Calibration of an on-board noise measuring device by simultaneous measurements of trackside noise of three different wheelsets for the ETR500 FS train

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Abstract: An on-board device for bolting to the axlebox of a railway vehicle or locomotive to measure rolling noise close to the wheel surface has been developed by the authors (**1**, **2**). Even though laboratory calibration and test runs have shown that the measured noise data are consistent, there was no way to prove that they were in accordance with the on-ground measured ones. Italian State Railways (FS) have performed tests with different wheelsets to evaluate the efficiency of several noise-reduction solutions; during these tests it was possible to repeat noise measurements on-board, therefore obtaining a sufficient amount of data to calibrate the device and to analyse in detail the behaviour of such wheelsets. Calculated calibration constants prove that on-board measured data can be used with confidence to estimate noise levels at several distances from the track, thereby reducing the necessity of long and expensive on-ground tests to measure environmental noise pollution.

Keywords: railway noise, noise measuring device, noise pollution estimation

1 INTRODUCTION

Railway noise, with its peculiar characteristics, is a well-known topic in the transportation field (**3**, **4**, **5**). As a contribution to the knowledge of noise generation mechanisms and with the goal of reducing noise measurement times and costs, the authors developed a noise measuring device to be bolted to the axlebox. Even when careful design and laboratory tests gave a potentially good solution, and extensive tests during test runs gave repeatable data, no calibration of the device had ever been performed by simultaneously measuring noise at the trackside. By comparing these two sets of data it should be possible to find a 'propagation constant' that relates on-board with trackside sound pressure levels.

FS performed three series of test runs to evaluate the on-ground noise emission behaviour of different wheelsets to be used on the standard ETR500 high-speed train. During these tests it was possible to undertake additional tests using the on-board device, even if, unfortunately, some conditions were not optimal from an acoustic point of view. Nonetheless, the collected data allowed the correlation between the two data sets to be determined. It also showed that for the different tested wheel types, within the whole speed range (apart from a limited number of scattered data) the difference between the two data sets was a constant (the above-mentioned 'propagation constant') function only of the distance of the fixed point microphone from the track. This means that the sound propagation pattern can be identified by a well-designed set of fixed point measurements, and that the noise at those locations and for any train speed can be easily calculated from the on-board collected data.

Recorded noise signals have been processed to obtain 1/12 octave band frequency spectra, showing how each wheelset has a typical 'signature'.

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2 DESCRIPTION OF TEST RUNS

The Istituto Sperimentale (IS) of the FS carried out a test programme in March 1994 to measure the noise emission levels of new wheelsets to be used on the coaches of the ETR500 high-speed train, whose series production was imminent. While the prototype ETRY500 carriage had 890 mm diameter tangentially curved web two-piece wheels (Fig. 1), standard ETR500 coaches will be equipped with new very light 890 mm diameter single-piece wheels.

Since noise reduction is a critical topic, three series of four wheelsets were prepared, some with noise reducing devices. A brief description of tested wheelsets follows:

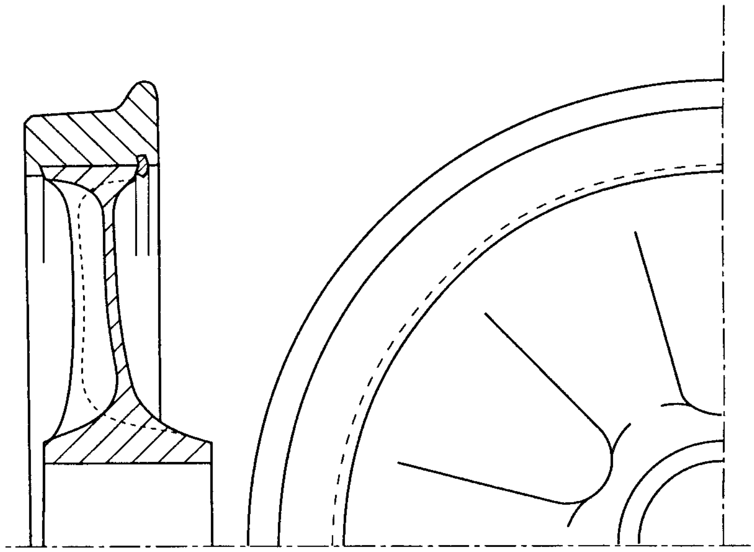

Fig. 1 The ETRY500 tangentially corrugated web wheel

(a) new wheelsets (solution 'untreated') (Fig. 2a);
(b) new wheelsets modified with a ring inserted in a groove in the internal side of the tyre with the interposition of a high damping material (solution 'dampers', externally undistinguishable from the 'untreated' wheelset) (Fig. 2b); and
(c) new wheelsets modified with damping layer metal leaves bolted to a ring press fitted into the internal side of the tyre (solution 'absorbers') (Fig. 2c).

