Experimental analysis of wheel noise emission as a function of the contact point location

A. Bracciali*, F. Piccioli

Dipartimento di Meccanica e Tecnologie Industriali, Università di Firenze, via Santa Marta 3, 50139 Firenze, Italy

Accepted 9 May 2003

Abstract

Recent analyses show that the wheel noise emission depends on the lateral position of the contact patch area on the wheel tyre. This displacement from the nominal position is such that different wheel modes are excited, resulting in a different frequency and amplitude composition of the wheel related noise component. In this paper the results of a test programme held on the ETR500 Italian high-speed train are shown. Thanks to a special device mounted under the axle box comprising a microphone and a windshield, it has been possible to measure the wheel noise continuously up to 300 km/h in tangent track and in curves. The behaviour of wheels in different condition of line curvature is shown, together with the results from a new type of constrained layer damped wheel.

© 2003 Elsevier Ltd. All rights reserved.

1. Introduction

Though several microphone array solutions exist and are extensively used to separate the wheel and the rail components in the overall trackside noise, it proves difficult to repeat such measurements under repeatable conditions in numerous trackside locations along a given railway line. As the wheel emission is acknowledged to be particularly important at high speeds, and at those speeds at high frequency, the use of a specific wheel noise measuring device mounted under the axle box can be useful to measure the wheel condition continuously and under all conditions.

Each body vibrates as a weighted sum of its eigenmodes, provided that they are excited by a mechanical input acting at the eigenfrequencies. The wheel–rail contact nominal (geometrical) interface point can be easily calculated from the wheel and the rail profiles and from the wheelset and track gauges, and the wheel natural (free) response can be estimated with numerical

---

*Corresponding author. Tel.: 39-055-479-6292; fax: 39-055-479-6400.
E-mail address: bracciali@ing.unifi.it (A. Bracciali).

0022-460X/$-see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0022-460X(03)00708-9
FEM calculations or measured under the application of known forces through experimental modal analysis.

During the normal operation of a train, the bogie dynamics and attitude are such that the wheels rarely touch the rails in the nominal position, resulting in a wheelset angle of attack (yaw angle) and a lateral displacement different from zero.

Two parameters affect the excitation under displaced conditions: the different spins given by a non-zero angle of attack, and the $Y/Q$ Nadal’s ratio between the lateral force and the vertical force. It is widely known that only a proper combination of wheel and rail profiles results in a regular and continuous conicity variation, i.e., a conicity that is normally quite low for centred running and that provides a centring effect without generating undesired hunting phenomena. For the classical UIC 60 rail with a $1/40$ conicity angle, a wear profile with optimal coupling properties has been adopted as a result of UIC studies. This profile, called ORE 1002S, is such that the contact point moves regularly and evenly from the nominal point to the wheel flange. On the other hand, by using the same wheel profile but with rails with an inclination of $1/20$, as used for example in Italy, it is possible that the wheel touches the rail at two points, one on the wheel tread and the other on the wheel flange. In this case the $Y/Q$ ratio is not uniquely determined by the common normal to the profiles. However, since the wheel is restrained, any combination of $Y/Q$ that does not induce derailment is allowed.

Under these conditions, the exact determination of the wheel excitation would require a simultaneous measurement of the lateral wheelset displacement, the actual track gauge and the vertical and lateral forces acting on the wheelset. Clearly this measuring set-up is quite expensive and complicated, requiring optical (laser) transducers for profile measurement and a strain gauge rotating (telemetry) arrangement for force estimation.

The wheelset attitude (angle of attack and lateral creep force) depends on numerous mechanical bogie and car body parameters, and normally is different for front and rear bogies and for leading and trailing wheelsets for each bogie. Speed, moment of inertia, local friction conditions, suspension behaviour, and wheelset curving (steering) capabilities make the problem very difficult to solve with sufficient reliability.

