Continuous external train noise measurements through an on-board device

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This work shows the results of a series of external noise measurements made on board a high-speed train. The tests were carried out using a specially designed device to be bolted to the axlebox of a carriage or locomotive protecting a microphone placed at a short distance in front of a single wheel. The philosophy of such a device is explained and the criteria regarding its design, the laboratory tests carried out on the device, its application to Italian State Railway's ETR500 train and the results obtained in various trials are reported. The reliability and repeatability of the results are analysed.

1 INTRODUCTION

The noise generated by a train increases with speed according to laws still not fully defined but certainly dependent on many factors. It is the unanimous opinion of several researchers, for example Lotz (**1**), that this noise is caused principally by the interaction of wheel and rail up to a speed in the order of 300 km/h, while above this the aerodynamic component takes on greater importance. For electrically driven trains the noise produced by the pantograph seems to be of minor importance because it must be kept small for aerodynamic resistance and contact dynamic reasons.

The noise generated by trains became a subject of fundamental importance in the 1960s with the beginning of regular high-speed passenger services and increased public awareness of noise pollution.

The measurements conducted by Italian Railways (**2**, **3**) and the principal railway administrations (**4**) have underlined the very high noise at high speeds. Usually the measurements of sound pressure are carried out at fixed points placed at standard distances from the track. Measurements of this type give a plot of noise versus time that usually draws attention to the higher noise levels from the locomotive compared with the coaches, and A-weighted spectral analyses show highest noise components in the 500 Hz to 2 kHz range.

Although such measurements are completely satisfactory when they are intended to check noise levels at property at the side of the track, they do not completely confront the problems relative to noise in as much as:

1. Every test run gives valid measurements for only one speed; to establish a trend for acoustic emission as a function of speed, numerous costly test runs must be carried out.
2. Testing various types of permanent way (ballast, concrete sleepers) may be extremely expensive.
3. For a fixed-duration signal the accuracy of level estimation reduces for low bandwidths. For example, a typical test train, comprising two locomotives and five or six coaches (giving a train length of approximately 200 m) will pass a fixed point in about 2.5 s when running at 300 km/h. This means that low-frequency analysis will not be able to follow the peaks and troughs of amplitude variation, which could be up to 10 dB throughout the train passage.

From what has been said it is clear that verifying the effect of any modification to the design of the track and/or the axles is affected by high measurement costs, since it is not possible to identify the effect of mechanical parameters (roughness and/or shape of rotating surfaces, number and position of brake discs, etc.) by analysis of the passage of a single axle, as it takes only about 30 ms (!) to cross at 300 km/h the 2.5 m that are the typical wheel pitch.

On the basis of these remarks a completely different approach to the measurement of noise was considered, looking for a method of measuring the noise emitted by a single wheel in a continuous way, that is at every point of the line and at any speed. In this way the noise emitted through the entire speed range could be evaluated by just a few test runs and particular frequencies or speeds at which peculiarities in noise emission occurred could be identified easily.

At the same time the effects of any change in the wheelset–rail system could be immediately assessed on the basis of the test on a single modified axle and not on an entire train.

For homogeneous trains, in the hypothesis that rolling noise is prevailing over the other sources, the perceived noise at any distance can be easily estimated by appropriately adding the sound pressure level (SPL) measurements made on a single wheel.

To measure the noise emitted in the most reliable way it was decided to locate a microphone as close as possible to the main noise. The device illustrated in this paper consists of a metallic casing, protecting the microphone, bolted under the axlebox of a FS ETR500 prototype carriage, so that the microphone was at a distance of about 140 mm from the wheelplate (Figs 1 to 4).

It should be emphasized that the proposed method does not claim to be a substitute for the existing one but an additional instrument to provide further engineering information to the designer of rolling stock and to railway operators. It evidently allows for the fast and accurate evaluation of noise versus speed plots and of

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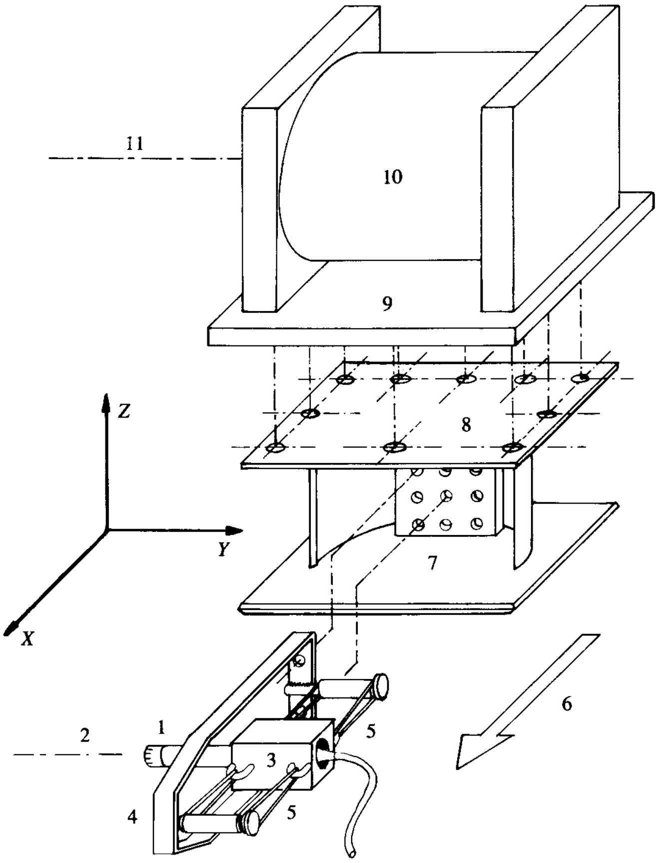


Fig. 1 The device and its installation under the axlebox. The microphone head is just in front of the wheelplate. 1, microphone; 2, microphone axis; 3, microphone support; 4, frame; 5, elastic strings; 6, airflow direction; 7, protecting device; 8, device upper plate; 9, counterplate; 10, axlebox; 11, wheelset axis

prototype performance, but the last word regarding the noise perceived in a given place will always require classical ground measurement, especially when the evaluation of the efficiency of fixed structures, such as anti-noise barriers, is involved.