Figure 3 shows the 'absorbers' wheelset, and Fig. 4 shows a comparison of this with the 'damper' solution.

A brief description of the tests performed is necessary to understand some quite unusual measured behaviour. An

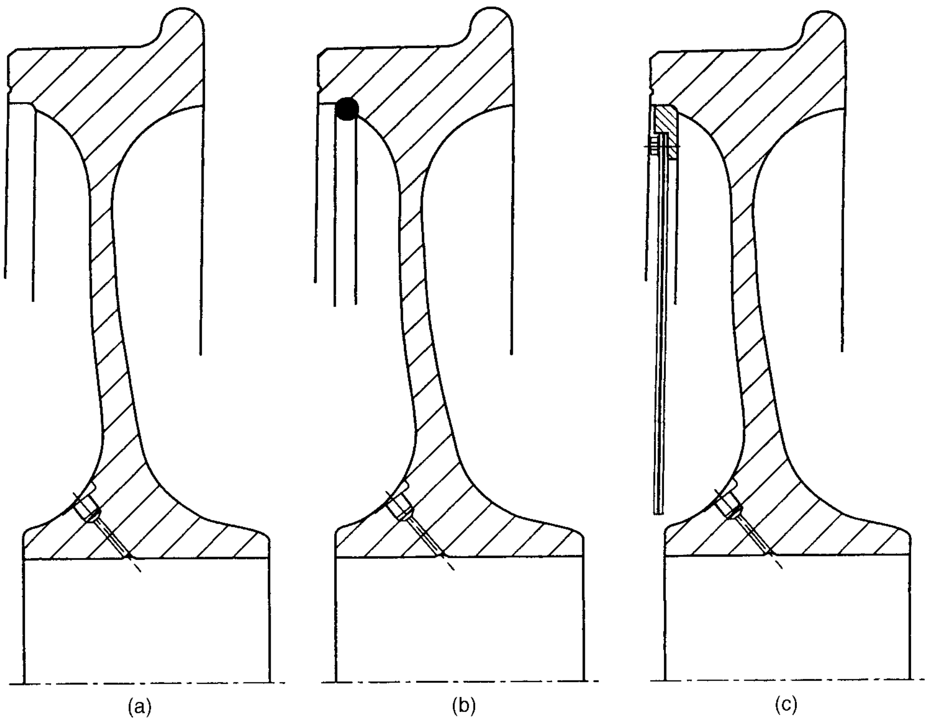

Fig. 2 The new 890 mm ETR500 wheels 'untreated', with 'dampers' treatment and with 'absorbers' treatment

