Journal of Sound and Vibration (1979) **66**(3), 355–362

GROUND VIBRATIONS FROM PASSING TRAINS†

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(*Received* 16 *July* 1979)

As railway operating practice has evolved, so trains have become faster and also in the case of freight trains heavier, with increased axle loads. To carry this traffic, heavier track has been introduced and maintenance programmes intensified. This paper examines the residual problems of ground-borne vibration, the vehicle and track features which might be responsible for generation, how it is propagated, and how it might affect wayside buildings. Experimental work has suggested various significant features of railway design which might merit attention.

1. INTRODUCTION

Since the earliest days of underground railways in urban areas, there has been complaint of house vibration caused by the passage of trains. Discussion of this subject was covered by a paper at the first Workshop [1], and we do not propose to cover the same ground again. Rather, we would like to consider the related problem of the vibration caused by traffic on surface railways, a subject which has been treated very little.

The operation of modern railways has been attended by an increase in train weight, train speed and wagon axleload. At the same time greater attention is being paid to track quality; the use of continuous welded rail is common, heavier rail sections and heavy concrete sleepers are being introduced together with deeper ballast, whilst regular mechanised maintenance of track line and level is the rule. Clearly, the change in vehicle and train requirements has been matched to some extent by developments in track design. There seem nevertheless to be a few scattered complaints by wayside residents of vibration due to the passage of trains.

The object of this paper is to summarize the vibration problem under the headings of generation, propagation, building response and perception, to present a few of the experimental results which have been obtained during studies made on British Railways, and to discuss some of the lessons which might be learned from these.

2. GENERATION

It is clear that when a train stands on the track, a stress pattern is produced in the ground beneath and around the train which is sufficient to support the train (or any other vehicle). When the train moves the stress pattern will move with it, although modified to a small extent by the finite propagation velocity of the stress waves. This moving stress pattern must impress stress waves into the surrounding ground even in the absence of any imper-

† The following paper was written as a deliberate attempt to stimulate discussion during the Workshop session on ground-borne vibration. In consequence, it presents a collection of ideas, and a selection of the results of various experiments, rather than a rigorously reasoned treatise. It is presented here in the same spirit.

0022-460X/79/190355+08 $02.00/0

fections or periodic irregularities in the vehicle or the track. Whether this basic moving stress pattern is sufficient to cause a significant response in the wayside property is unknown, but there may certainly be particular geological conditions in which this does happen.

Obviously the practical railway has many features which are capable of supplementing the basic stress field beneath the train. Any unsteady riding of the vehicle such as bouncing, rolling, pitching and yawing must result in additional fluctuating forces on the track structure. Recognized defects such as eccentric wheels, unbalanced wheels and wheelflats may also contribute to ground disturbance. The track itself does not provide uniform support; the rails, themselves of fixed length, are supported on sleepers placed at regular intervals, and the sleepers are in turn surrounded by and rest upon stone ballast. This ballast bed may by its very nature provide a somewhat variable support, and voidage below the occasional sleeper is a well known fault. All of these track features can be expected to contribute to the stress field present in the ground below and beside the train, and hence contribute to the vibration disturbances which propagate to the wayside. Clearly some of these will produce a purely local effect in the case of isolated features, whilst others will provide a regular pattern moving with the train.

The extent to which these features promote vibration can be expected to depend on the speed of the train and the weights of the vehicles within it. The static weight of the train provides the basic stress field due to the train, whilst the unsprung masses and the suspension characteristics of the vehicles, allied to their speed, will determine the extent to which track and rolling stock characteristics enhance this stress field. Experimental evidence in support of some of these points occurs later in the paper.

3. VIBRATION PROPAGATION

Once transient stress variations are produced in the ground below the track, they will propagate away from the track as ground-borne vibration. A variety of modes of vibration are possible within the ground, and the principal types are the following: (a) compression waves, with particle motion being an oscillation in the direction of propagation; (b) shear waves, with particle motion being an oscillation in a plane normal to the direction of propagation; (c) Rayleigh waves, which are surface waves, with a particle motion generally elliptical in a vertical plane through the direction of propagation.