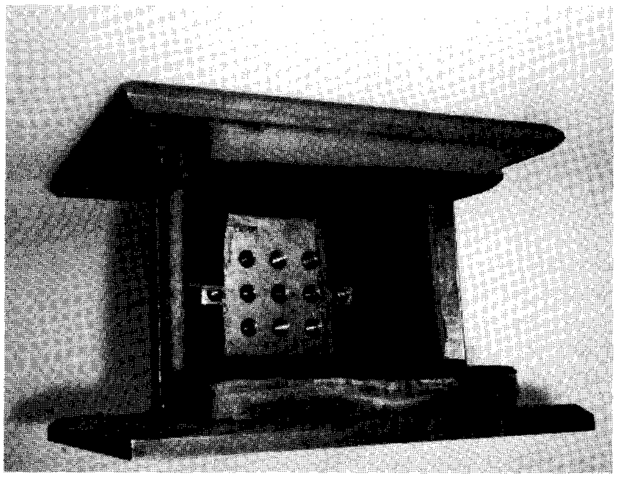


Fig. 2 Lined device as used for the field tests. The lining consists of a rubber foam layer glued between the plate internal surface and a corrugated rubber sheet

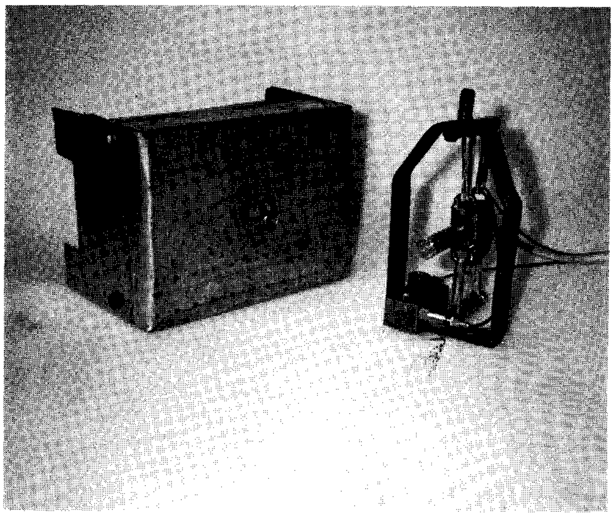


Fig. 3 Mounting block for the microphone with elastic suspension and assembly frame (right). Aluminium device cover protection (left)

2 DEVICE DESIGN CRITERIA

The device must:

1. Be easy to mount in any desired point (underneath the axlebox, under the coach body, on the roof, near the traction motor, etc.) and be easily moved or oriented against the airflow direction.
2. Have a shape that generates an aerodynamic flow that influences as little as possible both the noise emitted and the measuring capability of the microphone. The flow around the wheel and axlebox is in fact very disturbed and could generate aerodynamic noises which would impair the reliability of the measurements. The structure therefore must not only be an extremely limited source of aerodynamic noise but must also contribute to stabilize the flow.
3. Be big enough to house the microphone and connecting cables.
4. Be small enough to be bolted to the outside of the coach or bogie while still remaining within the clearance gauge.
5. Have sufficient mechanical resistance to protect the transducers in the case of collision with ballast stones or other small bodies.
6. Have a minimum installation, rotation and removal times to be handled in reduced train stops.
7. Be of low cost.

As can be seen, some of the specifications are in contradiction with one another. The prototype developed satisfies the criteria sufficiently. It is composed of a semicylindrical shell of good aerodynamic penetration, in the wake of which the measurement instruments can be easily placed. The shell is welded between two parallel plates designed to create a virtually bidimensional flow around the whole structure (Fig. 2). The upper plate has two groups of holes of constant pitch such as to be fixed in a series of different positions to a counter plate having corresponding holes integral with the axlebox.

The microphone is placed inside the protective structure on a removable frame (Fig. 3) and is equipped with

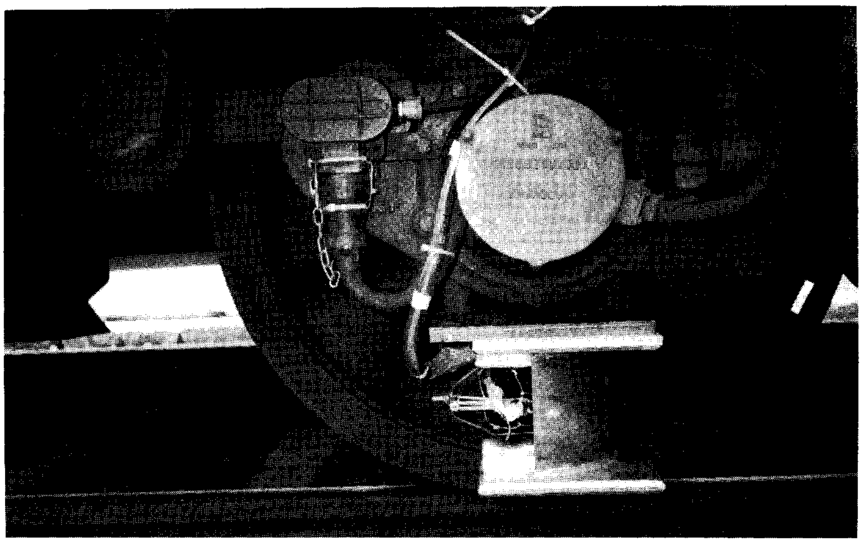


Fig. 4 Device assembled under the axlebox of an ETR500 carriage. The microphone is embedded in the spherical windscreen

