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Issues and Limitations on Measuring Building's Transfer Function

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ABSTRACT

In the planning stages for new buildings or transit systems, the effects of railway induced ground-borne vibration need to be considered. The propagation of vibration from the ground to a receiving room is a complex problem. It is common practise, within vibration assessment, for the buildings vibration response to be acquired empirically by either measuring the response of the building in question via an impact method, measuring the response on an equivalent type of building, or using pre existing published data (from the 70s and 80s) to derive a ground to building transfer functions. This paper compares, as a method of evaluating a building transfer function, impact method with actual rail pass-bys and recently collected response with published generalised response curves. The results presented suggests that, when using the impact method excitation process (point source), the distance of impact location to the building foundation is critical, drastically affecting the resulting transfer function. In addition when using train pass-bys as the excitation process, train length is shown to have an influence on the transfer function assessed. The pre-published data are also shown to have limitations for more recent types of construction.

Keywords: Rail, Vibration, Building, Transfer-Function

1 INTRODUCTION

Railway induced ground-borne vibration, is the most common and widespread source of perceptible environmental vibration. Whenever vibration levels exceed certain thresholds they may interfere with specific human activity as well as impact on vibration-sensitive devices (e.g. optical microscopes, hard drives). Vibration propagating through a building's structure can also cause 'structure-borne noise' (also referred as structural or radiated noise), this often occurs when imperceptible levels of ground-borne vibration set the building surfaces (e.g. walls, floors and other structural surfaces) into motion, which in turn cause an audible rumble sound in the frequency range 25 to 250 Hz, and secondary effects from rattling fixtures and fittings. This in addition may affect human activity and give rise to general annoyance and sleep disturbance.

When proposing new railways, alterations to existing routes, operational changes next to built up areas, or new buildings adjacent to the track it is good practice (and in some cases mandatory) to undertake an Environmental Impact Assessment targeted at estimating the degree of vibration (or ground-born noise) to which occupants (or sensitive equipment) may be subjected. In order to assist this process the procedure is typically broken down into three sub-systems: source (train's structure and the track-form); path (vibration propagating through the ground); and receiver (building structure and/or its elements).

The degree to which railway induced ground-borne vibration impacts on sensitive receptors is highly dependent on the characteristics of the impinging vibration, building foundations, and

their structure and form (i.e. a function of the specific design and the materials used). Due to the complexity of the problem, existing methods for determining building response to train induced vibration are largely empirical in nature, mainly expressed in the form of transfer functions (TF), describing the change in level that vibration undergoes at the intersection of two components (e.g. ground to foundation coupling). It is common practise for these TF to be evaluated by measuring directly on the building being assessed; or, in the case where the assessment is being performed at the scoping stage before construction, either by measuring on a similar building or by using case history information available (e.g. pre existing published data). However, there is very little pre-published case data available; with relevant guidance predicated on measurements taken in North American in the 70s and 80s.

Commonly, when measuring building response for the case where a new railway line is proposed, empirical assessments are carried out using an impact force as the excitation mechanism. As presented by Bovey (1983), impacting the ground with a load of a few kg yields enough energy to create a pulse like function (which approximates the Dirac delta function) that radiates spherically outward into the far field; this is a point source excitation method and commonly referred as impact-test. Nevertheless, depending on the distance between the track and the receptor, a train as an excitation mechanism can be best represented as a line source as proposed in FTA (2006). This paper will look into the consequences of using a point source excitation process when emulating a train induced TF by directly comparing the impact force method (using a sledgehammer) to a train pass-by induced transfer function. It will compare and verify some of the results obtained herein with previous published studies. The paper initially presents a review on relevant guidance for building vibration response then presents field data that shows the affect of trains against impact vibration assessment. It then presents data that shows the excitation within a building.