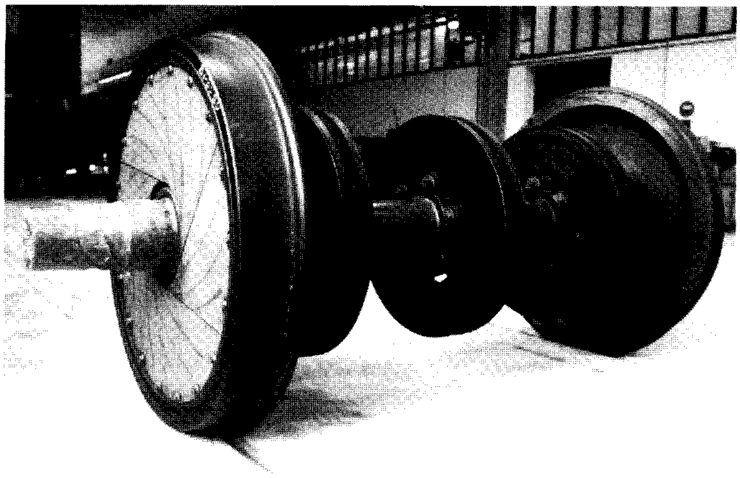

Fig. 3 Wheels with 'absorbers' treatment

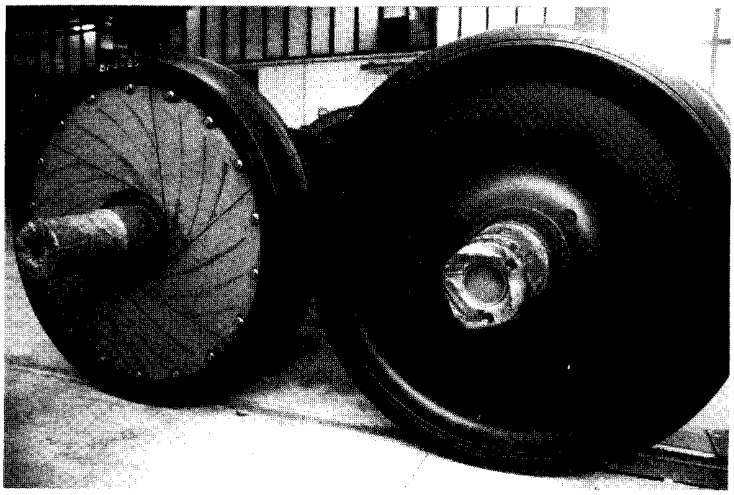

Fig. 4 Wheels with 'absorbers' (left) and 'dampers' (right) treatment

ETRY500 coach has been modified to accept new ETR500 bogies equipped with new standard wheelsets. This coach was part of a complete ETRY500 prototype train, with two locomotives and five other coaches; the noise emission of these was analysed in reference (**2**).

The wheelset mounting operation was made at the depot of Milano Martesana; test runs started immediately on the Florence–Arezzo part of the Direttissima Rome–Florence route with ballasted track, concrete sleepers and UIC 60 kg/m long welded rail (l.w.r.) at a maximum speed of 250 km/h. Six test runs per day for three consecutive days were undertaken to measure trackside noise, then the train was returned to Milan and the wheelset dismantled. The process lasted only one week and was repeated for the other two wheelsets in the following two weeks, minimizing the total time the train was out of service.

Even if these operations were satisfactory from an economical point of view, there were two major acoustic problems:

1. The wheelsets were always freshly turned, with a surface roughness much greater than the normal one for disc-braked wheelsets, and a higher noise level was probably produced.
2. The best solution, from an acoustic point of view, of modifying two adjacent coaches to highlight the noise emission behaviour of new wheelsets, was rejected by FS since it would have led to an increase in mounting times and costs.

It is important to note that the problems that arise from the first consideration do not influence in any way the calibration process of the device, since the only important thing was the chance to test three different wheelsets in a very short time on the same train (under the same geometrical conditions) independently from the details of their emission. The second consideration is, however, important and its implications will be clarified later.

3 MEASUREMENT DETAILS

As previously stated, simultaneous measurements have been made with two different methods:

1. *Fixed-point measurements* These are the classical measurements according to normal practice [see reference (**3**) for example] and they have been made with measurement microphones by IS personnel at several distances from the track axis. Since the four available wheelsets were applied to a single coach instead of to the bogies of two adjacent coaches, FS determined that the noise of one single wheelset could not be measured at 25 m from the track axis, since the noise produced by the wheelsets under test would be 'contaminated' by the noise produced by adjacent coaches. At 2.1 m from the track axis it is reasonable to suppose that a microphone measures the noise only of the bogie opposite it, this hypothesis cannot be safely made at the other 7.5 m 'classical' distance. Nevertheless, FS measured noise at this location, even if data collected here must be interpreted with great care.
   The test site was located about 15 km south of Florence and is considered as a 'free field' from the acoustical point of view.
2. *On-board continuous measurements* Measurements have been made without any interference to the FS-defined testing programme, confirming that the device can be used advantageously even during testing not specifically planned for this kind of measurement. The device mounted under the axlebox is shown in Figs 5 and 6.