Despite these difficulties, noise measurements under the axlebox with known general conditions, including speed, line curvature, wheel and rail profiles and weather conditions, can at least indicate whether lateral forces and wheelset attitude can significantly affect the noise emitted from the wheel. In this study the results from tests conducted in October 2000 on the high-speed Italian train ETR500 are shown. Tests conducted in the $175–300\text{km/h}$ speed range on the Direttissima line allow comparison of the wheel emission under different lateral accelerations. Also the emission of a damped wheel is shown, highlighting the different emissions of the two types of wheels.

2. The test programme

Italian State Railways (FS) contracted the University of Firenze to perform noise measurements within the framework of a scheduled test programme for aerodynamic drag measurements. Due to this particular scheduling, it has not been possible to control the test programme to obtain the best results for noise measurements; in particular, it has not been
possible to have trains run at speeds below 175 km/h on the test line, thereby excluding the
opportunity to evaluate the noise at low speeds where the track component should be dominant.
The test section was the high-speed “Direttissima” Firenze–Rome line near Firenze, where the
maximum speed is 300 km/h. The data from a transfer run from Milan to Firenze are also given as
examples of results on tangent track. It is not intended here to give details on the tests beyond
those strictly needed to explain the measurements of interest. The reader is referred to the paper

The monobloc simple curvature wheel under test was developed by FS in the early 1990s to
replace the earlier three-piece wheel. Because of its low weight and optimized lateral and vertical
static stiffness, it became the standard for ETR500 high-speed Italian trains and the Alstom
Italian Pendolino family (ETR450/460/470/480). Lucchini CRS, the research and development
branch of the wheel manufacturer, Lucchini S.p.A., developed a retrofit treatment consisting of a
curved metal sheet with a constrained polymer, developed and patented jointly with 3M Italia srl.
The new wheel, called Syope®, has the main advantage that it does not require any modification
in the actual wheel and vehicle structures nor to the maintenance operation; moreover the solution
can be applied in principle to any disc-braked wheelset. It cannot be applied to tread-braked
wheels because of the limited thermal resistance of the polymer.

The first decision taken related to the number of Syope® wheels to be used during the tests,
where they were to be fitted and the definition of the roughness of the surface of the tyres. The test
ETR500 trainset has 2 locomotives and 8 coaches (4 second class, 1 restaurant and 3 first class
coaches) and it was decided to machine only some wheelsets. The final composition of the train is
shown in Fig. 1, where it can be observed that the bogies have been treated in pairs belonging to
adjacent coaches, for trackside measurement reasons.

The test programme was very protracted and the noise measurements were not carried out
throughout the whole programme, while some tests concerned only trackside measurements
during train passages. Of the numerous tests specified by the only measurement protocol available
at the time of the tests, i.e., the draft of the European and International Standard prEN ISO 3095
[2], only rail corrugation measurements are described here.

Rail corrugation has been measured with a trolley based on acceleration measurements
integrated twice. The equipment, called CAT (Corrugation Analysis Trolley), is described in
Ref. [3]; only one trace, at the intersection of the vertical axis of the rail, has been measured
continuously on the surface for a length of 20 m either side of the trackside noise measuring
position. Both the rails have been measured; corrugation data have been processed with the
specific software RAS (Roughness Analysis Software) described in Ref. [4]. Although only one
line is measured over a long distance, the corrugation spectrum has been compared to the limit

![Fig. 1. Test train with wheel position “t” turned, “s” Syope®.](image-url)
given in Ref. [2] for the acceptance of a site for vehicle type testing. The RAS software has been modified accordingly to accept very long CAT files, thereby dramatically improving the certainty in the estimated amplitude for longer wavelengths.

It can be seen from Fig. 2 that the average spectrum of both rails slightly exceeds the ISO proposed limit; nonetheless it seems that it is quite acceptable following the rules stated in Annex D of the standard.

Fig. 2. Average corrugation spectra for both the rails at the Renacci measuring site along the Firenze-Rome “Direttissima” high-speed line.

Fig. 3. One of the wheel noise measuring devices mounted under the axlebox.
Noise measurements under the axle boxes were made using some special devices, developed during 1993–1994, to measure the noise emitted by the wheel [5–7]. These include wind protection and two parallel plates; the microphone was elastically suspended behind the wind shield (Fig. 3).