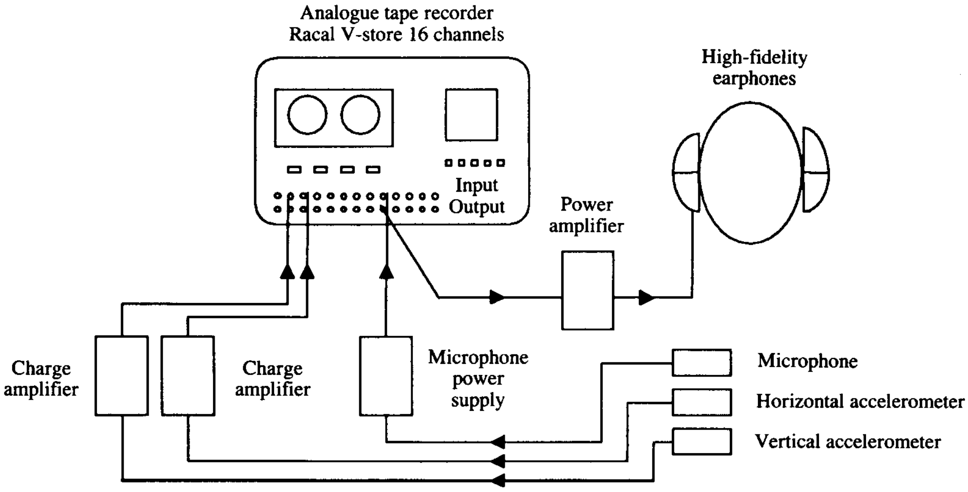


Fig. 5 On-board data collection instrumentation

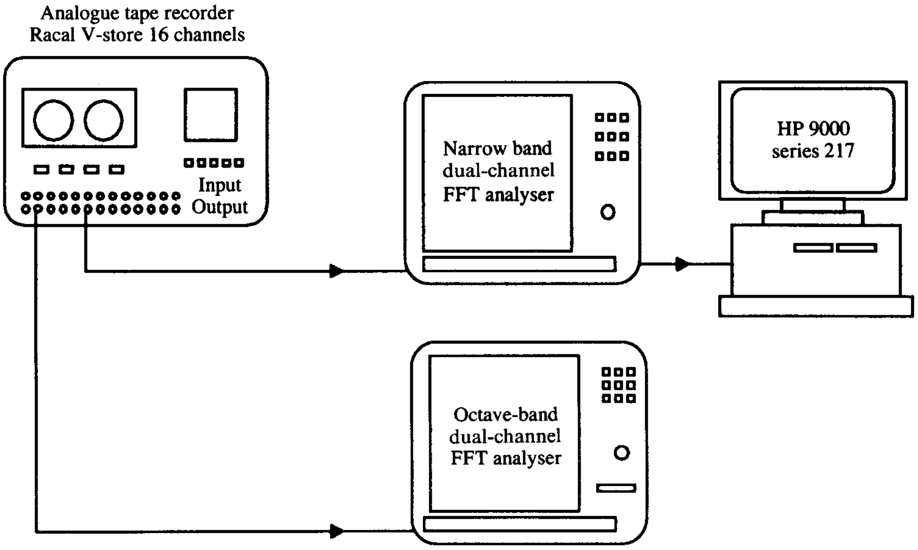


Fig. 6 Laboratory data analysis instrumentation

a windscreen. The frame is orientable in several directions, is designed to allow the easy removal of the transducer and may be equipped with accelerometers to monitor the vibrations transmission. The connection between microphone and frame is elastic to filter axlebox vibrations and tuneable to obtain frequencies sufficiently low (outside the acoustic field) whilst still avoiding a too high static flexibility.

The adopted solution consists of a small steel block with a hole in which the microphone–preamplifier group is interference fitted via a rubber sleeve (Fig. 3). The block is connected to a small frame via rubber straps of varying stiffness and number. The frame is equipped with brackets for the possible use of accelerometers and is then simply screwed to the structure. It is easy to see that this device gives the required protection to the microphone in only one travelling direction, while for the opposite one a protective cover has been developed (Fig. 3).

3 INSTRUMENTATION USED AND MEASUREMENT CHAIN

The measurement chain for on-board data acquisition is composed of (Fig. 5):

(a) acceleration chain: Brüel & Kjær (B&K) 4384 piezoelectric accelerometers, B&K 2635 charge amplifiers;
(b) microphone chain: B&K 4133 condenser microphone with preamplifier, B&K 2804 microphone supply;
(c) 16 channel Racal analogue VHS tape recorder with 15 in/s tape speed (sufficient for analysis up to 10 kHz).

