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ROLLING NOISE CONTROL AT SOURCE: STATE-OF-THE-ART SURVEY

N. VINCENT

Vibratec, 28 *chemin du Petit Bois*, *B.P.* 36, 69131-*Ecully cedex*, *France*

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Wheel/rail rolling noise is generally the predominant noise component radiated by railway systems. Considerable R and D work on rolling noise control has been initiated by the major railway companies during the last few decades which has led to the development of a significant number of technical solutions. In this paper, the main mitigation measures, both operational and still under development, are reviewed and assessed.

1. INTRODUCTION

The reduction of environmental noise from the operation of railway systems has become a major challenge for railway manufacturers and operators.

All types of railways are considered: light rail systems and metros in urban areas, main lines with freight or passenger rolling stock and high-speed rolling stock such as TGV and ICE.

For the majority of current situations, the wheel/rail noise, initiated at the wheel/rail contact, predominates over other sources; mechanical noise radiated by mechanical components such as motors, gears and fans is significant only at low speeds, and aerodynamic noise induced by air-flow interaction with the rolling stock is predominant at speeds above 250–350 km/h.

Fundamental investigations undertaken in the 1970s by some major railway operators have led to the emergence of effective technical solutions for rolling noise control, based on reliable scientific evidence.

This paper aims to review the main mitigation measures available today.

In section 2, some major historical steps leading to the present state of the art are summarized. In section 3, the main physical phenomena involved in wheel/rail rolling noise are briefly reviewed.

Finally, in section 4, the major potential means for rolling noise mitigation are presented and assessed. The state of development of each solution is also discussed. In the conclusion, the need for a rigorous strategy in rolling noise control is emphasized and an outline of the further investigations required is given.

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2. SUMMARY OF SOME MAJOR HISTORICAL STEPS

A brief historical survey of major investigations on railway noise carried out in Europe and the United States since 1970 is given in Figure 1.

The approach undertaken in the United States in the 1970s and continued in Europe since 1980 is exemplary from a scientific point of view; the basic physical phenomena accounting for noise generation were first identified by Remington [1–4] and Thompson [5–10]. A simulation model was initiated within British Rail Research and finalized with ERRI support. This software, called TWINS, has been thoroughly validated with several field measurement projects covering a broad range of European tracks and rolling-stocks [11–13].

Operating speeds from 60 to 350 km/h have been covered by the validation. Moreover, although there is a lack of published data, TWINS is very likely to provide correct simulation for urban systems such as light rail and underground, with speeds ranging from 20 to 80 km/h.

Recently structured and ambitious research projects have been started, aiming at optimization and development of solutions for rolling noise control based on firm scientific data.

At a European level, the OF WHAT project managed by ERRI in 1995 and 1996 has led to the development and testing of several prototype solutions in realistic conditions [14]. Following this project, three Brite Euram research projects, partly funded by the European Commission, were started and are currently under way [15–17].

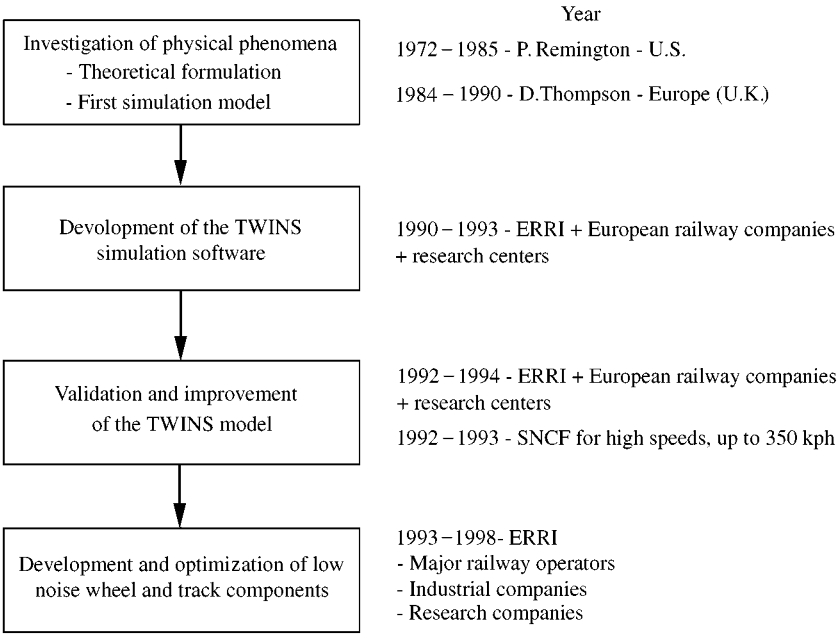

Figure 1. Main steps of research on rolling noise.