To speed up the tests and to compare several wheels, four identical devices were mounted under three coaches as shown in Fig. 4. Theoretically, the support system for the device allows rapid re-positioning of the device such that it would have been possible to measure after each change of direction; unfortunately, as the tests were conducted during a night-time traffic possession, only a couple of minutes were available for reversing. As this time was judged to be insufficient, two devices (#1 and #4) were permanently operating in the Firenze–Arezzo (south) direction while the others (#2 and #3) were operating in the opposite direction (north). The only results presented here are those relative to the latter combination of measuring points, for which trackside data are also available.

Sound pressure signals were analyzed and recorded using a real-time 1/12 octave band dual channel analyzer with a sampling frequency of 11.2 kHz per channel. A test run log file was compiled with the position along the line, the actual speed and the time of the measurement.
3. Test results

3.1. Trackside noise levels recorded at Renacci ($d = 7.5\, \text{m}, \quad h = 1.2\, \text{m}$)

Several treatment configurations were tested, including worn and turned wheelsets, aerodynamic and aeroacoustic fairings. Results are summarized in Fig. 5 and in Table 1.

3.2. On-board measurements on the Milan–Bologna line

During a transfer run all the devices were oriented in the running direction, and the signals were collected simultaneously at two microphones. A-weighted sound pressure levels from the standard wheel and the Syope® wheel resulting from a 12 km long track which was almost all tangent and with a constant 180 km/h speed, have been grouped in three homogeneous sections. It is suggested that the differences depend mainly on unknown track conditions. To eliminate spurious data, a selection has been made on the basis of cumulative curves. $L_A$ results are summarized in Table 2.

3.3. On-board measurements on high speed ‘Direttissima’ Firenze–Rome line

During the test runs, the speed usually increased rapidly to the planned test run speed. Obviously the measurements taken during braking have been discarded, as the noise produced by braking is not strictly related to wheel noise. The largest number of samples (around 50%) relates to speeds in the range 200–250 km/h, around 18% relate to speeds greater than 250 km/h and the remaining 32% to speeds between 100 and 200 km/h although it is not uniformly distributed. This uneven distribution of the data made it impossible to derive completely meaningful results which could be compared to the data shown in Refs. [5–7], but as already mentioned, it was not possible to modify the speed during the test runs.

Fig. 5. Trackside A-weighted noise levels at 7.5 m for different turned wheels solutions and bogie fairings. The effect of acoustic treatments to fairings is negligible (not shown).
An example of the noise measured under the axlebox for the standard turned wheel and the Syope turned wheel and the gain offered by the Syope is shown in Fig. 6. The two wheels are only 16 m apart, requiring no correction of the sample position.

From all the data collected it is possible to make the following observations:

- The noise level is extremely high (up to 130 dB(A) and above) and the dynamic range of the instrumentation was almost entirely used. Only a few records (5 samples in a total of 14 test runs) resulted in an overload and they have been removed from the analysis.
- The noise levels are variable (up to 5 dB(A); see also Fig. 2 in Ref. [8] for an example of the noise variability under a railway vehicle also at constant speed), due to the intrinsic instability of on-board noise measurements and of line profile and details (curves, tunnels, rail joints, switches, etc.). The implications of this evidence are discussed later.
- The benefit offered by the Syope wheel shows a large variability. Fig. 6 shows that for considerable lengths of line the reduction is around −10 dB(A) (km 217 to 221) while in other sections the change can even be positive (km 221 to 223) showing that the damped wheel is noisier than the standard wheel.

The latter observation shows a pattern in that in almost all the test runs similar behaviour was observed. A correlation was found between the curvature of the line and the noise emitted. Fig. 7 shows the details of test run 2402. To reduce the number of samples and to obtain more stable results, the data have been grouped for line sections of 200 m, and they are shown together with the curvature derived from the line description. It can be observed that the gain of the Syope wheel is smaller in left-hand curves while it is higher in right-hand curves. The noise emitted by the standard wheel remains constant or even increases in the right-hand curves, while the noise emitted by the Syope wheel decreases. This shows that the actual position of the contact point

### Table 1
Trackside measured A-weighted noise levels $L_{pA,max}$ with different wheels and under different noise reduction conditions