The microphone was chosen so that signals could be directly sent to the analogue recorder, which accepts up to 20 V input. The 4133 type microphone, having 10.7 mV/Pa sensitivity allows the measurement and direct recording on tape without the insertion of external attenuators up to around 160 dB, a value that was foreseen as improbable and which in fact was not reached. A microphone for the recording of a comments trace (speed, position, etc.) was available; to check on line the quality of the measurements an opportunely amplified hi-fi headphone was used.

Analyses of recorded signals were then performed in the laboratory using a narrow-band B&K 2034 dual-channel FFT analyser and an octave-band B&K 2133 dual-channel analyser. The signals were appropriately sampled and windowed, A-weighted and exponentially averaged with a confidence level of 1 dB (Fig. 6). The second method guarantees optimum statistical quality of measurements even if at low frequencies increased acquisition time is needed to reach the required stability. This does not represent a problem as the recorded signals are very long and stable. As a compromise between processing speed and accuracy, a 1/12 octave-band resolution was normally used.

4 DEVICE CALIBRATION

Any object inserted in a sound field and in an aerodynamic stream modifies them locally. The influences of airflow, acoustic reflection–diffraction phenomena, structure-borne noise and microphone diaphragm vibrations have been separately analysed and minimized as explained below.

4.1 Influence of airflow on microphone measurements

Because the microphone would be subject to aerodynamic disturbance, it was decided to protect it with a B&K UA0237 windscreen. To check the effectiveness of the protector it was tested in the free-flow section of a small wind tunnel at Florence University Energy Department, kindly made available for the occasion. Noise measurements were performed up to a nominal flow velocity of 100 m/s inside the device placed in the flow; at the same time corresponding measurements were taken at increasing distances from the airflow, showing decreasing SPL values. These values have been fitted with a regression curve that has been extrapolated to estimate the SPL value inside the device, giving a result in good agreement with the measured one. It can then be reasonably supposed that the presence of the device is not a significant source of added noise, as the successive measurements largely demonstrated.

4.2 Acoustic influence of the device on noise from the outside

The metallic structure of the protection device can modify the sound field acting on the microphone with reflection phenomena. For example, the two parallel plates can generate standing waves that add to the noise to be measured since it is practically impossible to obtain anechoic terminations because of the small overall dimensions of the object and as some areas must inevitably remain smooth to avoid the generation of aerodynamic noise. Nevertheless, attempts were made to reduce the effects of resonance by using an appropriate sound coating treatment applied to the internal surfaces. The best results were obtained with a combination of foam rubber and corrugated or rough rubber (Fig. 2).

The complete measurement device was checked in the 25 Hz to 11 kHz frequency range using two distinct sound sources excited with white or pink noise placed in a semianechoic chamber. A B&K 4224 sound source for the 0 to 4 kHz range and a midrange loudspeaker for the 4 to 11 kHz range were used. The sound pressure was measured in the same place either by the microphone alone or by the microphone installed in the device. The difference between the two signals represents the influence of the device on the original undisturbed sound field; it is plotted in Fig. 7 both for the untreated device and the lined one. The final solution was considered to be satisfactory.

4.3 Influence of noise generated by vibrating surfaces of the device

During the on-line tests the device is excited by the vibrations of the axlebox. The vibrating surfaces generate structure-borne noise that could corrupt the measurement. The Y (transverse) and Z (vertical) acceleration signals recorded during a preliminary test run at 245 km/h were supplied in the laboratory to a B&K 4808 electromagnetic shaker connected to the complete