In the ideal case when the ground is homogeneous the compression and shear waves propagate in all directions away from the source, and hence suffer substantial geometric attenuation, as well as losses due to the damping properties of the ground. The Rayleigh waves, being surface waves, do not suffer the same geometric attenuation, but are still subject to loss by damping. In practice the ground is far from homogeneous; it may well be stratified, and possess discontinuities. In such a case additional modes of vibration can propagate along the interfaces of strata, and mode conversion from one type of wave to another may be encouraged.

The various modes have different propagation velocities. The compression waves travel at typically 1000 m/s, whilst the shear and Rayleigh waves are much slower. Velocities for these seem typically to be about 200 m/s, but Rayleigh waves have been reported as slow as 35 m/s [2], although we have no experience of any so slow.

The vibration energy is not shared equally among the modes. Because of different geometric attenuations, the Rayleigh wave carries most of the vibration energy at significant distances away from the track. Reference [3] also suggests that for ground vibrations generated by the vertical oscillation of a flat plate on the ground, about two thirds of the total energy is carried by the Rayleigh wave.

A further significant factor is that high frequencies are attenuated much more rapidly than low frequencies, so that low frequencies dominate the spectrum at distances of more than a few metres from the source.

With the complication of so many modes of propagation, and the wide variety of geological conditions over which railways have to be built, it would not be surprising if trackside measurements at different sites produced a range of vibration values which bore no resemblance to each other. The experience which we have to date of vibration measurements in terms of vibration velocity level (linear over the range 2 Hz to 1000 Hz) made on a variety of sites in Great Britain, yields just the confused picture to be expected. Both the levels of vibration and the manner in which the level decays with distance vary in a manner which has so far defied prediction. The only measure of consistency to date is that changing from one site to another does not appear to alter the rank order of vehicles in terms of their vibration generation characteristics.

4. BUILDING RESPONSE

The vibration caused in buildings by passing trains can be due to both ground-borne vibration and to air borne noise. Examples of both mechanisms can be identified, and both may occur in some cases. Where both mechanisms do occur their separation can be very complex.

In this paper, however, we are concerned only with the behaviour of buildings when subject to ground-borne vibration; if building vibration does occur, disturbance is the usual result, not damage. Building response depends on the elastic properties of the ground, the type and depth of foundations of the building, the design and construction of the building, and even on the placing of furniture within the building. Those available modes of response which are excited will depend on the character of the disturbance passing through the ground, in particular the frequencies present, and their corresponding wavelengths. Obviously the frequency (f) and wavelength (λ) are connected by the propagation velocity (c) (or velocities, if more than one mode of propagation is present to a significant extent) according to the equation $c = f\lambda$. It may be that the local propagation velocity plays an important role in determining whether or not significant disturbance is caused to a particular building.

If the wavelength of the disturbance is long compared with the width of the building then the input to the building will be purely translational. A similar result could be expected if an integral number of wavelengths matched the building width exactly. When the building width corresponds to $(n - \frac{1}{2})$ wavelengths, where n is an integer, swaying of the building might be expected to result, which might be amplified by the natural sway frequency of the building.

In practice, of course, a combination of effects would occur, and many modes of vibration would be available for excitation, including those involving distortion of the building shell.

The important point which can be derived from this simple argument, however, is that if a building mode is to be excited, then the correct frequency must be present in the ground vibrations, but also the wavelength in the ground must be properly matched to the building dimensions. For example, if a building were inclined to sway at a particular frequency, there would be no excitation by the ground vibrations containing that frequency if the wavelength were such that only a translational input was provided.

If it were assumed that the spectrum of ground vibration due to trains on a given track was reasonably constant, it seems reasonable to suggest that for a wayside building to respond, it would have to have the appropriate modal frequency(ies) available, be of the right size (and orientation), and the local propagation velocity in the ground would have to be correct.

One of the features of ground-borne vibration is the erratic way in which it affects some buildings and not others. Perhaps the degree of matching required before the building responds could account for this.