2 BUILDING RESPONSE TO VIBRATION

As vibration passes from open ground, (free field) into a building (effectively from one medium to another) a change in vibration magnitude (and/or phase) will occur as the incoming signal becomes modified by either the boundary (foundation surface) or the different characteristics of the new medium (e.g. density) causing a rise or decay in vibration levels as a function of frequency. ANC (2001) states that, in general, vibration levels appear to reduce by up to 60% from free-field to foundation. However, due to significant variation in ground condition, foundation type, building construction and design ANC (2001) recognises that an overall value quantifying the expected change in level becomes unreasonable to suggest. Nevertheless, predicating on the fact that the buildings are considered less stiff in the horizontal direction, ANC (2001) puts forward a descriptive representative response, stating that a greater reduction in vibration between the ground and building is expected for vertical oscillation as opposed to horizontal oscillation and also refers to the likely amplification of vibration from edge to the centre of a room floor (due to relative stiffness). Further to this, it has been suggested (Dawn and Stanworth 1979) that swaying of buildings may occur if the width of the building corresponds to $n-1/2$ vibration wavelength; and, if the swaying coincides with the natural frequency of the building, amplification may occur. The natural frequency for the average dwelling is below 10 Hz (ISO 4866:2010), which is in the same resonate frequency range as what are described as loose soils and within the range of train induced vibration, thus resonance effects are expected.

Due to this complexity, some guidance (e.g. FTA (2006) and Nelson (1987)) describe structural response empirically, adopting measured data taken from published reports and

expresses the expected vibration level change against 1/3 octave-band frequencies for different types of building. Based on work by Wilson (1971) and Saurenman et al. (1982) both Nelson (1987) and FTA (2006) proposes a generalised set of identical empirical curves for foundation response based on a building's foundation type, structure and size. These curves suggest that for typical residential buildings, on spread footings up to 4 stories high, vibration levels can be attenuated by as much as 12 dB around the 63 Hz 1/3 octave-band. The curves also show that the degree of vibration attenuation follows the general rule quoted in FTA (2006) "the heavier the building construction the greater the coupling loss". It is also accepted that for building slabs in contact with the ground (slab-on-grade foundation) the floor will be subjected to similar vibrations as the ground, and the coupling loss is 0 dB for frequencies lower than the resonant frequency of the slab (Nelson 1987). Moreover, according to Kurzweil (1979) the coupling loss for lightweight buildings or for a building supported directly on rock is also 0 dB.

Once the vibration has reached the foundation it will propagate through the building's main structure (e.g. load-bearing external walls, structural columns, floor slabs etc...), typically losing a small portion of its energy. For the expected attenuation values per floor (as vibration is transmitted from floor to floor) FTA (2006) suggest an amplitude decrease of 1 to 2 dB per floor (i.e. 2 dB for the first 5 floors and 1 dB for the next 5 floors). Similarly, based on the work reference Nelson & Saurenman (1983), Nelson (1987) gives attenuation values ranging from 2 to 5 dB over the frequency range 16 to 250 Hz (3 dB is quoted when using a single figure for the attenuation from floor to floor). Equally, similar figures of 3 dB attenuation are reported by Ishii and Tachibana (1978) at lower floors and 1dB attenuation at upper floors. Ungar and Bender (1975) also give a reduction of 3 dB between each floor (at lower frequencies). However, Dawn and Stanworth (1979) showed that there can be large variation in the vibration levels as well as in the frequency content between two floors within a building.

The vibration travelling through the main structure will then propagate, either directly or through the supporting beams, into the building internal elements such as lightweight construction studwork walls (e.g. plywood, gypsum-board), where different parts of the building will damp or magnify the vibration. A building internal construction such as the walls, floor and ceiling, have the potential of amplifying vibration if the resonance of the structure coincides with the frequency of the induced vibration at the point of entrance to the structure. The difficulty in anticipating the response of the internal construction is due to the fact that typically these structures vary significantly in stiffness, mass and damping which significantly impacts on both magnitude and frequency of the structure's response. According to Nelson (1987), the amplification at a room floor is in the region of 5 to 15 dB for the frequency range 16 to 80 Hz. It is common for the floor to amplify vibration within the 10 to 30 Hz frequency range because the floor resonance frequency coincides with the peaks of the vibrations induced by trains. For a general vibration assessment, FTA (2006) recommends a 6 dB adjustment at its fundamental resonance frequencies.

