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VIBRATION FROM RAILWAYS

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INTRODUCTION

Vibration from trains, transmitted through the soil and foundations to nearby buildings, may be perceived by occupants as vibration but it will also produce acoustic radiation from the internal surfaces of the building at levels which may be perceptible as noise. In this selection from our recent work on vibration from railways, the first example concerns noise radiation in buildings subject to vibration from underground trains. The second example explores aspects of predicting vibration dose values from surface railways.

NOISE RADIATION

It is a common observation that vibrating surfaces radiate noise; if we know the vibration on a surface we can estimate the noise radiated by it. For instance, in BS2750:1980 Part 4 [1], the sound power W watts radiated from a surface of area S m^2 is given in terms of the space average of the mean square of the normal surface velocity $\langle v_{rms}^2 \rangle$ and the radiation efficiency σ:

$$W = \rho c \; S \; \langle v_{rms}^2 \rangle \; \sigma \quad \text{watts} \qquad ..(1)$$

where ρc = the characteristic impedence of air.

The corresponding mean square sound pressure p_{rms}^2 in a room is given in terms of the room absorption A sabins, approximately by

$$p_{rms}^2 = 4W \; \rho c \; / \; A \qquad N^2/m^4. \qquad ..(2)$$

Substituting eqn (1) into (2) and taking logs to the base 10 gives the predicted sound pressure level SPL re $2x10^{-5}$ Pa:

$$SPL = Lv + 10log(S/A) + 10log(\sigma) - 28 \quad dB \qquad ..(3)$$

where $Lv = 20log(\langle v_{rms} \rangle)/10^{-9})$ dB.

Lv is the space average normal velocity level in dB re 10^{-9} m/sec.

For third octaves of centre frequency f Hz, for which the approximation $a_{rms} = 2\pi f \; v_{rms}$ can be used, equation (3) can be written:

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$$SPL = La + 10\log(S/A) - 20\log(f) + 10\log(\sigma) + 16 \ \ dB \qquad ..(4)$$

where La is the space average normal acceleration level in dB re 10^{-6} m/s^2,

$$La = 20\log(\langle a_{rms} \rangle/10^{-6}) \ \ dB.$$

According to equation (4) predictions of the radiated SPL should be straightforward based on measurements or predictions of La and knowledge of S, A and o in each 3rd octave band. However, to set appropriate values of S, A and σ is not straightforward.

The radiation efficiency, σ, is about 1 at frequencies above the critical frequency of the radiating element(s). For masonry walls and floors commonly encountered in sound insulation problems, at least the mid and high frequency range of interest (ie above 250Hz) is above the critical frequency and we can take $\sigma = 1$. However, for train vibration and consequent noise radiation within buildings the main excitaion is at low frequencies where the radiation efficiency may be greater or less than 1.

If La is measured on different room surfaces, the surface area S can be measured and inserted in equation (4). But if La is predicted, the appropriate value for the radiating area, S, is less certain. Typically in a small room the surface area of one wall may be about 15% of the overall surface area and would yield a radiated sound power level 8dB less than that for the same vibration level taken over the entire room surface.

Uncertainties in the surface absorption coefficients at low frequencies will yield uncertainties in the value of the room absorption, A. Moreover, in small rooms acoustic resonances produce large spacial fluctuations in sound pressure level at low frequencies which are not predicted by equation (2).

These uncertainties, together with difficulties of predicting the vibration levels La, could yield errors of more than 10dB in noise predictions for underground trains. We could of course rely on a simpler relationship in the Transportation Noise Handbook, Nelson [2]:

$$SPL = La - 20\log(f) + 17 \ dB \qquad ..(5)$$

which was derived empirically from Canadian data and is the same as equation (4) when

$$10\log(S/A) + 10\log(\sigma) = 1 \ \ dB.$$

Alternatively, we could test the relationship between radiated noise and normal acceleration level by making simultaneous measurements of noise and vibration in existing buildings. The following results are from one such test.

One accelerometer and one microphone was used to make simultaneous calibrated DAT recordings of normal acceleration and sound pressure level for a total of 44 underground train passes in two, small, lower ground floor rooms of an office block at 41-43 Praed Street, London W2 which is close to Paddington Station.

Rooms used for the measurements were;

a small conference room of floor area 27m² with floor carpet on concrete, fabric covered timber panels on timber battens on block walls and a lay-in grid acoustic tile ceiling; vibration measurements were made on the timber battens on two walls,

a store room of 22m² with concrete floor and soffit, painted blockwork walls and french windows; vibration measurements were made on the concrete soffit and on one wall.