Measurements which we have carried out to date on a limited scale show that the foundations of a building vibrate in a manner very close to that of the adjacent ground, when excited by a passing train, except at certain frequencies. This is true both for horizontal and vertical vibrations (see Figure 1). It seems, however, that in the case of vertical vibration

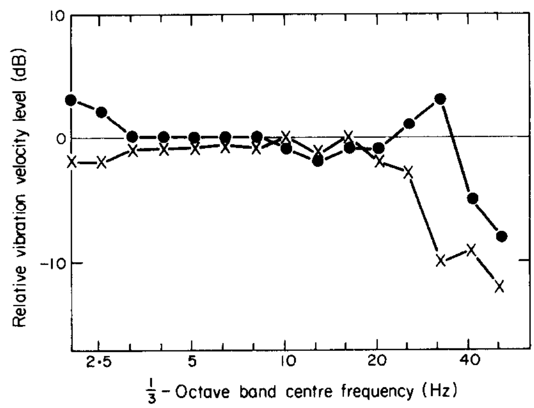

Figure 1. Building vibration level near foundations relative to vibration level of adjacent ground. —●—, Vertical vibration; — × —, transverse vibration perpendicular to wall.

the building shows a "resonance" in the 31·5 Hz 1/3 octave band, whereas at this frequency the building is notably decoupled from horizontal ground vibrations perpendicular to the wall. At higher frequencies progressive decoupling seems to occur for both horizontal and vertical inputs.

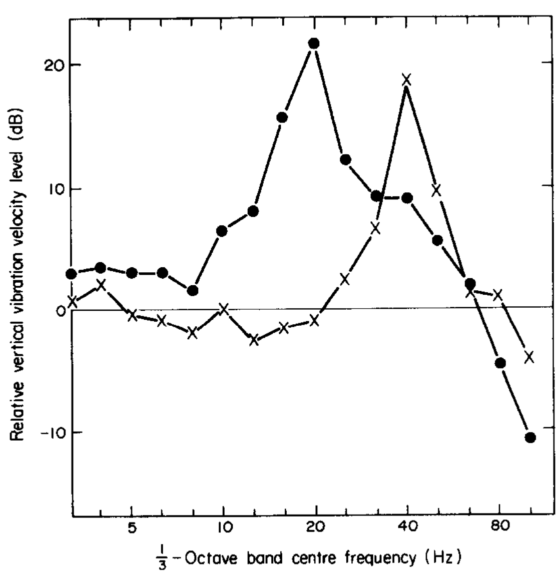

Figure 2. Building vibration levels relative to the ground. —●—, First floor; — × —, ground floor.

The same series of measurements has revealed noticeable dynamic amplifications, up to 20 dB at some frequencies in different parts of the building (see Figure 2). These are consistent with information from other sources.

One further point concerning building response is worth mentioning. If the train were to travel faster than the propagation velocity of the ground vibration, the effect would be to form a shock wave in the ground similar to the bow wave of a moving ship. It seems likely that the effect on nearby buildings would be serious. The lowest Rayleigh wave velocity quoted by Hannelius for his work on clay soil in Sweden at 35 m/s (126 km/h) is much slower than many trains in other parts of the world! Even when train speeds only approach the vibration propagation velocity, the effect will begin to be apparent.

5. PERCEPTION OF VIBRATION

There are many references to work on the perception of vibration by human beings, and references [4–6] are a sample of these. The International Standards Organisation has also established a norm in this field [7].

We do not want to discuss these criteria further except to point out that these thresholds are derived essentially for continuous exposure and determined under laboratory conditions. We would like to question whether these criteria are suitable for judging the response of people in professional or domestic surroundings to the transient event which a train pass-by represents.

6. EXPERIMENTAL OBSERVATIONS

In an attempt to throw some light on the source of ground vibration it is of interest to analyze some measurements which we have carried out on the walls of a single storey building situated about 42 m from a heavily trafficked railway line. Measurements were made of both vertical and horizontal vibration acceleration on a wall parallel to the railway line, and these signals were integrated to yield vibration velocity.

Among the traffic which passed the building were trains of 100 t tank wagons and trains of 100 t bulk carriers of granular materials, both types being bogie vehicles with 4 axles (25 t per axle). The speeds of these trains ranged up to almost 100 km/h. Although the vibrations produced in the building were readily measurable, they were not perceptible.