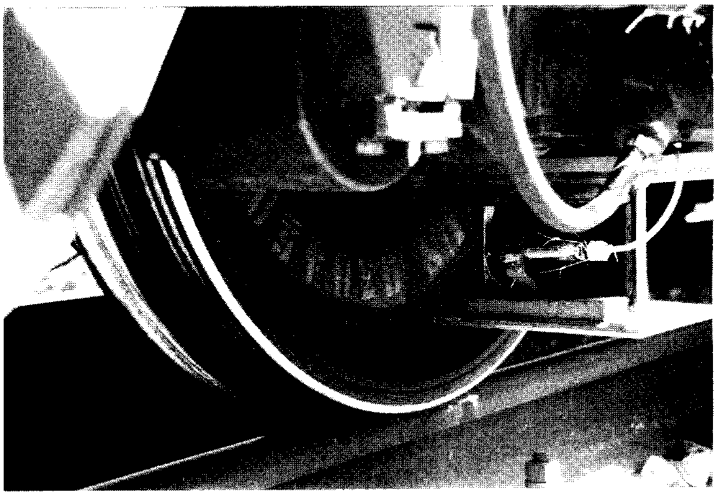

Fig. 5 External noise device detector mounting under ETR500 axlebox—'dampers' wheelset

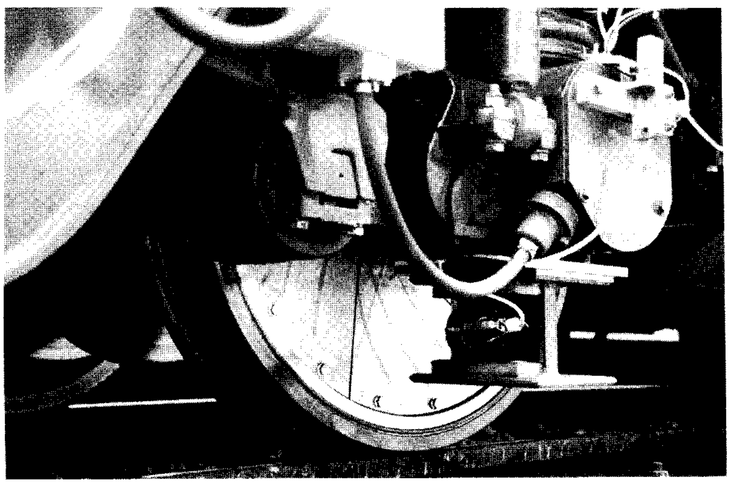

Fig. 6 External noise device detector mounting under ETR500 axlebox—'absorbers' wheelset

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Noise measurements at the fixed location, in front of which the train passed at different speeds during the various test runs, are limited to a maximum number of $18/2 = 9$ (six test runs in three days), since only the passage of the train on the track close to the microphone position is measurable. For normal operational reasons it was not possible to pass the measurement location at all the planned speeds. Planned train speeds were 150, 200 and 250 km/h.

The chance to vary the speed before and after the on-ground measurements test site was possible thanks to FS cooperation. Numerous valid measurements have been made at 100, 125, 150, 175, 200, 225 and 250 km/h in only four test runs (only one morning needed), independently from the running direction. Each measurement was obtained by averaging 30 samples, with a very good BT product (**6**) even at very low frequencies. Therefore, in every test run it was possible to make 20–25 measurements without any interference to the FS original test programme.

The railway line used for these tests has numerous tunnels, bridges, trenches and switches. This has obviously no influence on the ground test, since a test place with the required characteristics can be selected, but it reduces the length of homogeneous line useful for on-board measurement. In this case it did not prove a problem since a large amount of reliable data were collected on-board, even if a more uniform line could further decrease, if possible, the already reduced measurement times.

On-board collected signals were recorded on an analogue tape recorder mainly for back-up reasons since they had been directly real-time processed during test runs, using a spectrum analyser with $1/n$th octave digital filters. This dramatically reduces the time needed for data post-processing, which was therefore limited to the discarding of wrong data and to the evaluation of their statistical properties (averages, standard deviations, least squares fits). The results and the graphs relative to each morning of measurements were available in the afternoon.

4 SOUND PRESSURE LEVEL Lp(A) MEASUREMENT RESULTS

A-weighted sound pressure levels Lp(A) measured on-board are plotted with their least-squares fit lines in Fig. 7, in which regression coefficients are also indicated.