From the above it can be seen that relevant guidance documents such as ANC (2001), Nelson (1987) and FTA (2006) predicate on limited published data, mainly from Nelson & Saurenman (1983) and Ishii and Tachibana (1978) which largely reflects the older North American construction types which may not be applicable elsewhere. Moreover, construction methods have recently changed significantly, especially the internal structures where lightweight construction is increasingly being adopting (e.g. gypsum board walls and ceilings). Thus, further updated data reflecting regional construction trends is now required

for effective vibration assessment. In addition there appears some discrepancy between suggested levels attenuation between floors from different authors.

3 TRANSFER FUNCTION ACQUISITION METHODOLOGY

The first part of the investigation (Section 3) addresses the degree of compatibility between the two main excitation processes commonly used when measuring a ground-to-building TF. This is done by directly comparing the impact-test induced TF, using a sledgehammer (where the signal emitted is characterised as point source of a transient nature), to rail pass-by induced TF, using different types of trains (where the signal emitted is conventionally characterised as a line source of a non-stationary nature).

TFs, herein, reflecting the change in magnitude (phase is not considered) were computed as such:

$$|H(f)| = 20 \log \left(\frac{G_{BB}(f)}{G_{AA}(f)} \right) \quad \text{Equation 3.1}$$

Where G_{BB} , representing the system's output, is the power-spectrum measured at the structure being evaluated (e.g. bedroom floor) and G_{AA} , representing the system's input, is the power-spectrum measured at the ground in front of the building facing the rail track (assumed to be the signal entering the building or the element being evaluated). The resulting $|H(f)|$ is then recombined into 1/3 octave-bands.

The effective frequency range of each TF is a function of signal-to-noise ratio of both measured G_{AA} and G_{BB} signals. Thus, the effective frequency range is dependent of the distance from transducers to excitation system, soil characteristics and, most significantly, the excitation process induced vibration characteristics (e.g. the spectral frequency range).

All TF presented throughout Section 3 were evaluated based on simultaneous measurements in the vertical orthogonal direction (i.e. z-axis) which is the dominant direction at the ground when considering rail induced vibration at a distance. For the ground-to-building, TF transducers were located, according to (ISO 4866:2010), at a lower point on the main load-bearing external wall close to the ground (representing the foundation's response) facing the rail track, and approximately 2 metres from the foundation (representing the free field response). Since all the buildings used in this test were approximately 10 metres long only one measuring position along the load-bearing external wall and the ground was used.

This paper reports on six cases (scenarios) which can be broken down into two groups according to the type of building and rail structure (surface or underground) being assessed. The first group consists of detached (or semi-detached) residential buildings adjacent to a surface rail track. The dwellings can be characterised as 2 story brick buildings on strip footings with a ground bearing floor slab having the dimensions of approximately 10 by 7 metres. The second group comprises 3 story brick terraced buildings, supported also on strip footings with a ground bearing floor slab (no basement) close to an underground track. On Section 3 (comparing TF excitation methods) only the first group was considered.

3.1 COMPARING TF EXCITATION METHODOGY

The representative train pass-by induced TF (referred in the following figures as "Train induced") is the resulting average of seven individual rail pass-by induced TFs. The error bar

(represented by the black i-beam) illustrate and compares the spread of data at each 1/3 octave band. All representative impact (sledgehammer) induced TF result from the average of 10 impacts (increasing the signal-to-noise ratio by approximately 12 dB), all shown to have very small degree of data spread.

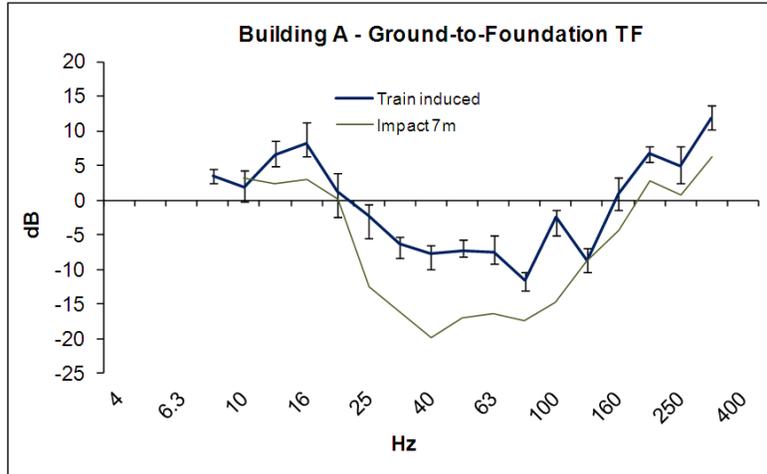


Figure 3.1: Case A, comparison of excitation process using ground to foundation TF