One of the factors which is clearly of interest is the effect of train speed on the level of measured vibration. Figure 3 shows the way in which vibration velocity level (linear over

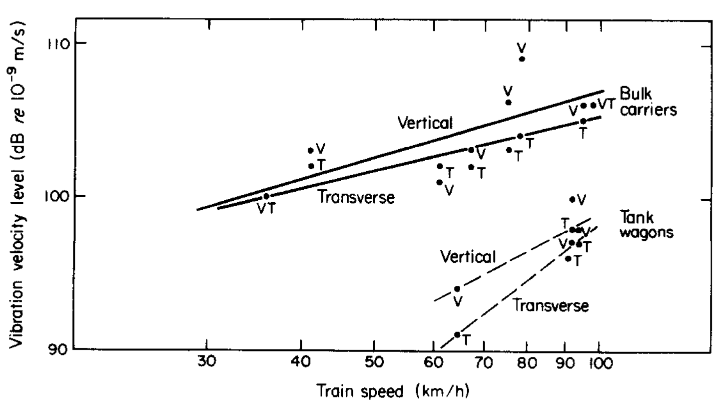

Figure 3. Vibration of building wall 42 m from track at different train speeds (linear level, 2–1000 Hz).

the range 2 Hz to 1000 Hz) varies with train speed for the two types of train mentioned above. As might be expected†, the levels increase with increasing speed, the effects being stronger for the bulk carrier. The records made at this site have also been subject to both narrow band and 1/3 octave analysis, and Figure 4 presents typical spectra for the same

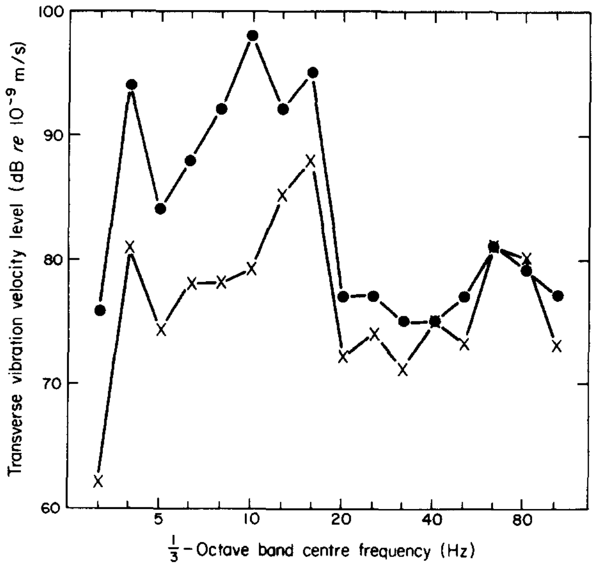

Figure 4. Transverse vibration velocity level spectrum of building wall 42 m from track. —●—, Bulk carrier wagons, 96 km/h; — × —, oil tank wagons, 94 km/h.

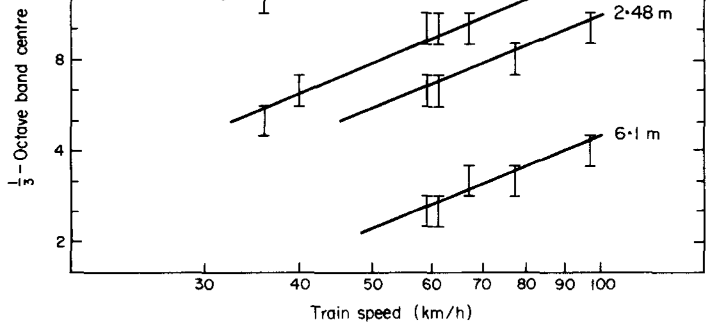

Figure 5. Position of peaks in train vibration spectra *vs.* speed of train. (Measurements on building 42 m from track.)

† More recent measurements have shown that this may not always be so.

two types of vehicle. The spectra are somewhat similar, although the bulk carrier generally shows a higher level, significantly so over the range of 1/3 octave bands up to 20 Hz.

Careful analysis of these spectra for traffic at various speeds showed a variation of spectral character with speed, with significant shifting of peaks in the spectrum. In order to investigate this effect further, the frequencies of the peaks in the spectra were plotted against train speed, and an example of this plot (a "Campbell diagram") for the 100 t bulk carrier is shown in Figure 5. The "points" (or ranges representing 1/3 octave bands) can be connected by a series of parallel straight lines, and a characteristic wavelength can be assigned to each of the lines. Some of these wavelengths turn out to have a clear relevance to railway construction. For example, the upper line, representing 0·7 m wavelength corresponds to the spacing of the sleepers. 1·78 m is characteristic of a recognised long wavelength corrugation which is supposed to have its origin in the roller pitch of the straightening machines used by the rail manufacturers. Since the rails are 18·3 m long (3 × 6·1) and the vehicles are 12·49 m long (almost 2 × 6·1), the coincidence of these lengths probably accounts for those peaks corresponding to the 6·1 m wavelength, since a pair of bogies will pass a rail weld every time the train moves forward half a vehicle length.