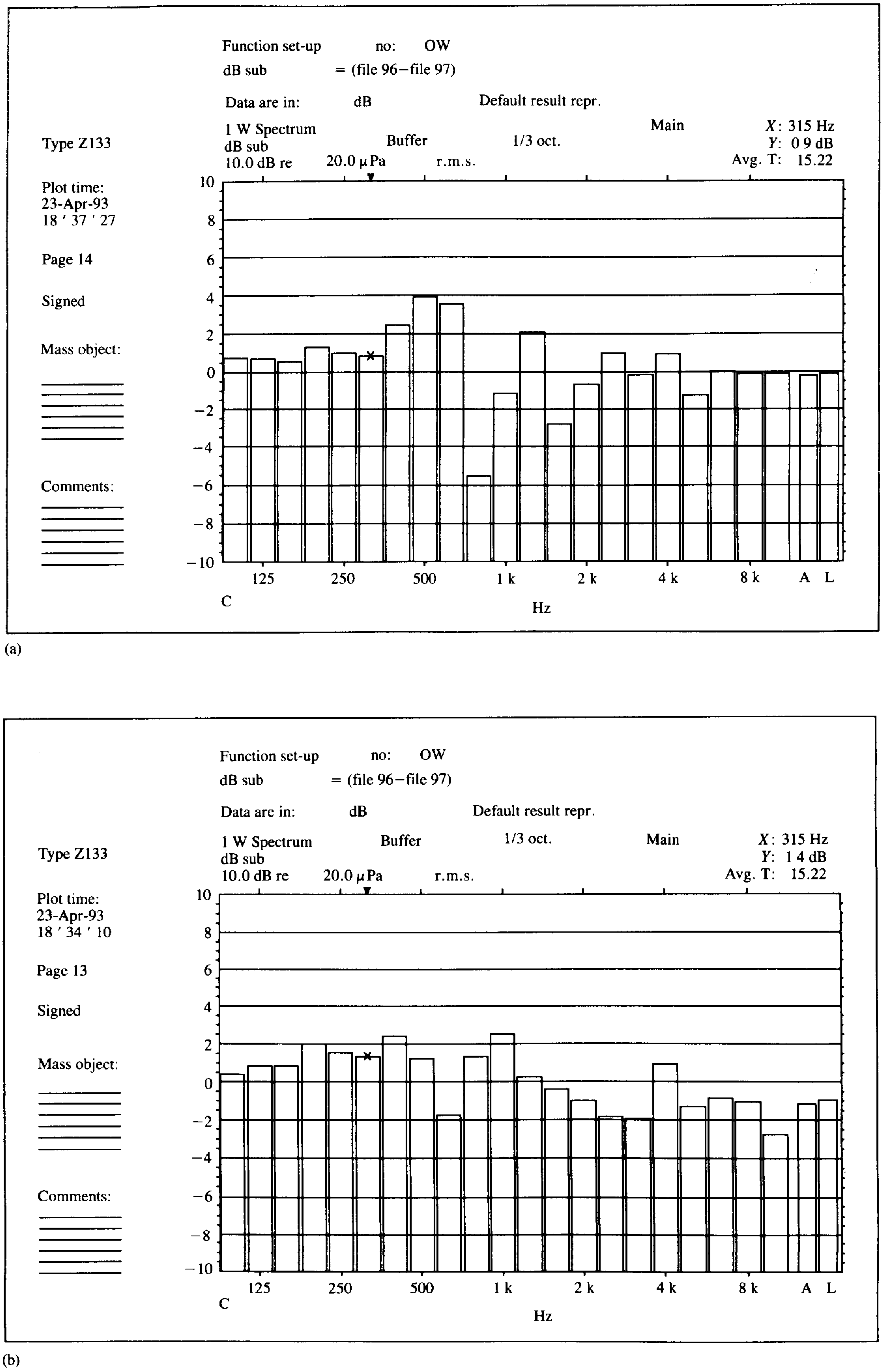


Fig. 7 Device-introduced disturbance up to 4 kHz; (a) unlined device, (b) lined device

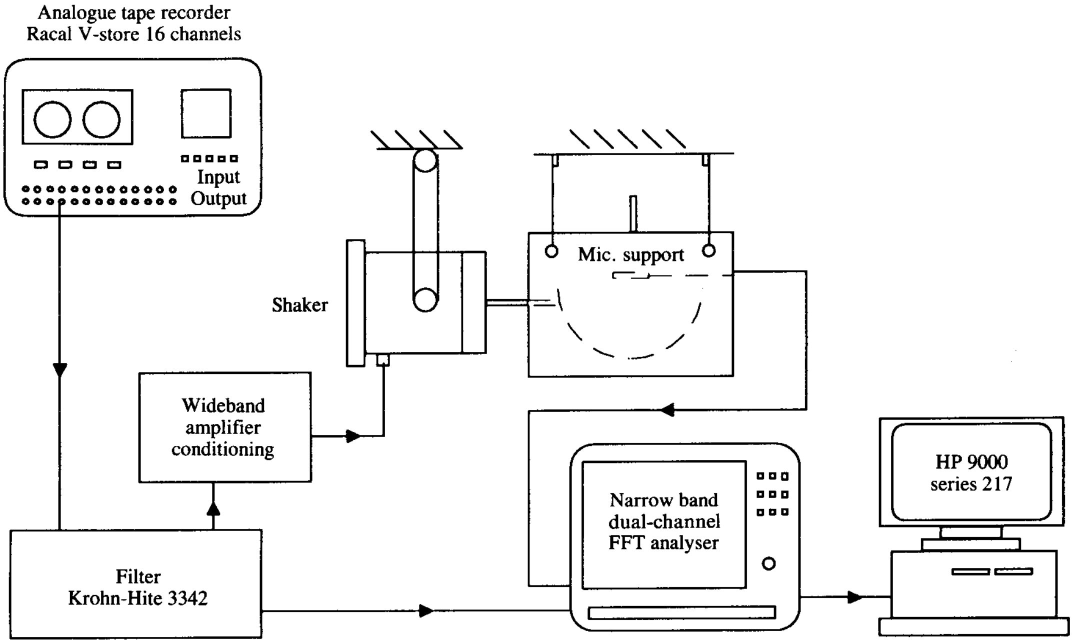


Fig. 8 Laboratory application to the instrumented device of the acceleration signals gathered in field tests

structure (Fig. 8). The overall vibration plus system noise level recorded during this test was 57.3 dB(A), notably lower than the noise measured during the final acoustic tests. Thus it was concluded that this effect did not influence the measured results.

Although interesting, the results from the accelerometer signals recorded are not analysed here.

4.4 Influence of vibrations on the measured noise

Condenser microphones like the one used in these tests are made of a membrane that measures the variations in acoustic pressure, transforming them into electrical signals. When this membrane is subjected to mechanical vibrations, the microphone 'hears' these vibrations as noise, falsifying the measurements in progress. The typical sensitivity of B&K 4133 microphones is around 67 dB/(m/s^2) r.m.s. when the vibration is normal to the membrane (**5**).