These three projects aim to develop mitigation measures at source; the Silent Track project deals with track components, the Silent Freight project focuses on rolling stock optimization and the Eurosabot project is investigating brake shoe materials to reduce wheel tread degradation.

In parallel, several major railway companies (including DB, SNCF, NS) are conducting similar projects [18–20].

3. BRIEF SUMMARY OF MAIN PHYSICAL PHENOMENA

A brief review of the main physical phenomena responsible for wheel/rail rolling noise is useful in order to obtain a better understanding of the solutions presented in the next section.

Squeal noise, which generally arises in sharp curves, is not treated here since it involves very specific generation mechanisms, although the rolling noise solutions which have a favourable effect on squeal will be noted.

The four physical steps involved in rolling noise emission are explained in Figure 2. Wheel/rail excitation originates when passing vertical defects in the rolling surfaces in the contact patch. This induces a forced relative displacement. These vertical defects ΔZ (roughness) must be absorbed by the combined vibratory displacement of wheel and rail, and local elasticity at the contact.

The roughness can be expressed as

$$\Delta Z = Z_{rail} + Z_{wheel} + Z_{contact}.$$

The typical defect characteristics (no severe rail or wheel wear) which are relevant for noise emission have wavelengths from 0·3 to 20 cm and amplitudes from 0·5 to 50 μm.

The wheel and rail then vibrate according to the mechanical behaviour of each element: excitation of the main wheel natural frequencies, wave propagation along the rail away from the contact point and to a lesser extent vibration transmission to

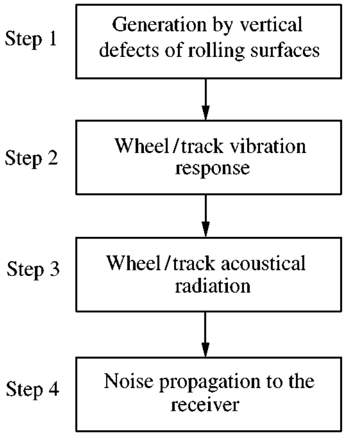

Figure 2. Physical steps in rolling noise emission.

the sleeper and the track support. The vibrating components (wheel, rail and sleepers) act as loudspeakers. Finally, radiated noise propagates away from the track.

In normal operating conditions, the relationship between roughness amplitude ΔZ and emitted noise level remains linear; a slight harmonic roughness with a wavelength λ and an amplitude $\Delta Z(x) = Z_0 \sin 2\pi x/\lambda$ will generate a harmonic noise level at frequency $f = v/\lambda$ with an amplitude proportional to the roughness amplitude Z_0, where v is the rolling speed.

The same physical phenomena occur over a broad range of operating speeds from 20 to 350 km/h. Consequently, they cover all types of rolling stock with steel wheels from light rail systems to high-speed trains.

For very poor surface conditions (severe defects such as wheel flats, rail joints, rail corrugation), the relationship is no longer linear but the basic physical phenomena remain unaltered.

In the case of loss of contact, the displacement-type excitation is replaced by an impact excitation. However, impact noise can be treated in exactly the same way as rolling noise.

4. REVIEW OF MITIGATION SOLUTIONS

Potential means for noise control can be considered for each of the steps of wheel/rail noise generation shown in Figure 2.

However, solutions corresponding to steps 2 and 3 are normally taken together, as these two steps are strongly coupled.

The main relevant solutions currently available on the market or under technical development are summarized in Table 1, where gain relates to noise reduction.

The potential acoustical gain claimed for each solution must be considered carefully for the following reasons.

Track-side noise levels (recorded on a fixed point close to the track) are made up of the sum of two components: wheel radiation and track radiation. Consequently, the respective contribution of these two components must be known in order to quantify the effect of modifying any single component on the overall noise level. For instance, when wheel radiation is predominant, any reduction in track sound radiation will not noticeably affect overall rolling noise levels and *vice versa.* In the general case, no precise law can be derived to quantify the respective contributions of wheel and track radiation. Either of the two components may predominate depending on the situation. The only trend which can be given is the following; the higher the wheel diameter and train speed, the higher the wheel contribution. Thus, for example, track radiation generally prevails over wheel radiation in the case of light-rail transport systems in urban areas.

