise

The main aeroacoustic sources have been identified from different studies [1,3,53] on high speed trains around the world. These are mainly the Shinkansen, TGV, ICE and Transrapid. The importance of each source contribution varies depending on the shape and technology of the train, but the main sources are the pantograph, the recess of the pantograph, the inter-coach spacing, the bogie, the nose of the power car, the coach walls, the rear power car, the louvres and the cooling fans. Of these, the two main aeroacoustic sources on conventional high-speed trains are the pantograph and its equipment, and the bogie area, particularly the leading bogie.

4.2.1. Pantograph noise

Noise barriers along the track shield rolling and aeroacoustic sources at the bogies but do not shield aerodynamic sources on the roof such as pantographs. As a result, pantograph noise can be significant, at least subjectively. Pantograph noise generation is mainly due to vortex shedding around cylinders of the pantograph and the physical phenomena are now quite well understood. Optimization of pantographs have been mainly carried out in Germany and in Japan. Until now pantograph noise in Japan has been reduced by installing covers on the train roof around the pantograph region. However, since the pantograph covers themselves generate aerodynamic noise a ‘new low-noise pantograph’ without covers is under development [54].

A number of experiments were carried out in wind tunnels in Germany for the optimization of cylinder shapes as well as for testing the principle of ribs which allow coherent vortex shedding to be broken up and hence reduce noise generation. Adding the component sound levels associated with each region of the pantograph that is investigated, the total noise level due to the pantograph was reduced by nearly 5 dB(A) in the wind tunnel. Unfortunately, in field tests, the overall reduction of generated sound was not as great as that achieved in the wind tunnel. As a conclusion, the noise reduction potential for conventional pantographs is limited and new pantograph concepts must be considered, including optimization of the pantograph in interaction with its equipment (e.g. insulators). A new ASP-pantograph is also currently under development with respect to its aerodynamic and mechanical design. This development uses computer models to estimate the aeroacoustic noise. Initial calculation results for a recently developed novel pantograph head are presented in Ref. [30]. A level reduction of 10 dB(A) is predicted.

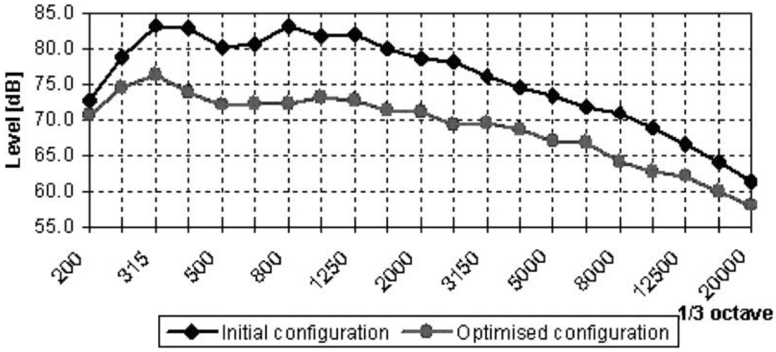

Fig. 10. Spectrum in the bogie area of a TGV obtained in wind tunnel, comparison of the initial configuration with a good combination of solutions.

4.2.2. Aerodynamic noise in the bogie area

Aeroacoustic phenomena that can occur in the bogie area are complex. Due to this complexity, it is useful to implement different kinds of tool to improve the knowledge of physical phenomena and find some solution concepts [53]. Identification of bogie aerodynamic sources was carried out at SNCF through wayside measurements with the array illustrated in Fig. 2. Further characterization of these sources was investigated with on-board measurements using the COP technique previously explained. It was also seen in Section 2 that CFD can be useful for classifying different solution concepts for the bogie area of a TGV. The most efficient solutions identified in the SNCF study were tested in the wind tunnel [55] and encouraging results were obtained. Fig. 10 shows the comparison of the spectra between the initial configuration and the best combination of solutions. Relative to the sum of uncorrelated sources, shielding would be the best solution. The optimized solution, comprising fairings on the bogie as well as shape modifications to the front end to modify the flow in the bogie area, allowed a reduction of 3 to 10 dB to be achieved across the spectrum, giving a reduction of 7.9 dB in the total A-weighted sound level in the wind tunnel. An extrapolation to operating high-speed trains, including the effect of other possible sources, could lead to a substantial reduction of 5 dB(A). These results must nevertheless be confirmed with field measurements.