Preliminary on-line tests were carried out to evaluate the global acceleration transmissibility of the elastic microphone support. The frequency spectra for *Y* (normal to the installed microphone membrane; see Fig. 1) accelerations in the axlebox and on the support, shown in Fig. 9, underline the high overall reduction in acceleration level. Lower attenuation factors are present only at very low frequencies well outside the audible noise range. The accelerations recorded on line at 245 km/h on the support were reproduced in the laboratory using a 3 Hz high-pass filter and supplied to an

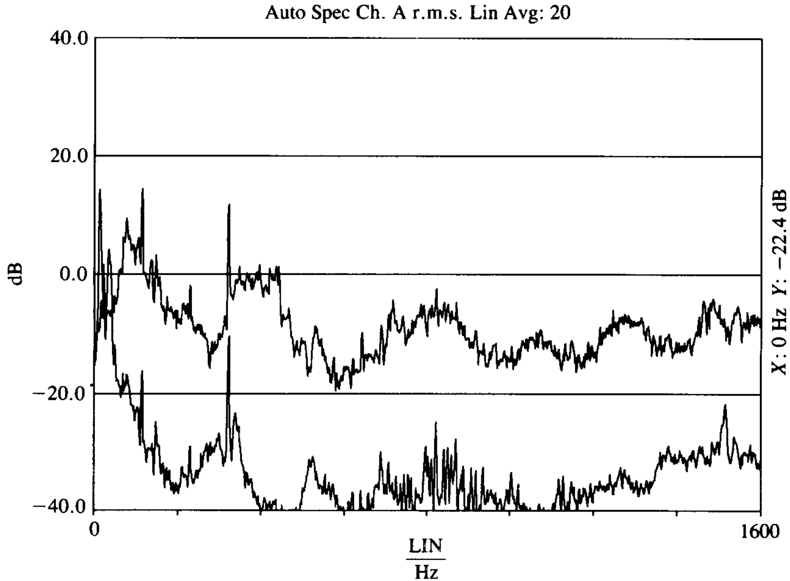


Fig. 9 Recorded *Y* acceleration spectra; axlebox (upper trace) and microphone support (lower trace); speed 245 km/h

electromagnetic shaker exciting the microphone positioned on a specifically constructed device. The difference between the noise measurements carried out with and without accelerations, a measurement that quantifies the effect of microphone vibrations, resulted in negligible change. It was therefore concluded that effective decoupling between the membrane surface and the axlebox was obtained.

5 ON-LINE TEST METHOD DETAILS

The test runs were carried out in May and June 1993 on the ETR500 train in the standard configuration of six carriages between two locomotives. The device was bolted under an axlebox of a trailer coach normally used for electrical tests (Fig. 4). The tests were performed on the 1° Bivio Arezzo Nord–Bivio Rovezzano section of the Arezzo–Firenze line, on the new high-speed line called 'Direttissima' (DD). The device was not rotated at every change of direction for reasons of time and safety; the Firenze–Arezzo run was therefore not used for the measurement. The maximum speed of 295 km/h was reached in only one run because of other test requirements. The sound pressure and the axlebox's vertical (Z) and transverse (Y) accelerations were measured, while the longitudinal (X) accelerations were considered uninteresting.

6 ANALYSIS OF SOUND PRESSURE LEVEL (SPL) TEST RESULTS

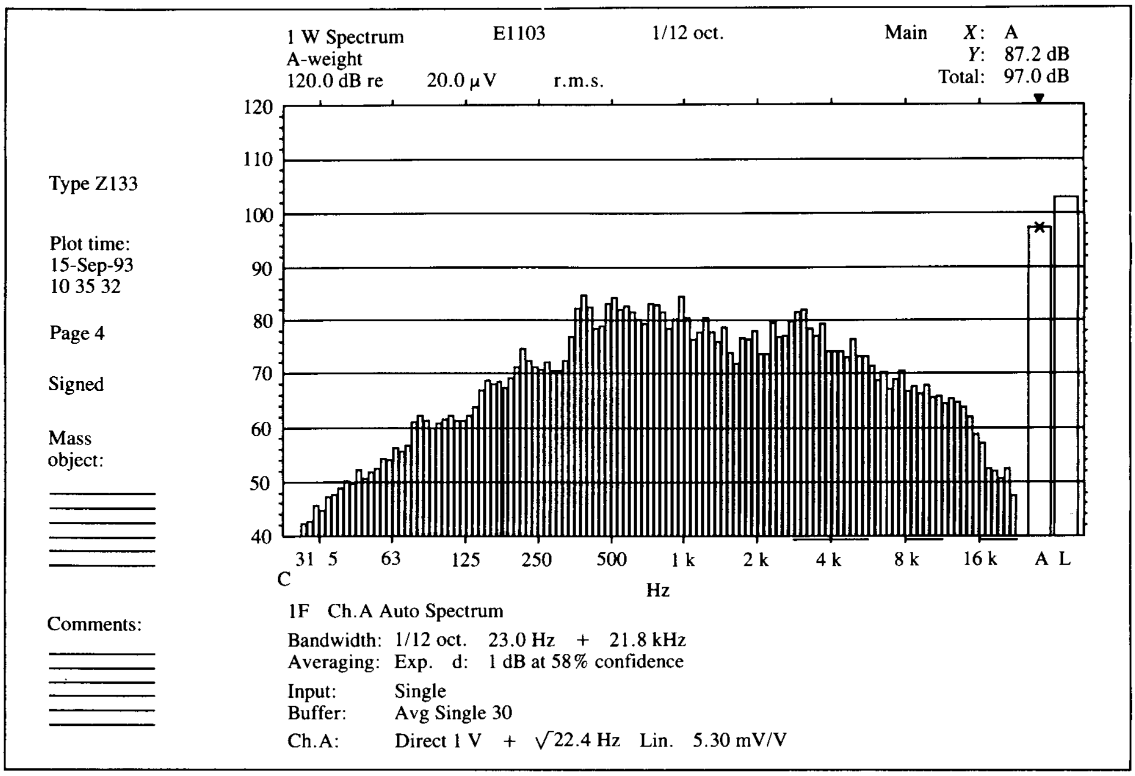
Recorded sound pressure signals were analysed with the method indicated above, manually triggering the start of the processing procedure. For this reason the error in repeatability of each measurement was of the order of 0.5 dB.