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Standard (dB(A))</th>
<th>Standard + fairings (dB(A))</th>
<th>Syope (dB(A))</th>
<th>Syope + fairings (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>88.4</td>
<td>86.2 (−2.2)</td>
<td>84.4 (−4.0)</td>
<td>82.8 (−5.6)</td>
</tr>
<tr>
<td>235</td>
<td>93.2</td>
<td>90.0 (−3.2)</td>
<td>88.6 (−4.6)</td>
<td>86.5 (−6.7)</td>
</tr>
<tr>
<td>260</td>
<td>97.0</td>
<td>91.9 (−5.1)</td>
<td>91.8 (−5.2)</td>
<td>88.3 (−8.7)</td>
</tr>
<tr>
<td>295</td>
<td>98.4</td>
<td>94.4 (−4.0)</td>
<td>94.1 (−4.3)</td>
<td>90.8 (−7.6)</td>
</tr>
</tbody>
</table>

### Table 2
Noise reduction offered by Syope wheel compared to standard wheel for the transfer run at 180 km/h. The average gain on the whole section is $−6.6±2.3$ dB(A)

<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>3500 m</td>
<td>4000 m</td>
</tr>
<tr>
<td>Gain</td>
<td>$−6.3±2.4$ dB(A)</td>
<td>$−6.2±1.9$ dB(A)</td>
</tr>
<tr>
<td>Censored gain(percentiles)</td>
<td>$−7.4±1.5$ dB(A) (5–90%)</td>
<td>$−6.2±1.5$ dB(A) (5–100%)</td>
</tr>
</tbody>
</table>
Fig. 6. Time history of $L_{pa}$ emitted by the wheels during a run 2402 at a test speed of 200 km/h (left). Gain offered by Syope wheels (right).
Fig. 7. As Fig. 6 with data grouped following a distance-based criterion (1 sample = 200 m). The curvature in m$^{-1}$ multiplied by 10$^4$ is also shown.
and the presence of driving forces have a large effect especially for the damped wheel; in general, the exact contact point location depends, once the rolling stock has been specified, primarily on the line curvature, the superelevation and the speed.

This behaviour has been verified in all the test runs. The data have been grouped into homogeneous line sections (tangent track, left curves, right curves). Within each category, and also to overcome some inevitable uncertainties and local deviations, only data between the 10 and 90 percentiles have been retained (this procedure is correct as the average remains unchanged while only the standard deviation decreases). These results are shown in Fig. 8 and in Table 3; it can be seen that in the tangent track the gain is around 4.5 dB(A).

These results are an average over all the speed range. A more detailed analysis was performed on the single run for \( L_{pA} \) levels and spectra, depending on the attitude of the wheel, for the whole run, and in a section of the line where the speed is reasonably constant (Tables 4 and 5).

As a zone where the speed is almost constant can be recognized in each run, for example for run 2402 between km 206 and km 223 with a speed of 200 km/h, it is possible to analyze this zone in order to eliminate the influence of the speed.

As the number of data recorded is different for tangent track, right- and left-hand curves, the statistical influence of each value is not the same. For example, only about half the data are available for left-hand curves compared to the other two conditions. In order to obtain data equally for the three conditions a specific test programme would have been needed, where different train speeds were observed over different line sections with the required mix of tangent
track, left- and right-hand curves and hopefully with the same condition in terms of track infrastructure (tunnels, bridges, viaducts, superstructure, etc.).

Data were acquired continuously, so they are strongly affected by local track imperfections, like rail joints and switches; these events are not representative of the noise intrinsically emitted by the wheel. For this reason a further analysis attempted to isolate an array of values that can be considered to be unaffected by local factors (Fig. 9). The values are selected from consecutive stretches of the line in order to minimize the effects of different track conditions. The results of this analysis can be considered representative of the noise emitted by each wheel in each condition (tangent track, right curve, left curve).