4.3. Other sources

4.3.1. Curve squeal

The squeal noise emitted by wheels in curves differs from rolling noise in being excited by unstable transverse forces. At the last workshop it was noted that little progress had been made on modelling curve squeal in recent years compared to rolling noise [13]. Since then, however, in a series of papers [56–58] Heckl has developed a mathematical model for curve squeal in the time domain, a frequency-domain model to study which modes are prone to squeal and investigated the possibilities of a simple active control system using feedback control. This was demonstrated on a small experimental rig.

De Beer et al. [59–61] have extended the frequency-domain model of Heckl and studied squeal experimentally using a laboratory test rig allowing the yaw angle, lateral position and vertical load to be varied as well as the speed. Good agreement with the predictions are found. In particular, the model shows that the propensity to squeal depends on the lateral position of the contact on the wheel. The mode that is excited depends on this position. In general, squeal is more likely for contact positions towards the outer edge of the running surface. This suggests the possibility of using gauge reduction or modified rail profiles to help to control squeal. The model can also be used to study the benefits of different counter-measures such as lubrication and wheel damping treatments.

4.3.2. Locomotive exhaust noise

The noise emitted from exhaust of self-powered locomotives is a problem generally associated with stationary and low-speed trains. In the United States, railways primarily use diesel-electric power for freight trains. Exhaust noise tends to dominate the noise emission levels for these trains up to speeds of approximately 60 km/h when wheel/rail noise becomes significant. Problems from exhaust noise arise due to the low-frequency components below 200 Hz. Passive silencers for low frequencies need to be large and heavy to provide adequate noise reduction with minimum back pressure. Such silencers are acceptable for stationary power plants, but not for moving locomotives. The size requirements decrease for higher frequencies above 200 Hz, so that an adequate silencer can be accommodated within a locomotive. A promising noise reduction approach for diesel exhaust is the incorporation of a hybrid active–passive system—the active system used to reduce the low-frequency tonal components of a diesel engine, and the passive system for the higher frequencies. Remington et al. [62] tested a prototype active–passive system on a locomotive and obtained 4–9 dB(A) noise reduction, depending on the operating condition. Under idling conditions, the low-frequency components were reduced significantly, which has the possibility of providing great improvements for noise-sensitive areas near rail yards.

Other types of self-powered locomotive have gas-turbine engines. A new turbine locomotive has been developed for passenger service in the United States [63]. This locomotive has an engine similar to that used in helicopters, which is extremely compact and light weight. The small size of the engine allows room for a silencer, made all the more effective because of the high-frequency noise characteristics of turbines rotating at very high speed.

4.3.3. Traction motor noise

Noise from traction motors tends to be surprisingly significant for many diesel-electric and electric trains. Hanson and Barsikow [3] found traction motors to be the dominant source from power cars on the Acela (US Amtrak High Speed Train) during tests up to 240 km/h at the Transportation Technology Center in Colorado. No further diagnostics were performed, but it was estimated that a 5 dB reduction in traction motor noise would have resulted in a reduction of 1 dB in the noise level at 30 m from the track. Noise from traction motors was found to have a 40 log speed relationship for the Acela.

4.3.4. Cooling fans

Cooling fans tend to dominate the noise emissions from a power car under stationary and low-speed conditions, especially during hot-running conditions. Because the need for cooling is nearly continuous, fans tend to run at a steady speed, sometimes with a low speed setting for cool conditions and a high speed setting for hot conditions. Fan noise can be annoying to passengers on station platforms, especially after the train pulls in from its high-speed journey. The Acela tests [3] showed cooling fans to have a weak noise versus speed relationship (approximately 6 log speed), but with a high steady noise component (81 dB(A) at 5 m). In Ref. [64], Cleon and Willaime discussed the potential improvements in noise from an axial fan used on an SNCF railcar, concluding that the acoustic emission could be reduced by 10 dB while improving its airflow performance.