Each reported value represents the result of 30 averages. By listening to the noise signals it was possible to identify precisely the location of local phenomena (tunnel entry, track joints, turnouts) and also identify occasions of signal overload. These were excluded from the analysis. In the only measurement made in the Firenze–Arezzo direction, however, notwithstanding the partial protection following the presence of the cover, serious instances of overload were identifiable. As an example Figs 10 and 11 show two of the many noise spectra measured during tests.

The measurements in similar conditions were averaged when possible. Unfortunately, the runs were not organized specifically for this type of experiment, therefore the intermediate speeds (120, 150, 160, 180 km/h) were only maintained for brief periods principally for other test reasons, otherwise the train was brought quickly to the 'classical' test speeds (220, 250, 260, 280 km/h). The values at the lower speeds were measured during the starts from stops on the main line and measurement times were therefore much reduced.

Figure 12 plots the values of SPL in function of speed. The standard deviation σ of the averaged values ranged from ± 0.2 dB to from $+0.7$ to -0.8 dB(A) and from ± 0.4 to from 1.3 to -1.5 dB. The statistics were derived from linear pressure values and converted to dB to give mean level and standard deviation of level. Obviously, it is only through rounding that it is possible to present $\pm\sigma$ limits on a logarithmic scale. All the values refer to homogeneous test conditions, that is open-air sections with ballasted track.

The data shape appears sufficiently regular to confirm the absence of acoustic or aerodynamic saturation phenomena. The least-squares regression lines for the noise in linear and A-weighted examples are given by the equations:



1 W Spectrum E1103 1/12 oct. Main X: A
A-weight Y: 87.2 dB
120.0 dB re 20.0 μV r.m.s. Total: 97.0 dB

Type Z133

Plot time:
15-Sep-93
10 35 32

Page 4

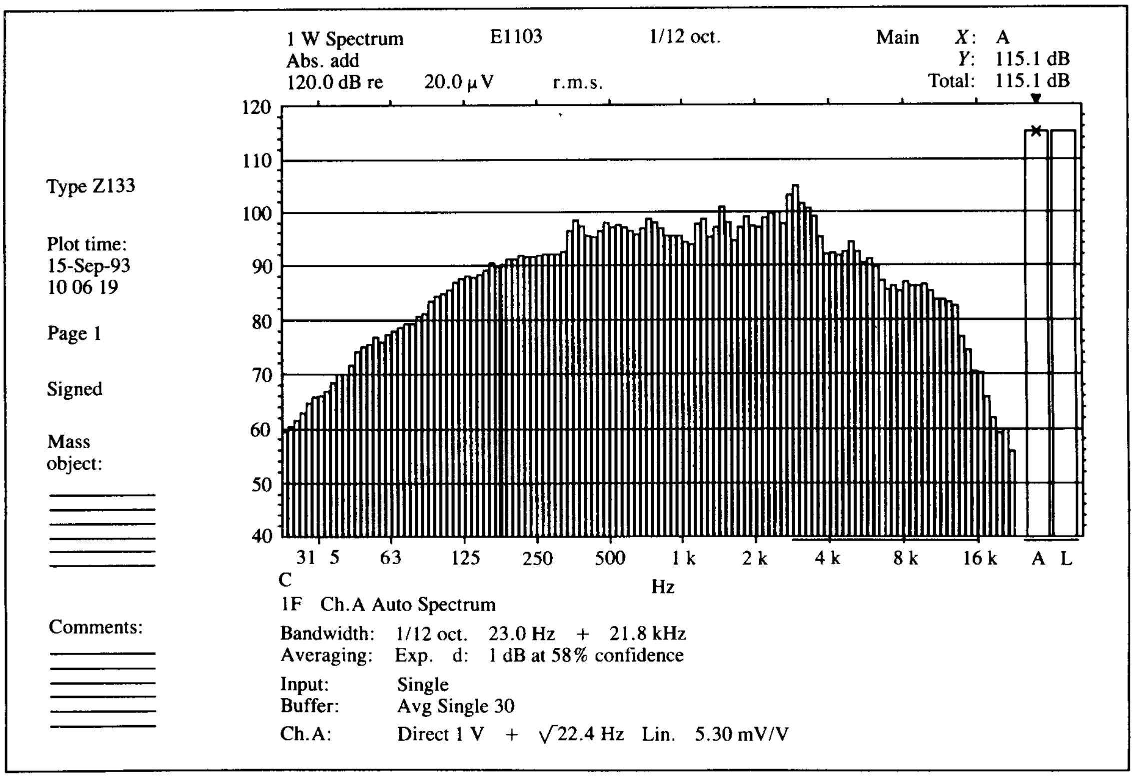
Signed

Mass object:

Comments:

1F Ch.A Auto Spectrum
Bandwidth: 1/12 oct. 23.0 Hz + 21.8 kHz
Averaging: Exp. d: 1 dB at 58% confidence
Input: Single
Buffer: Avg Single 30
Ch.A: Direct 1 V + √22.4 Hz Lin. 5.30 mV/V