Case ‘A’ (Figure 3.1) consists of a recently built dwelling, 25 metres from a railway on embankment. Only class 158 ‘Express Sprinter’ (two vehicles train) induced vibration were used as the excitation mechanism when inferring the TF represented by the blue line in Figure 3.1.

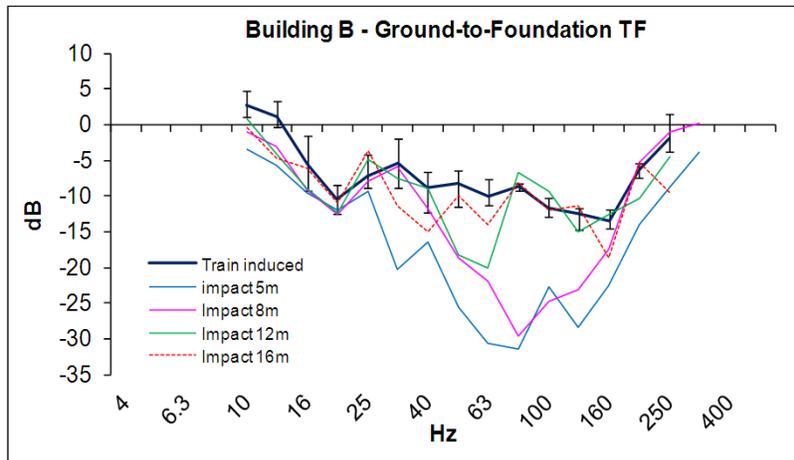


Figure 3.2: Case B, comparison of excitation process using ground to foundation TF

Case ‘B’ (Figure 3.2) consists of a dwelling, 60 metres from the rail track. Pass-by induced vibration generated by class 43 HST (10 car), 91 (10 car), 222 ‘Meridian’ (5 car), 142 ‘Pacer’ (2 car) and 185 ‘Pennine’ (3 car) trains were used to represent ‘Train induced’ TF in Figure 3.2.

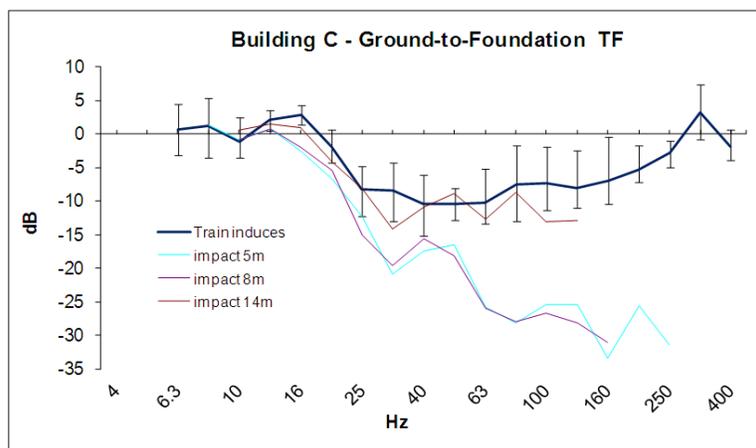


Figure 3.3: Case C, comparison of excitation process using ground to Foundation TF

Case ‘C’ (Figure 3.3) consists of a dwelling located 25 meters away from the rail track. Pass-by induced vibration generated by classes 43 HST, 222 ‘Meridian’, 170 ‘Turbostar’ (3 cars) and 158 ‘Express Sprinter’ (2 car) trains were used to represent ‘Train induced’ TF in Figure 3.3.