The potential acoustical gain achievable on the wheel or track component is heavily dependent on the original design. For example, a 4 to 6 dB (A) wheel noise reduction can be achieved by optimizing the shape of a wheel with a large diameter (920–1060 mm), whereas only 1–3 dB (A) will be obtained on small diameter wheels (660–800 mm).

TABLE 1

Solutions for rolling noise control and acoustical gain in dB (A)

Step	Technical solution	State of development		Noise reduction (dB (A))			Effect on wheel squeal in curves
		Prototype	Industrial	Wheel emission	Track emission	Overall emission	
1. Minimization of wheel/rail roughness	*Wheel*						
	Appropriate material for brake-shoe	×	×	2–10	2–10	2–10	
	Removal of tread brakes		×	2–10	2–10	2–10	
	Appropriate slip-slide control system		×	2–10	2–10	2–10	
	Regular wheel grinding		×	2–10	2–10	2–10	
	Track						
	Regular rail grinding		×	2–10	2–10	2–10	
	Removal of rail joints		×	2–10	2–10	2–10	
2–3. Minimization of wheel and track acoustical radiation	*Wheel*						
	Shape optimization	×	×	1–6	—	0–4	
	New wheel web material	×		1–6	—	0–4	
	Addition of damping	×	×	5–10	—	0–6	Yes
	Resilient wheel		×	4–6	0–3	0–4	Yes
	Screens on the web	×	×	1–6	—	0–4	Yes
	Track						
	Stiff and damped rail-pads	×	×	—	1–6	0–5	
	Addition of damping on the rail	×		—	2–6	0–5	
	Optimization of rail shape	×		—	0–4	0–4	
	Embedded rail	×	×	—	0–4	0–4	
	Sleeper optimization	×		—	0–2	0–2	
4. Mitigation of sound propagation	*Wheel*						
	Vehicle skirts	×	×	2–6	0–2	0–4	
	Absorbing platform	×	×	1–2	1–4	1–3	
	Rail screen	×		—	3–6	0–3	
	Rail screen + vehicle skirts	×		2–8	2–8	2–8	

It is therefore essential to carry out a preliminary investigation of wheel and track acoustical properties (including quantification of the respective contribution of both components), prior to designing any set of solutions for rolling noise control. The lowest figures in Table 1 correspond to the smallest effect to be expected in unfavourable conditions whereas the higher figures define the maximum effect for the most favourable conditions.

4.1. CONTROL OF ROLLING SURFACE ROUGHNESS

The improvement of the wheel and rail roughness is the primary measure which must be considered in practice, since a 10–20 dB (A) noise reduction can be achieved for rolling surfaces in poor conditions (wheel or rail corrugation, severe wear) [21].

Wheel: Investigations carried out over the last 20 years have shown that the cast-iron blocks of tread braked rolling stock are very abrasive on wheel surfaces. Most railway companies which have either replaced the cast iron by other materials, such as composites, or substituted disc brakes have observed an overall rolling noise reduction ranging from 5 to 10 dB (A) [22–24].

On light rail systems such as tramways which are usually disc-braked, efficient wheel slip/slide control systems are required to prevent any wheel flats.

Furthermore, regular wheel grinding on the workhop is required for most rolling stock. An optimal schedule must be chosen depending on the operating conditions.

Rail: The only mitigation technique available at the present time is rail head grinding by means of a grinding train. Several railway operators currently apply an acoustical grinding policy for their tracks [18, 25]. The track portions to be treated are detected by means of on-board noise or vibration records. Appropriate rail grinding leads to a 10–15 dB (A) noise reduction for extreme cases (corrugated rails with good wheel condition). Reduction by 3–6 dB (A) is more typical, on regularly maintained networks. However, rail grinding remains a curative technique; at the present time, no widely acknowledged preventive solution is available for reducing roughness growth, in spite of studies currently under way [17].

4.2. MINIMIZING WHEEL RADIATION

Several solutions have reached the production stage and are available today.

4.2.1. *Wheel shape optimization* [18, 26, 27]

The wheel noise is principally made up of the sum of two components: tread radiation (radial vibration) and web radiation (axial vibration).