4.3.5. Structure-borne noise

Noise from trains on bridges has been a topic of concern in urban areas where elevated railways have been used to traverse water courses or to provide a grade-separated route. Structure-borne noise from bridges is very difficult to control due to the relatively compliant structures and large radiating surfaces involved. The results of three studies of bridge noise re presented in Refs. [65,66]. Perhaps the most elaborate treatment was that proposed for a viaduct in Hong Kong [65] where environmental regulations required a 24 dB(A) reduction from the unmitigated noise of a train on the structure. A concern for this treatment is, of course, the great cost.

4.3.6. Horn noise

Noise from train horns at grade crossings has resulted in the most complaints about train noise in the United States as reported by the Federal Railroad Administration. There are over 150,000 grade crossings in the United States and a new federal law requires the horn to be sounded by every train at every one of them. Currently there are waivers for about 2500 crossings, but under the new law waivers will be permitted only under certain conditions where the grade crossing has been rendered sufficiently safe. Train horns are required to attain a level of 96 dB(A) at 30 m in front of the locomotive, but most horns are set at a level of 115 dB(A). Removing the waivers on the 2500 crossings would expose about 350,000 people to new noise levels that are deemed unacceptable [67]. Concerns for adverse public reaction have led to an ongoing study sponsored by the US Federal Railroad Administration on ways to minimize horn noise at the wayside. Some of the methods being investigated include improved directivity of locomotive-mounted horns and stationary, pole-mounted horns at grade crossings.

4.4. Future

The reduction of rolling noise has reached a stage where theoretical models are quite mature and a number of research or demonstration projects have been carried out to show that low-noise vehicles and tracks can be designed. However, before this technology reaches widespread implementation, many non-acoustical aspects will require further work so that lower noise can be achieved without substantially increasing cost or compromising operational or safety constraints. Although economic studies point to low-noise technology often being more cost-effective than tall line-side barriers, large-scale implementation has yet to be embarked upon. In Switzerland an ambitious retro-fitting programme has been initiated, concentrating on braking technology, and the UIC initiative on replacement brake blocks should also mark a turning point in railway noise control if practical difficulties can be overcome.

Future developments on high-speed train aeroacoustics could be focussed now on the implementation of solutions on rolling stock, mainly for pantograph and bogie area sources. The development of prototypes could take advantage of the knowledge achieved in the studies previously carried out and mentioned in this paper. This should be done with the participation of manufacturers.

For other sources on locomotives and power cars, the favourable results of the test on a hybrid active–passive system for controlling locomotive exhaust noise suggest that more work in that area could provide relief from noise around yards or layover facilities where locomotives idle for long periods near residential areas. Detailed studies of traction motor and cooling fans could result in significant benefits for power car noise emission. Research could result in horns that are more directive than at present by using, for example, source arrays or specially designed baffles.

5. Conclusion

For the past 10 years, significant progress has been made in railway noise source identification, both in developing identification methods, and in the understanding of the physical mechanisms of the sources themselves. As far as identification methods are concerned, microphone array methods have been made operational, even for high speed train applications. Experimental assessment of vehicle and track contributions to rolling noise is still in progress.

Rolling noise models can be considered to be well advanced, whereas aerodynamic noise, although characterised by empirical models, still deserves further attention and theoretical analysis. Progress is also being made for squeal noise in curves. Little research has been carried out into brake noise for railway applications, although its has been extensively investigated in the automotive sector. The noise from locomotive fans could benefit from research carried out recently in other sectors.

Attention must still be given to modelling and to working on each of the various sources in order to direct effort towards those measures with the greatest practical noise reduction potential, and with regard to the relative importance of each source in the overall noise level. It has been shown that various levels of refinement and modelling of each source are required according to the application. For example, prediction of sound propagation in the environment requires 'cruder' source models than studies of the mechanisms of squeal noise generation. Bridges between different levels of modelling are now urgently needed, also because legislators are now considering placing limits on noise creation. Proposals for target levels for overall noise should benefit from research carried out on sources. This will ensure that such limits are attainable and realistic, taking account of the potential for reduction of each source.

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