IS personnel measured on-ground Lp(A) at 2.1 m and 7.5 m from the track and supplied the number of valid measurements, regression equations and correlation coefficients. These data are relative to the peaks in the sound pressure pattern corresponding to the passage of the single wheelset. The statistical properties of the two data sets are summarized in Table 1.

Using these equations to compute Lp(A) at 100 km/h and 250 km/h, that is, the limits of considered speed range, it is possible to obtain the results shown in Table 2. Taking on-board measured data as a reference and discarding clearly wrong values, it is possible to see how the differences between these values and trackside noise are

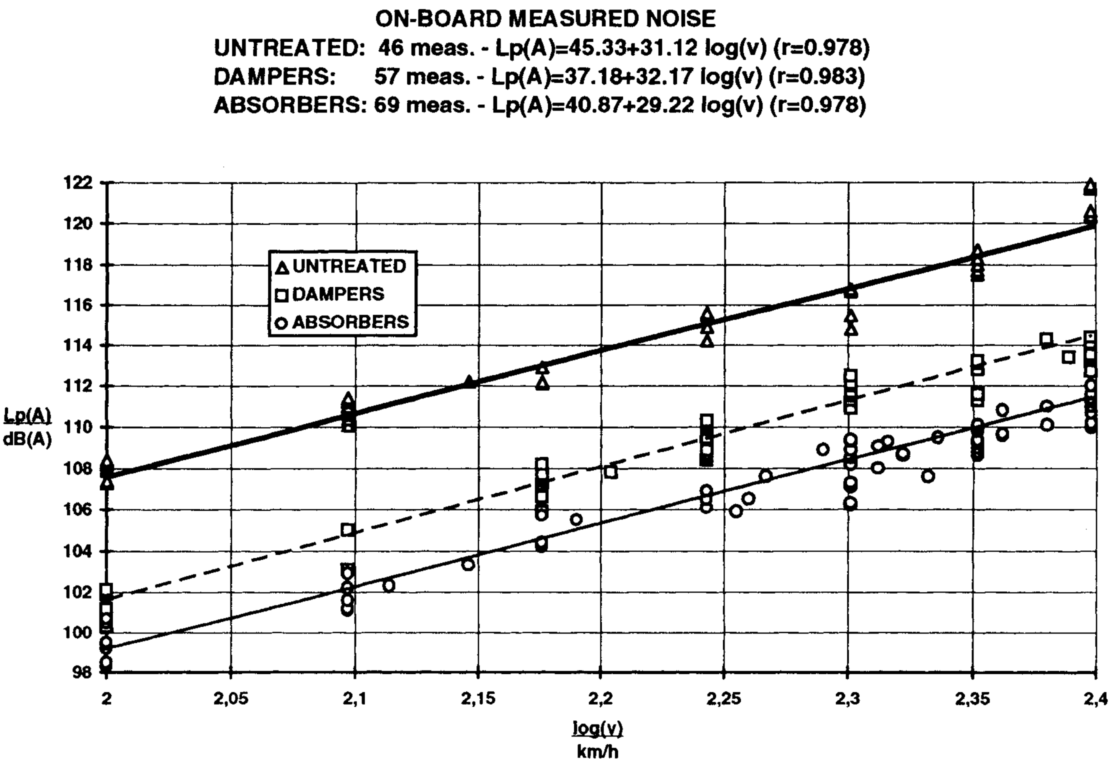

Fig. 7 On-board measurements and least-squares linear regression equations

Table 1 Number of measured noise levels Lp(A), least-squares linear fit regression equations and correlation coefficients r. For each wheelset on-board measurement time was one morning, while on-ground measurement time was three days

Type of wheelset	DMTI on-board	I.S. 2.1 m	I.S. 7.5 m
Untreated	Lp(A) = 45.3 + 31.1 log (v) 46 meas. —r = 0.98	Lp(A) = 38.2 + 28.1 log(v) 8 meas. —r = 0.98	Lp(A) = 22.7 + 31.6 log (v) 8 meas. —r = 0.98
Dampers	Lp(A) = 37.2 + 32.2 log (v) 57 meas.—r = 0.98	Lp(A) = 28.2 + 30.1 log (v) 9 meas.—r = 0.96	LP(A) = 14.9 + 32.9 log (v) 9 meas.—r = 0.99
Absorbers	Lp(A) = 40.9 + 29.2 log (v) 69 meas.—r = 0.98	Lp(A) = 38.9 + 23.0 log (v) 6 meas.—r = 0.71	Lp(A) = 22.8 + 27.6 log (v) 6 meas.—r = 0.98