For Case ‘A’ the difference observed (in Figure 3.1) between the impact-test (green line) and the train induced TF (blue line) suggest that the impact-test induced TF misrepresents the train induced TF by as much as 10 dB within the 25 to 125 Hz frequency range. For this site (Case ‘A’), due to accessibility restrictions, 7m was the maximum distance for which impact-tests could be undertaken. Figure 3.2 and 3.3 (case ‘B’ and ‘C’ respectively) suggests that the impact induced TF approximates the train pass-by induced TF as distance increases (excitation to measuring point).

The discrepancies observed between the impact-test and train pass-by TF can be attributed to the types of wave-front that each of the two excitation methods produce. The train (seen as a line source) yields a cylindrical surface wave where its wave-front, which approximates a plane wave, strikes the building foundation being measured homogeneously (as illustrated in Figure 3.4 left), with approximately the same magnitude throughout. The impact-test (seen as point source) yields radial cylindrical surface wave, where its arch shape wave-front impinges on the building’s foundation being measured unevenly; thus less contribution at the measuring point (assuming the transducer is located midway as seen in Figure 3.4 right) from vibration entering the extremes of the foundation.

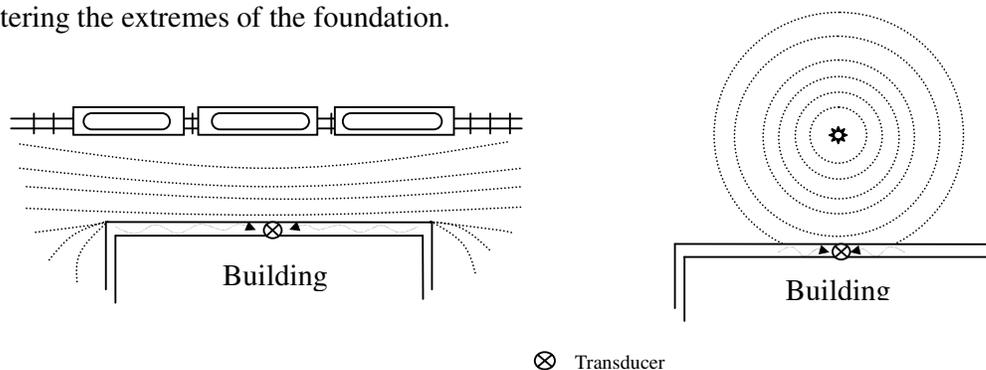


Figure 3.4: wave-front striking the building’s foundation; left pass-by induced, right impacting the soil

Based on the fact that any point source resulting wave-front approaches a plain wave-front as distance increases, a critical distance (as a function of the building footprint) should be considered when emulating the building's response to rail induced vibration through the impact method. However, in high density urban areas the critical distance may be impractical due to obstruction and/or access; furthermore the resulting energy from an impact-teat also needs to be reconsidered when attempting to excite the building's structure from a distance as sufficient impact energy may not reach the building.

When examining the spread of data presented in the figures above the error bars in Figure 3.1 (Case 'A') shows some consistency between all TFs that makeup the representative "Train induced" TF. However, according to the error bars in Figure 3.2 some frequency bands show more consistency than others. When comparing Figure 3.1 to Figure 3.3, the error bars suggest more consistency between all TFs that makeup the averaged TF in Figure 3.1 where only one class of trains was used than it does for Figure 3.3. This suggests that different class of trains, as an excitation mechanism, yield different TFs. The following section considers this further.

3.2 TRAIN SIZE IMPACT ON THE RESOULTING TF

When isolating each individual TF that make up the average for case 'C' (Figure 3.3), it was found that the length of the train was the most significant characteristic contributing to the deviation from the mean presented in Figure 3.3.

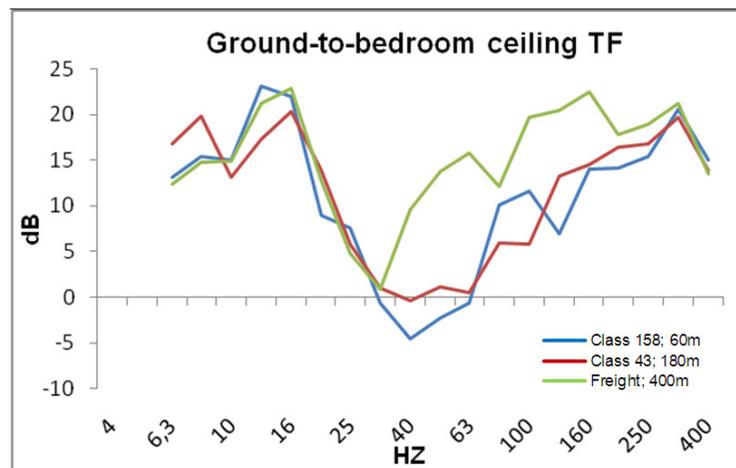


Figure 3.5: Ground to bedroom ceiling TF as a function of train length measured at site C.