The greater the wheel diameter, the greater the web radiation compared to tread radiation. For instance, for a conventional wheel with a 920 mm diameter, web radiation accounts for about 75% of total wheel noise.

Wheel shape optimization consists of minimizing web axial vibration and hence the web radiation component. It proves to be an interesting solution since it does not require any change of material or any additional devices.

A wheel noise reduction of 3–6 dB (A) can be obtained with high diameter wheels, depending on the reference design. However, the acoustical gain proves to be quite small in the case of small wheels (diameter below about 800 mm). Moreover, the optimized shape must be compatible with thermal requirements in the case of tread braked wheels.

4.2.2. *New materials for the wheel web*

The implementation of a thick web made of material with a high stiffness-to-density ratio is an alternative for minimizing web radiation without increasing wheel weight. Aluminium-webbed wheel prototypes have already been assessed in practice [12] and carbon fibre webs are also being considered [18]: 3–6 dB (A) of wheel noise reduction can also be expected.

4.2.3. *Wheel damping*

The installation of damping devices on the wheel is an efficient way to control wheel noise. This type of solution consists of damping the main natural frequencies of the wheel between 1000 and 5000 Hz which account for the major part of the wheel vibration and radiation energy. Most systems available today are based on dynamic absorbers, and some have been installed on wheels for many years.

A wheel noise reduction of as much as 8–9 dB (A) can be achieved in the best cases with a reasonable addition of weight (about 15% over the initial wheel weight). However, most devices available today cannot be fitted onto freight wagons with tread braked wheels, because of the high temperature which may occur during severe braking.

4.2.4. *Resilient wheels*

Resilient wheels have been in common use for many decades on light rail rolling stock in urban areas. Appropriate tuning of resilient layer dynamic properties can provide a simultaneous reduction in wheel and track radiation. Potential noise reductions of up to 4–6 dB (A) on the wheel, 0–3 dB (A) on the track, and 0–4 dB (A) on overall rolling noise, can be expected [29]. Consequently, the resilient wheel is an important concept for rolling noise control. It is however not acceptable for tread-braked rolling stock. In addition, it requires accurate optimization since poor tuning of resilient layer properties can lead to increase of noise.

4.2.5. *Screens on the web*

A complete shielding of the web on both sides of the wheel by means of damped steel plates (a three-layer steel/elastomer/steel shield) connected between the hub and the tread can lead to a 3–6 dB (A) reduction of wheel noise. This is due to the following effects: strong reduction in the web radiation component (shielding effect) and slight reduction in tread radiation (damping effect brought about by the shield connection).

4.3. MINIMIZING TRACK RADIATION

Whilst the technology is available for controlling wheel noise radiation, most potential solutions for controlling rail radiation are still under development. Track radiation is a sum of a rail radiation component, which is generally predominant, a sleeper component, which is often significant but rarely dominant and a track support component which can be neglected in most situations. At the present time, the most promising mitigation measures consist of minimizing the rail radiating length by inhibiting the propagation of vibration along the rail. This effect can be achieved either by optimizing the rail-pad properties or by adding dynamic absorbers to the rail.

4.3.1. *Optimized rail pads*

Theoretical studies [30] have shown that track noise can be minimized by setting the vertical dynamic stiffness of the rail pad to a high stiffness optimal value. In parallel to this, the pad damping loss factor must be increased. A noise reduction of 3–6 dB (A) has been predicted for track with concrete sleepers and this has been confirmed in field experiments [18]. However, the installation of such high stiffness rail pads is liable to reduce the mechanical protection of the sleeper against rolling impact and strengthen ground-borne vibration levels. Furthermore, the effect of optimized rail pads on track equipped with wooden sleepers remains limited.

4.3.2. *Dynamic absorber on the rail*

This solution may prove to be a good alternative for those cases in which rail-pad optimization cannot be considered. A similar reduction of track noise of 3–6 dB (A) can be expected by installing properly tuned dynamic absorbers along the rail (10–20 kg per meter of rail) [18, 30]. Prototype dampers have already been successfully tested on real tracks; however, additional development efforts remain necessary to produce such products commercially.

4.3.3. *Rail shape optimization*

The optimization of the rail shape (for example by reducing foot width) remains a potential method of reducing track noise (gains from 0 to 4 dB (A)). However, this solution would not be simple to implement as it is likely to require a complete redesigning of the rail fastening system.