The accelerometer was moved after each train pass and the microphone after about each third train pass. DAT recordings were analysed in 3rd octave bands over centre frequencies 20 - 200 Hz to obtain maximum acceleration levels and sound pressure levels for each train on time weighting "slow", in the frequency range 20 - 200 Hz.

Using these vibration data, predicted 3rd octave band noise levels were calculated from equation (5) and compared with the measured noise levels. Table 1 shows the mean results and standard deviations. At low frequencies the calculated noise levels exceed the measured levels, whereas at higher frequencies the reverse is true. Interestingly, in the region of 63Hz which is probably the most important subjectively, there is broad agreement between the measured and calculated noise levels. Absolute values of the means and standard deviations of the noise and vibration measurements are also given in Table 1.

	3rd Octave Band											
	20	25	32	40	50	63	80	100	125	160	200	
Mean diff dB	10	7	6	5	2	-2	0	-1	-2	-4	-6	
Std dev dB	4	4	5	5	3	3	3	3	4	3	3	
Mean SPL dB	57	61	64	64	64	67	63	58	54	52	49	47dB(A)
Mean La dB	76	79	82	83	83	84	84	80	77	74	72	

TABLE 1 Differences between measured 3rd octave band noise levels and those calculated from measured acceleration levels according to equation (5).

PROBLEMS IN PREDICTING VIBRATION DOSE VALUES

With a meter which reads Vibration Dose Value VDV [3] directly, measurements in existing buildings near railway lines should be straightforward, in principle. However, to <u>predict</u> vibration exposures is another matter. For vertical vibration, which usually predominates and is of most interest [4], the model for predicting internal narrow band (3rd octave) vibration levels, $La_i(int)$, from external trackside narrow band vibration levels, $La_i(ext)$, is

$$Law_i(int) = La_i(track) - Ra_i + Wf_i + Wr_i + Wg_i \quad dB \qquad ..(6)$$

where

Ra_i = vibration attenuation from trackside to base of building,

Wf_i = vibration attenuation/amplification from soil to building foundation,

Wr_i = vibration attenuation/amplification from foundations to assessment point in building superstructure,

Wg_i = whole body 3rd octave band frequency weightings

La_i = 3rd octave band (i) vertical acceleration level, in dB re $Aref=10^{-6}$ m/s², La_i = 20log($Arms_i$/Aref) dB.

Lwa_i = 3rd octave band (i) weighted vertical acceleration level, dB re $Aref=10^{-6}$ m/s², Lwa_i = 20log($Awrms_i$/Aref) dB, ie $Lwa_i = La_i + Wg_i$ dB.

Frequency weightings for the physical effects of vibration transmission (ie all except Wg_i) could be quantified by measurement on sites and in buildings with similar characteristics to those of the building being assessed. For instance, simultaneous measurements in the soil and on the base of a building will give an indication of the attenuation from soil to foundations. Similarly, simultaneous vibration measurements in the base of a building and on an upper floor (centre span) will quantify vibration amplification in the superstructure. Some results are shown in Fig 1.

It is not clear from BS6472:1992 what the frequency weightings Wg_i should be. This standard refers the reader to BS6841:1987 [5] where in Table 1 and section 6 frequency weighting Wb (0.5 to 80Hz) seems to be recommended for perception and discomfort of vertical vibration whether the recipient is standing, seated or recumbent. This is not the same as the Z-axis frequency weighting of BS6472:1992 which takes the same form as Wg in BS6841:1987. We used the latter, taking the asymptotic values stated in Table 3 of BS6841:1987.

Thus, using equation (6) and taking antilogs, weighted mean square 3rd octave band vertical accelerations, $Awrms_i(int)$, to which people will be exposed, can be predicted. For a given train the overall rms weighted acceleration is obtained from the sum of the squares of n narrow band rms weighted accelerations:

$$Awrms(int) = \{ \sum_{i=1}^{i=n} Awrms_i^2(int) \}^{0.5} \quad ms^{-2} \qquad ..(7)$$

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Using the approximation of BS6472:1992 for signals with crest factor less than 6, an estimated vibration dose value, eVDV, is obtained for a given train of duration T seconds:

$$eVDV = 1.4\ Awrms(int)\ T^{0.25} \quad ms^{-1.75} \qquad ..(8)$$

By applying this predictive method to different train types and knowing from timetable information the numbers of trains, overall vibration dose values can be predicted for day or night and compared with appropriate targets. Guidance is given in BS6472:1992.