Figure 3.5 shows three ground-to-bedroom ceiling TF, each induced by a different size train. Although each train induces a different TF there is a large discrepancy between the TF derived using a 400 m long train in comparison to the other two shorter trains.

For this study, the response of a bedroom's ceiling to the incoming rail induced vibration (measured on the ground) was chosen since it strengthens the discrepancy as a function of train length, as seen in Figure 3.5. Nevertheless, at the foundation the deviation between TF, as a function of train length, was also observed, however, not to such significant levels.

As a way of investigating the inconsistency observed in Figure 3.5, the degree of linear relationship between the input and the output was analysed through the coherency function, γ_{xy}^2 , defined by the equation:

$$\gamma_{xy}^2 = \frac{|G_{xy}(f)|^2}{G_x(f) G_y(f)} \quad \text{Equation 3.2}$$

Effectively the analysis will expose the degree to which the signal measured at the bedroom ceiling (system's output) is a function of the signal measured at the ground (system's input). This function ranges from 1 to 0 where 1 represents total coherency (or correlation) between the input and output signal, and 0 no correlation.

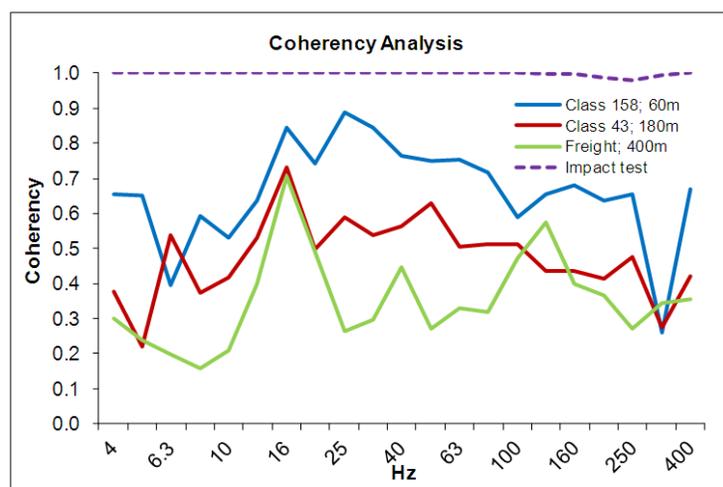


Figure 3.6: coherency analysis expressing the correlation between the measured data at the ground and bedroom ceiling for each excitation signals.

For train pass-bys, Figure 3.6 suggests that not all dynamic activity measured at the receiver's location (i.e. bedroom ceiling) is a result of the dynamic activity measured at the ground. This phenomenon especially applies for long pass-bys (see Figure 3.6 Freight; 400m), where a large portion of its resulting vibration simultaneously enters the building through a number of alternative routes without necessarily all passing through the ground's measuring position. As for the case of a sledgehammer impact (Figure 3.6 Impact test) close to the transducer (5m) the resulting vibration which excites the ceiling is captured in its entirety at both measuring points.

Effectively this suggests that for standard train induced vibration TF evaluation based on simultaneous measurements at two points, (where one point represents energy at the input and the other at the output) is open to inconsistencies. However, for practical reasons this study suggests that when considering train length up to approximately 180m the method can be used without compromising the TF to an unreasonable degree as shown in Figure 3.5 by the good agreement of TFs from shorter trains.

4 BUILDING ELEMENT RESPONSE TO RAIL INDUCED VIBRATION

This section presents and compares 'ground'-to-'building element' TF measured on different buildings with similar characteristics. The internal structure response of lightweight

construction (such as wooden suspended floors) is effectively what determines the degree of impact that a sensitive receptor is subjected to.