4.3.4. *Embedded rails*

Grooved rails inserted in the road are currently found on city centre tramway lines. In such situations, sound can only be radiated from the top of the rail and, to some extent, by the adjacent interface layers with the asphalt. Compared to conventional track layout, rail radiation is reduced over the medium and high frequency range from 500 to 5000 Hz (reduction of radiating area). On the other hand, embedded rail radiation is increased at low frequencies, below 300–500 Hz, due to baffling by the ground (monopole type radiation of embedded rail as opposed to dipole type radiation of free rail). An overall acoustical reduction ranging from 0 to 3–4 dB (A) can be expected, according to the shape of the roughness excitation spectra.

4.3.5. *Sleeper optimisation*

In all cases, heavy and compact sleepers (low radiating area) will reduce noise. For this reason, concrete bibloc sleepers are preferred to concrete monobloc sleepers, and wooden sleepers are a poor in terms of noise. The light steel base plates supported by soft pads on certain tracks with concrete track support may also induce significant sound radiation. For most cases, the maximum achievable track noise reduction by means of sleeper optimisation will not exceed 2 dB (A).

4.4. REDUCTION OF SOUND PROPAGATION CLOSE TO THE SOURCE

The conventional acoustical screens which may provide up to 15 dB (A) noise reduction are not considered here, since the present paper focuses on noise control at source.

Skirts on the rolling stock: Skirts fixed on the bogie can partly shield wheel radiation and to a lesser extent, track radiation. The acoustical efficiency of skirting depends on the respective contributions of wheel and track radiation. Moreover, the area covered by the skirt should be sufficiently large; the skirt length must be greater than the wheelset distance on the bogie, and lower edge as close as possible to the rolling plane.

In the best configurations, up to 3–4 dB (A) track-side noise reduction can be achieved [31–33]. In the case of sound reflecting track support such as concrete, a noise absorbent layer should be added, either on the inside of the skirt or below the car body.

Low rail screen: The design of low screens close to the rail can provide upto 0–3 dB (A) reduction of track-side noise levels. However, a potential acoustical reduction of 5–8 dB (A) can be expected with simultaneous implementation of rail screen and vehicle skirts [31–33]. At the present time, neither of these two concepts is widely used, mainly because of operating and maintenance constraints. However, vehicle skirts are being considered for new rolling stock.

Sound-absorbent material on the platform: Sound reflecting track materials such as paving stones, asphalt (tramways) or concrete (light rail, trains) do not provide any noise absorption effect, unlike ballasted or gravelled track support systems. The use of sound-absorbent materials on concrete platforms (gravel or grass lawn for tramways in bus-lanes, or porous layers on train slab-track) can provide a rolling noise reduction of 2–4 dB (A) [34].

5. CONCLUSION

Strategy for rolling noise control: Bearing in mind the number of potential mitigation measures available for the design engineer, a reduction of railway rolling noise of 3–10 dB (A) seems to be realistic in the future. This may be achieved by retrofitting of existing systems or design of new systems. However, apart from specific cases such as freight rolling stock with cast iron brake shoes a significant reduction will require the simultaneous implementation of several solutions.

As a result of the theoretical understanding and the experimental simulation tools available at the present time, a rigorous methodology can and should be carried out by the railway engineer in order to design the most cost-effective package of solutions.

The methodology to be adopted for the retrofit of an existing line requires the following:

- *Acoustical assessment*: quantification of the roughness of wheels and rails (measurements) and quantification of the acoustical properties of the wheel and the track (measurements and/or computation).
- *Investigation of solutions*: quantification of the acoustical gain provided by all relevant mitigation measures and numerical study to assess several packages of solutions.
- *Development of prototypes*: this step is required when existing solutions cannot be used.
- Implementation in the field and final testing.

A similar methodology could be recommended for the design of new lines, replacing the first step by an assessment of the necessary acoustical requirements for the project.

Requirements for future work: In spite of the considerable progress achieved since 1970 rolling noise control research must be continued. At a commercial level, the developments of mitigation measures on the track and, to a lesser extent, on the vehicle should be brought to completion (e.g. rail pad and fasteners optimization, rail absorber, wheel optimization, vehicle skirts).

At a more fundamental level, research into roughness growth on rolling surfaces should be increased in order to substitute the present curative treatments by preventive measures.

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