On this basis, Figure 2 shows predicted values of eVDV on the first floor of a house for a number of freight trains, compared with the site eVDV, the latter being based on measured site vertical acceleration without corrections for the response of a building.

The extent to which this estimating procedure conforms to the intention of BS6472:1992 depends, among various factors, on the assignment of an appropriate root mean square value to the weighted acceleration time history and on whether the crest factor is less than 6, both at the recipient. But the time histories at the recipient are not known, it is these which we are trying to estimate or at least to represent by rms and VDV descriptors. Trackside time histories are all we have, of which some examples are given in Figure 2. These are vertical acceleration (31.5Hz 3rd octave band) in the ground recorded on a DAT tape recorder at 17m from the track for freight trains on the North London Line. Table 2 shows measured crest factors and the ratio of root mean quad (rmq) to rms values.

Crest factors, Cr, were measured on the B&K sound level meter Type 2231 with Type 1625 filter set, by taking the difference between "maxP" and "Leq" and converting to a ratio:

$$Cr = 10^{(maxP-Leq)/20}.$$

The ratio of rmq to rms values was calculated digitally by sampling the AC output of the 2231 at 500 samples/sec and calculating the rmq and rms values directly, ie by digital realisation of the integrals:

$$Armq = \{1/T\int_0^T a^4(t)\ dt\}^{0.25} \qquad Arms = \{1/T\int_0^T a^2(t)\ dt\}^{0.5}$$

where a(t) is the instantaneous acceleration, m/s^2, and T is the duration of the train pass by.
Table 2 also shows two particular cases; first, a pure tone of 159.2Hz which is the acceleration signal from the B&K calibration exciter Type 4294 for which the crest factor is theoretically 1.4 and the ratio of rmq to rms values is theoretically 1.11. The other is a random signal with Gaussian distribution and zero mean, for which the theoretical ratio of rmq to rms values is 1.32, $a_{rmq}^4 = 3\ a_{rms}^4$, [6].

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Event N°	Duration seconds	$L_{eq,T}$ dB La dB	Cr	$L_{rmq,T}$ dB	rmq/ rms	TYPE OF EVENT
CAL TONE Gaussian		100.0	1.45	100.9	1.11 1.32	calibration tone, 159.2 Hz
(7)	41	83.4	6.6	87.6	1.62	1 loco, 10 container wagons
(8)	17	86.3	5.4	90.1	1.55	1 loco, 6 liquid O_2 tanks
(16)	46	82.5	4.5	85.8	1.46	1 loco, 15 roadstone wagons
(17)	38	82.5	7.8	86.6	1.60	1 loco, 16 Royal Mail cars
(18)	29	82.4	6.8	86.1	1.53	1 loco, 15 roadstone wagons

TABLE 2 Crest factors and ratio of rmq to rms values for a selection of freight train time histories (vertical acceleration in 31.5 Hz 3rd octave band) in soil at 17m from the North London Line. Acceleration levels are in dB re 10^{-6} m/s². The sensitivity of the equipment was increased by 40dB after recording of the calibration tone.

In Table 2 the mean crest factor is 6.2 and the mean rmq/rms ratio is 1.55 (3.8 dB). The latter is a little greater than the approximation used in BS6472:1992, namely an rmq/rms ratio of 1.4 (2.9 dB) for Cr < 6, and casts some doubt on the reliability of the estimated vibration dose values. More importantly, we can see the difficulty in assigning an rms value to the time histories, by eye. It would therefore be in the spirit of BS6472:1992 to make a more direct determination of VDV by calculating rmq weighted acceleration values in terms of the weighted instantaneous acceleration Aw(t) at the recipient, of duration T seconds:

$$VDV = \{ \int_0^T Aw^4(t)\,dt \}^{0.25} \qquad ..(9)$$

or

$$VDV = Awrmq.T^{0.25} \qquad .(9a)$$

The starting point is trackside vibration time histories, ie unweighted instantaneous acceleration tape recordings. These data could be filtered to obtain 3rd octave band time histories $A_i(t)$, raised to the power four and integrated to give 3rd octave band rmq vibration values:

$$Armq_i = \{1/T \int_0^T A_i^4(t)\,dt \}^{0.25} \quad m/s^2.$$

Two questions then arise:

1) Can the same 3rd octave band frequency weightings be applied to rmq values as were used for rms values in equation (6)?