Fig. 10 Recorded noise spectrum, dB(A); $v = 70$ km/h



1 W Spectrum E1103 1/12 oct. Main X: A
Abs. add Y: 115.1 dB
120.0 dB re 20.0 μV r.m.s. Total: 115.1 dB

Type Z133

Plot time:
15-Sep-93
10 06 19

Page 1

Signed

Mass object:

Comments:

1F Ch.A Auto Spectrum

Bandwidth: 1/12 oct. 23.0 Hz + 21.8 kHz
Averaging: Exp. d: 1 dB at 58% confidence

Input: Single
Buffer: Avg Single 30

Ch.A: Direct 1 V + √22.4 Hz Lin. 5.30 mV/V

Fig. 11 Recorded noise spectrum, dB(A); $v = 280$ km/h

(a) using a linear speed scale (Fig. 12a):
$\text{SPL(A)} = 92.1 + 0.087\,v$
correlation coefficient = 0.9903
$\text{SPL(Lin)} = 96.0 + 0.108\,v$
correlation coefficient = 0.9877

(b) using a logarithmic (base 10) scale (Fig. 12b):
$\text{SPL(A)} = 34.2 + 33.15 \log(v)$
correlation coefficient = 0.9908
$\text{SPL(Lin)} = 24.2 + 41.17 \log(v)$
correlation coefficient = 0.9870

The slope of the regression lines appears to be very close to those reported by other authors (**3**, **4**) for fixed-point measurements. The SPL values at the different velocities are larger than those reported in the quoted references, but this is obvious because of the difference

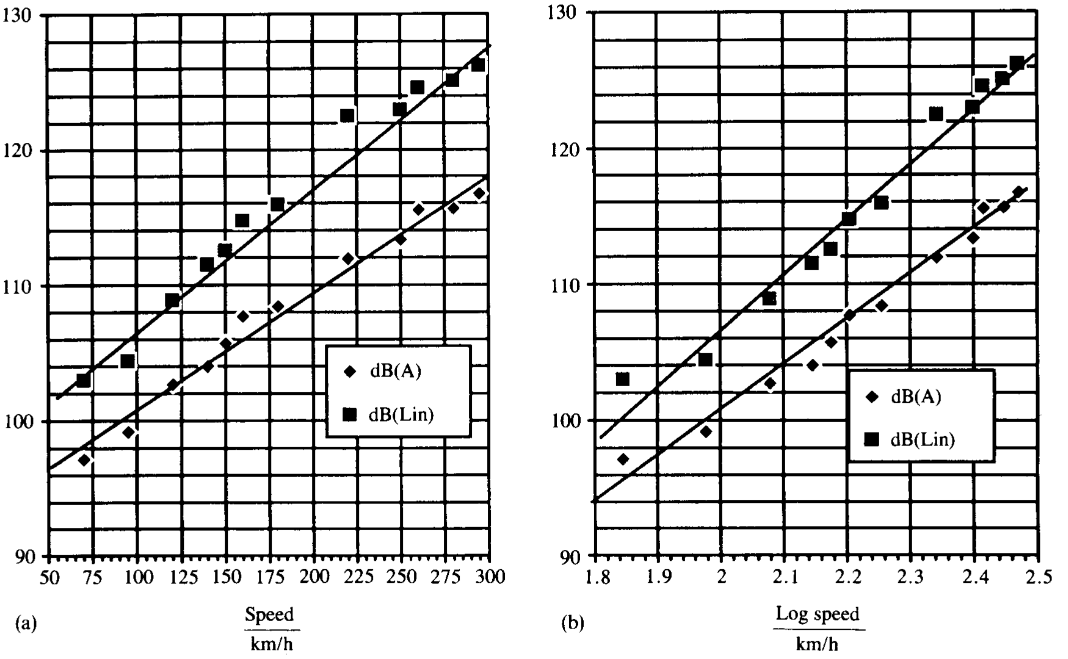


Fig. 12 Linear and A-weighted recorded SPL values versus speed (km/h): linear speed scale (left), $\log_{10}$ speed scale (right)

in distance from the noise source. All this demonstrates the assumption, over which this work was based, that in a wide range of velocities the noise perceived at 25 m is directly related to the noise emitted by the wheel. The formula of the noise in a given point of the space produced by a source or a series of sources can be found in a number of references (see for example **2**). Giving the coefficients of these formulae is beyond the scope of the present work but not of future papers, and would require simultaneous on-board and on-ground measurements, but even with the few data actually available it can be affirmed that this direct relation does exist.

As the device designed and tested performed its tasks in a very satisfactory way, the effectiveness of the proposed testing procedure appears to be confirmed.

7 CONCLUSIONS

This work has demonstrated how, for the study of noise generated by railway vehicles, beyond the classic fixed-point measurement system, a new and relatively inexpensive single point measurement system, attached to the bogie, can be advantageously employed and is capable of recording noise emitted along any track by a single wheel. This noise in a homogeneous train is directly related to the noise which is recorded at a given distance from the track (for example 25 m), but the noise emitted by a single wheel set may give valuable information about the effect of any modification introduced in that single unit and about the effects of wheel and track wear.

The device used was calibrated evaluating the effects of any possible cause of error; the measurements made on track gave fully satisfying results, permitting, for example, clear discrimination between the different noises arising from travelling over ballast compared with a continuous platform, on track and in tunnel or slow and fast lines, leading the way to new and different research projects.

ACKNOWLEDGEMENTS

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