Table 2 Sound pressure level Lp(A) measured and estimated on the axlebox at 100 km/h and 250 km/h

Speed = 100.00 km/h		Corr IS 2.1 = 13.76 dB			Corr IS 7.5 = 21.27 dB		
	DMTI	IS 2.1 m	Delta dB	Final error	IS 7.5 m	Delta dB	Final error
Untreated	107.59	94.44	13.15	−0.61	85.90	21.69	0.42
Dampers	101.52	88.40	13.12	−0.64	80.70	20.82	−0.45
Absorbers	99.31	84.90	14.41	0.65	78.00	21.31	0.04
Speed = 250.00 km/h		**Corr IS 2.1 = 13.76 dB**			**Corr IS 7.5 = 21.27 dB**		
	DMTI	IS 2.1 m	Delta dB	Final error	IS 7.5 m	Delta dB	Final error
Untreated	119.98	105.62	14.36	0.60	98.47	21.50	0.23
Dampers	114.32	100.38	13.94	0.18	93.79	20.53	−0.74
Absorbers	110.94	94.05	16.89	3.13	88.98	21.95	0.68

almost constant and function only at the distance from the track axis (columns 'Delta dB'). Averaging these differences to evaluate the 'propagation constant' and correcting on-board data with it, final differences are very small (columns 'Final error'), less than 1 dB. These constants are 13.76 dB(A) at 2.1 m and 21.27 dB(A) at 7.5 m and they allow the prediction of noise at these points by simply measuring the noise on the axlebox of this vehicle. If this law of Lp(A) level decay was confirmed for other types of wheelsets, the estimation of train noise at the distance from the track corresponding to the various on-ground measurement locations would be immediate. No difficulties have been found with measurements at 7.5 m, and the constant remains valid for both loud and silent wheelsets.

It is noted that only the value at 250 km/h at 2.1 m for 'absorbers' wheelsets does not coincide with the on-board measured one, probably due to the limited amount of on-ground data (only six measurements) that are quite scattered ($r = 0.71$, the difference between these points is between 3 and 5 dB at the same speed!).

The comparison between the different types of wheelsets is shown in Fig. 8 on the basis of the noise levels measured under the axlebox. 'Dampers' wheelsets reduce noise by about 5–6 dB, while 'absorbers' wheelsets reduce noise by about 8–9 dB with respect to 'untreated' wheelsets. These values are quite high, and are probably due to a high noise emission of 'untreated' wheelsets, perhaps caused by turning roughness.

In Fig. 8 the data from a previous series of tests made on tangentially corrugated web wheelsets are also shown (**2**). The noise emission of tangentially corrugated web wheelsets is clearly lower than the corresponding 'untreated' ones due to two possible reasons:

(a) they are probably more rigid dynamically in the lateral direction and can have a lower radiation efficiency for geometrical reasons; and
(b) their tyres were sufficiently worn to eliminate turning roughness effect on noise. [This reduction has been estimated to be in the order of 2–3 dB (P Scarano, personal communication, 1994)].

The estimation of the external sound pattern requires wheel radiation and air propagation models. The development of such models [see (**7**), for example] lie outside the scope of this work, even if their use in conjunction with the developed testing device could give the best results in terms of the cheap estimation of the noise at an arbitrary distance from the track and environmental noise pollution reduction.