2) When appropriate frequency weightings have been applied, should we sum the squares or sum the quads of the individual weighted rmq narrow band values to obtain the overall rmq, or use some other procedure?

For time histories where rmq is proportional to rms, ie Armq = const x Arms, such as Gaussian distributions, it can be shown that the same frequency weightings apply to the square of rmq values as to the square of rms values and the overall frequency weighted rmq^2 is the sum of squares of the individual 3rd octave band rmqs. However, in general these rules do not apply; if individual 3rd octave band rmq values are used to evaluate vibration signals with large crest factors, that is signals suspected to be non Gaussian, there is no general procedure for frequency weighting and combining 3rd octave band levels in that case. Possibly answers could be found in the theory of random processes by extending Parseval's theorem, they are are not contained in BS6472:1992.

REFERENCES

[1] BS2750:1980 Part 4, Field measurement of airborne sound insulation between rooms. Annex B, Measurement of flanking transmission.

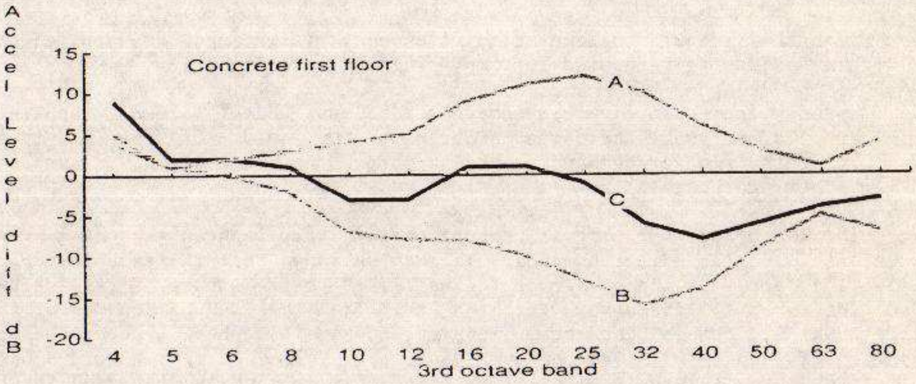
[2] Paul Nelson (ed), Transportation Noise Reference Book, Butterworths, 1987.

[3] BS7472:1992 Guide to Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz).

[4] T M Dawn, The wayside vibration from trains, Proc IoA Vol 11 Part 5 (1989), p111-119.

[5] BS6841:1987 Guide to Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.

[6] B E Cooper, Statistics for Experimentalists, Pergamon Press, 1969.



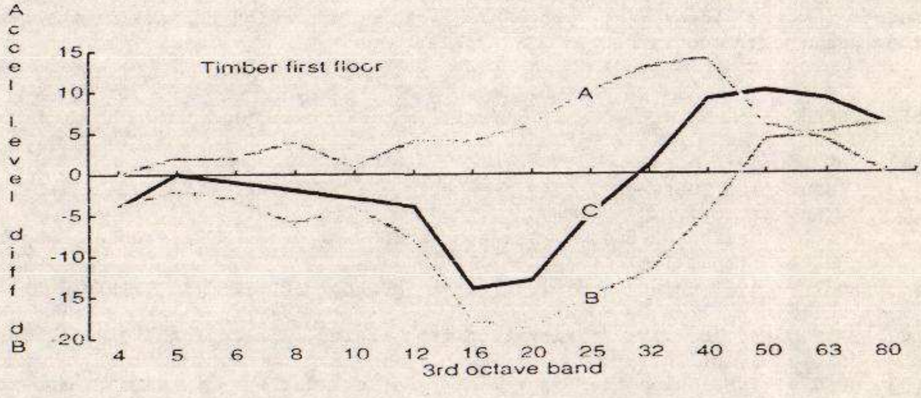
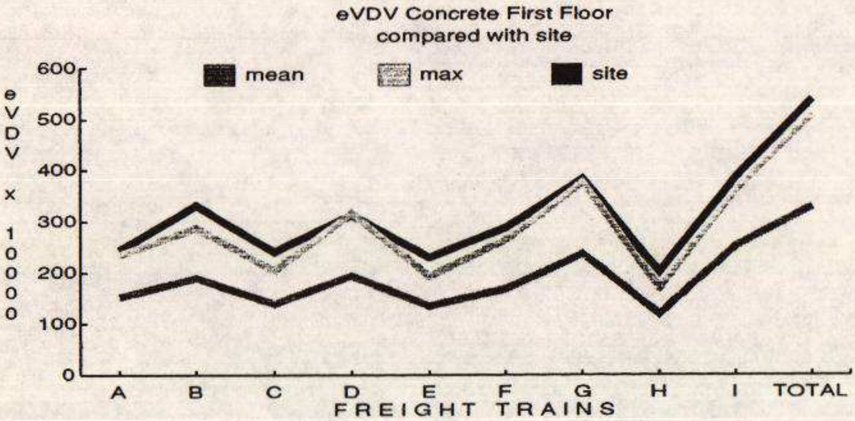