Spectra derived from selected data are shown in Fig. 10. Two sets of results are illustrated: one for a run 2402 with a speed of 200 km/h, and one for a run 2501 with a speed of 250 km/h. A spectrum is shown for each condition of line curvature. It should be noted that the line considered has tangent sections and both left- and right-hand curves with a radius of curvature of 4000 m and cant $h = 135$ mm. At speeds of 200 km/h, this results in a non-compensated acceleration of $a_{nc} = -0.11$ m/s$^2$ (cant deficiency $h_d = -17$ mm) with lateral forces directed towards the inside of
the curve. At 250 km/h, $a_{nc} = 0.32 \text{ m/s}^2$ (cant deficiency $h_d = 50 \text{ mm}$) with lateral forces directed towards the outside of the curve.

Overall gains of the Syope$^R$ wheel in the different track sections are shown in Table 6. They are mainly located at medium and high frequencies. However, it should be pointed out that a prominent peak appears at approximately 650 Hz in the spectrum for the standard wheel when the train runs at 200 km/h, while this peak appears neither in the spectrum of Syope$^R$ wheel at 200 km/h, nor in the spectrum from both the wheels when the speed increases.

A similar peak at a slightly different frequency (about 700 Hz) had already been observed in tests performed during 1994 at a speed of 190 km/h with a prototype ETR 500 train equipped with standard wheels [7]. This phenomenon is probably connected to resonance (modal behaviour) of the wheelset and should be investigated further with more detailed analysis.

The influence of the peak at 650 Hz on the overall noise is about 1 dB(A) in tangent track and left-hand curves (the peak level is almost the same as that of the peaks at higher frequency) and 0.3 dB(A) in right-hand curves. This appears to contrast with the results shown in Table 6, where the greatest variation in gain is for right-hand curves. It should be pointed out however that the change in benefit is due to a change in the noise emitted by both wheels, and does not show that the Syope$^R$ and the standard wheel noise change with speed in the same way. Moreover, it should also be noted that when changing the speed from 200 km/h to 250 km/h, the non-compensated lateral acceleration in both curves changes from negative to positive values, as previously stated, strongly affecting interaction forces between wheels and rails.
Fig. 10. Spectra for Syope® (black) and standard (white) for different line curvatures at 200 km/h (left) and at 250 km/h (right).
In contrast with earlier studies, it has proved impossible to define an $L_{pA}$-speed regression curve as the data are almost all grouped in the 200–250 km/h range. Data at lower speeds are often measured either during braking (and therefore discarded) or during fast acceleration (transient) phases.

4. Conclusions and further developments

During a test programme, the behaviour of a new type of damped wheel ($Syope^{\text{R}}$ manufactured by Lucchini CRS) has been compared to standard ETR500 wheels and to different noise reduction solutions (fairings applied to bogie area). Simultaneous measurements performed at the trackside and on-board confirm that a combination of both damped wheels and fairings give the highest noise reduction. Whether it would prove impossible or un-economic to apply both the solutions, $Syope^{\text{R}}$ wheels can give noise reductions higher than fairings in every tested situation. It should be noted that from maintenance point of view the $Syope^{\text{R}}$ wheels require no specific provisions as they can be used as replacements on any disc braked vehicle, while fairings can limit the visual inspection of some vital parts of the bogie.

Due to different data recording procedures, on-board measurements under the axle boxes showed previously unobserved noise emission behaviour depending on the line curvature. Unfortunately, due to the limitations in the test programme, it was not possible to carry out a more detailed analysis, but the influence of the lateral contact point under the action of centrifugal forces is clear.

A strong resonance appeared at a certain speed that can introduce dangerous fatigue phenomena, discomfort in the passenger cabin, and abnormal tyre wear. It is intended to perform an experimental modal analysis of the entire wheelset to verify the correspondence of the individual frequency (around 650 Hz) and some wheel/axle eigenmodes.

It is hoped, with the agreement of FS Trenitalia (the rolling stock owner), to repeat some measurements under more controlled conditions.

Acknowledgements

The authors would like to thank Italian State Railways FS for the fundamental help given during the test programme; Lucchini CRS for the permission to publish the results, and for the help during the test campaign and for supplying RAS software as part of a research collaboration; and Dr. Stuart L. Grassie who kindly performed corrugation measurements.
References