5 ON-BOARD NOISE FREQUENCY ANALYSIS

One of the major advantages of on-board measurement is the possibility of performing correct frequency analysis also at very low frequencies, where fixed point analysis encounters severe limitations. In fact the BT product [B = filter bandwidth (Hz), T = passing time of a wheel (s)] is

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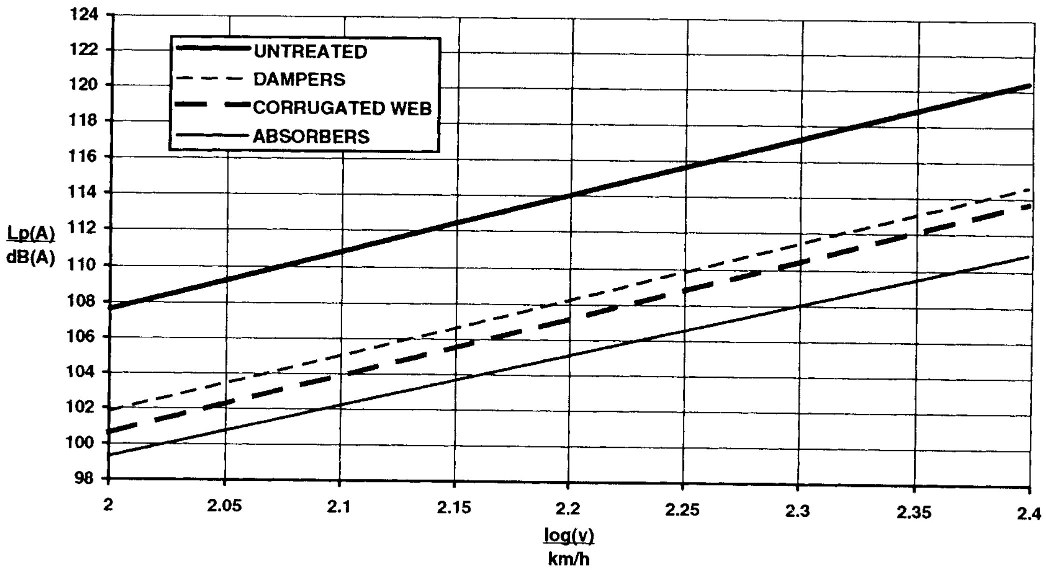

Fig. 8 Regression lines for the three wheelsets tested and ETRY500 prototype tangentially corrugated web wheelsets

very small: at 250 km/h the statistical measurement uncertainty for the 500 Hz centre frequency band is about ±2 dB(A) with 1/3 octave band resolution and ±4 dB(A) with 1/12 octave band resolution. Barsikow *et al.* (**8**) reduced this problem by using an array of microphones, obtaining good results but with expensive instrumentation and sophisticated analysis techniques. For on-board measurements, each made of 30 samples for a total duration $T \approx 18$ s, this problem does not exist even at lower frequencies and even using 1/12 octave bands.

Frequency spectra for the tested wheelsets are shown in Fig. 9 from which it can be concluded that:

(a) wheelsets ‘untreated’: high frequency noise components increase with speed and become predominant for this wheelset. Overall levels are the highest of all the wheels, up to about 10 dB(A) higher than the best solution (‘absorbers’). The trend is not very regular with speed;
(b) wheelsets ‘dampers’: the increment of sound pressure level with speed is almost constant in all frequency bands, with significant spectral components in the 630–3000 Hz range. These wheelsets have an intermediate acoustical behaviour in accordance, for example, with Lotz (**9**);
(c) wheelsets ‘absorbers’: dominant peaks exist at about 630 Hz, 1100 Hz and in the range 1600–1800 Hz. The whole spectrum varies almost linearly and regularly with speed. These wheelsets have the best overall behaviour;
(d) wheelsets ‘tangentially corrugated’: these results (**2**) are reported for completeness to show how these older wheelsets did not have the peak at around 630 Hz but had a notably ‘flat’ spectrum.

6 CONCLUSIONS

In this paper the problem of calibrating the on-board noise measuring device developed by the authors has been tackled. Extensive but fast measurements on three wheelsets for the ETR500 led to the following conclusions:

1. The on-board data collecting technique proved once again to be the best solution to give fast, cheap and reliable noise data—very important for qualification/acceptance of different wheelsets.
2. On-ground noise measurements, even with lower statistical reliability, correspond to on-board ones, allowing the computation of correlation coefficients necessary to estimate noise level at various distances from the track by measuring only the noise under the axlebox.
3. As an auxiliary result, frequency analysis of recorded noise highlighted a typical behaviour for each type of wheelset, information certainly useful for reducing wheelset noise and designing anti-noise screens and barriers. It is important to note that each type of wheelset has its own behaviour so that on-board anti-noise screens should be optimized.