FIGURE 1 Vertical 3rd octave band acceleration measurements on two storey buildings subject to surface train vibration. Data shown are worst case, ie maximum measured amplification and minimum measured attenuation.

A first floor La minus ground floor La
B ground floor La minus external soil La
C aggregate amplification external to first floor

Data for timber first floor courtesy of John Miller (from his house in Cricklewood). Data for concrete floors from two storey light industrial unit.



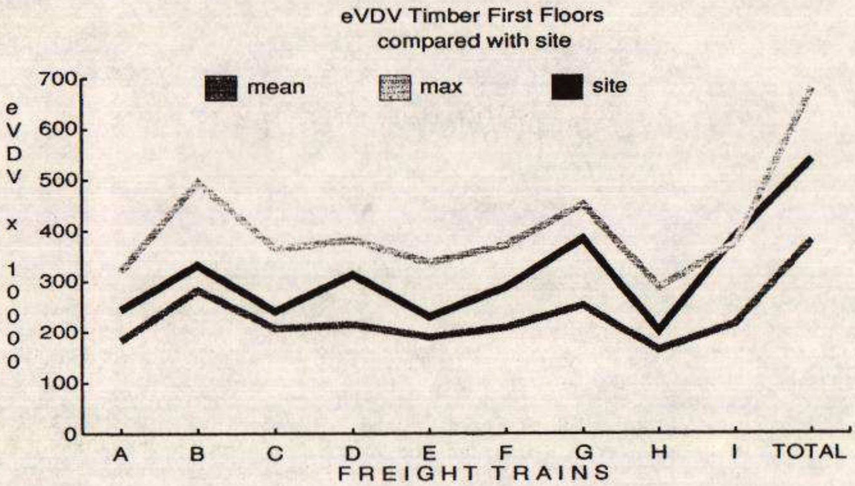
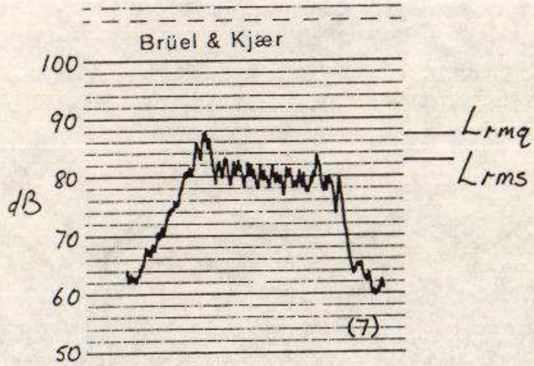


FIGURE 2 Predicted vibration dose values in houses for a selection of freight trains, compared with site (ie soil) estimated vibration dose values for the same trains.



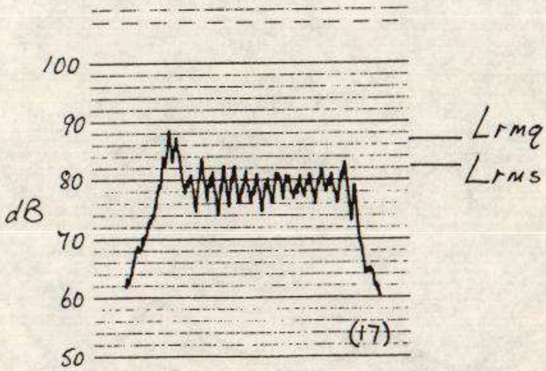


FIGURE 3 Illustrative 3rd octave band (31.5 Hz) vertical acceleration time histories for freight trains on the North London Line. Measurements obtained from a steel stake in the ground at 17m from the nearest track - see Table 2.
Level Recorder:
Paper speed 1mm/sec
Writing speed 16mm/sec ("slow")
Lower limiting frequency 20 Hz
Ordinate: Acceleration level, dB re 10^{-6} ms^{-2}