We can find no engineering significance in the 2·48 m wavelengths, although it happens to be 1/5 of the vehicle length. It does, however, correspond to the difference frequency between the 1·78 m and 6·1 m wavelengths.

Although the results from this analysis are interesting, a word of caution is necessary so that the problems in its use are underlined. Whilst 1/3 octave bands are plotted on the diagram, the actual frequencies through which the lines pass were determined by narrow band analysis. The peaks varied erratically in magnitude from one train speed to the next, depending presumably on the effect of particular resonances in the vibration path. It must be remembered that this assessment was made on the walls of a building 42 m from the railway. It is surprising and notable that no fixed frequencies (characteristic of the vehicles' suspension) occur; those would of course yield horizontal lines in the diagram.

It is perhaps worth adding some comment on the factors which might be responsible for the differences between the two types of 100 t vehicle for which the curves of Figure 4

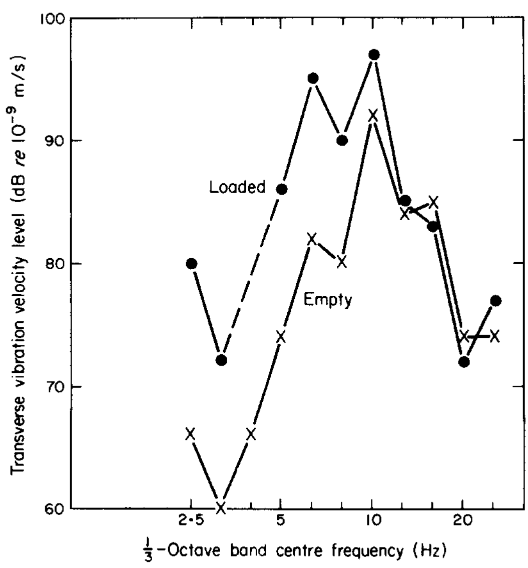

Figure 6. Response of building wall to loaded and empty bulk carrier trains—60 km/hr.

were drawn. The oil tank wagons are fitted with bogies having a secondary suspension, but no primary suspension, whereas the bulk carriers have primary suspensions but no secondary. On this basis it might be supposed that the oil tank wagon would generate a higher ground vibration than the bulk carrier by virtue of the higher unsprung mass. In fact the reverse is the case, and two factors may lead to this result. Firstly, the bulk carrier is shorter than the oil tank wagon by 5·5 m (12·49 m to 18 m), so that the basic stress in the ground is higher by virtue of the higher linear density of the train. Secondly, we believe that the friction dampers on the bulk carrier may have too harsh an action in some circumstances, so that the effective unsprung mass is increased; experiments are planned to investigate this possibility further.

Figure 6 demonstrates the difference in building response between loaded and unloaded bulk carriers passing. The difference occurs mostly at low frequencies, where it is of the order of 12 dB. The ratio of the vehicle weights in these two cases is of a similar order, i.e., $20 \log \{M(\text{loaded})/M\ (\text{empty})\} = 20 \log \{100/24{\cdot}4\} = 12{\cdot}25$ dB, which suggests that the total vehicle mass rather than the unsprung mass is the important factor.

7. CONCLUSION

In this paper mechanisms have been discussed which can be involved in the generation and propagation of ground-borne vibration, and factors which might influence the response of buildings subject to this vibration. Preliminary experimental results have been presented which seem to confirm some of the ideas discussed. The authors take the view that the propagation velocity of the ground disturbances may be an important parameter and should be determined in any experiments of this type carried out.

ACKNOWLEDGMENTS

We would like to thank the British Railways Board for allowing us to publish this paper, and to thank also our colleagues on British Railways, both inside and outside the Research and Development Division, who have helped in this work.

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