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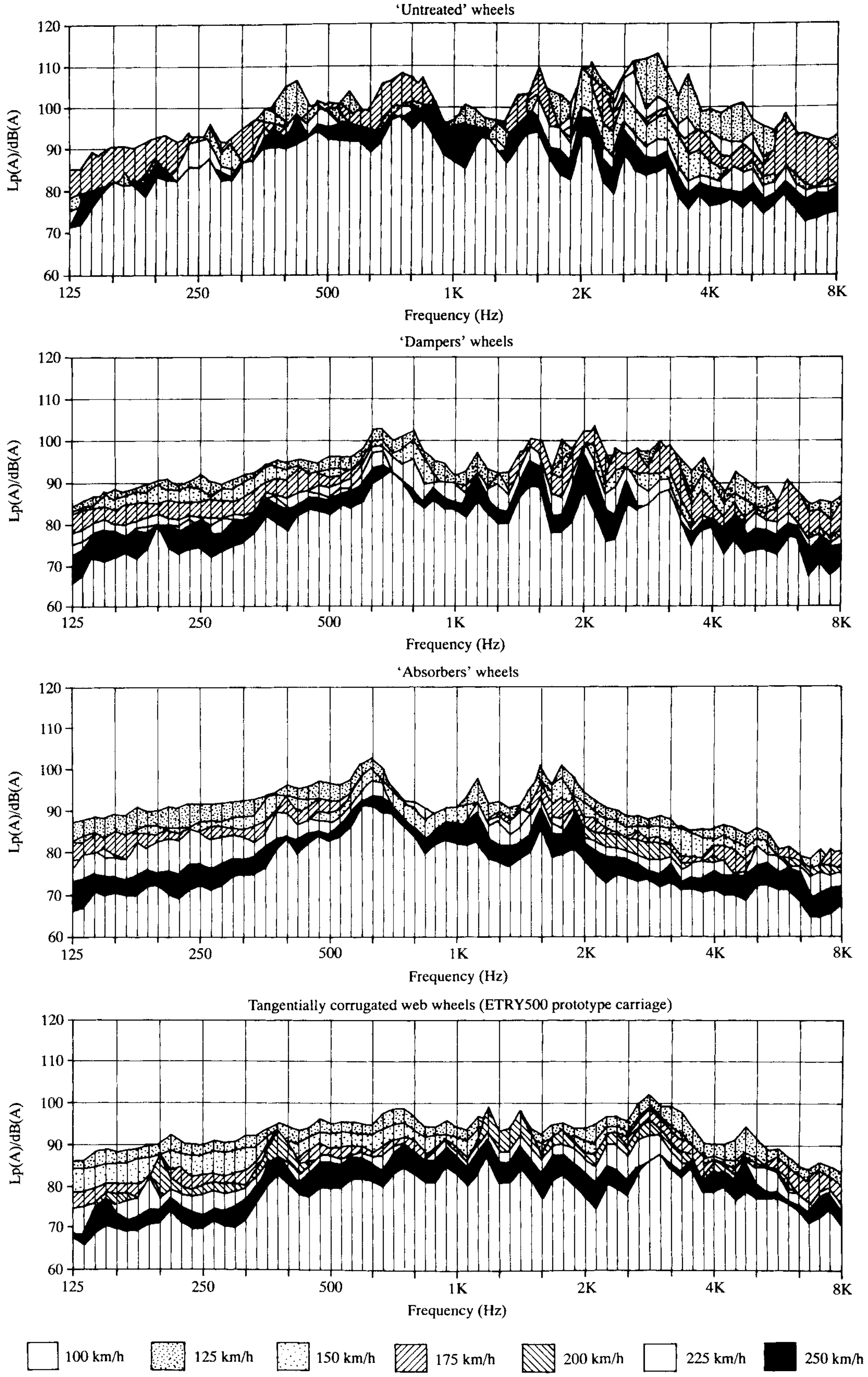

Fig. 9 1/12 octave band frequency spectra for 'untreated' (top), 'dampers' (middle), and 'absorbers' (bottom) wheelsets; 1/12 octave band frequency spectra for tangentially corrugated web wheelsets

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