The TFs presented herein were determined by simultaneous measurement as before. Apart from the wall response, all other measurements reflect the structure's vertical response. The free field to wall TF reflect the wall's horizontal response to the free field rail induced vertical response. Furthermore, due to the deviation observed between different types of excitation system the TF presented in this section were derived using passenger trains (60 to 180 meters long).

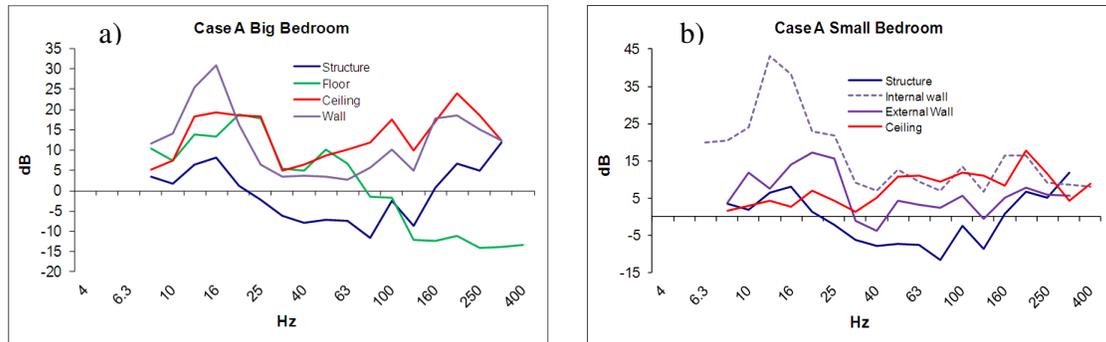


Figure 4.1: Structural response of the building (blue line) that houses two bedrooms. a) structural elements response of the big bedroom; b) structural elements response of the small bedroom.

Figure 4.1 presents the foundation response along with main lightweight construction structure response of a semi-detached house adjacent to a surface rail track. Figure 4.1a corresponds to a big bedroom of approximately 4 by 5 metres, located on the first floor of the dwelling; Figure 4.1b corresponds to a small bedroom of approximately 2.5 by 3.5 metres, also located on the first floor of the same dwelling. The wall and ceiling of both rooms used a gypsum board type of construction. Although both partitions represented in Figure 4.1b (internal and external walls) have the same dimensions (approximately 3.5 by 2.5) the internal partition includes a door. Furthermore, the channels supporting the external wall (dash line in the figure) are fixed to the main load-bearing brick wall. These two features might explain the wall's response discrepancy observed.

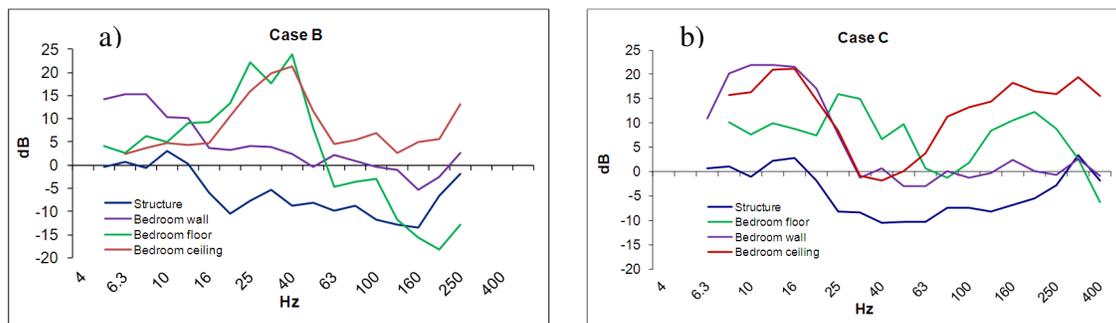


Figure 4.2: Structural response of two similar buildings (blue line) along with their bedroom structural elements response.

Figure 4.2 exhibits the building foundation response along with the bedrooms (approximately 3 by 4 metres) partition response located in the first floor of two similar detached dwelling (next to a surface track). For both cases the ceiling (red line) is constructed out of plasterboard, supported by wooden joists, the masonry wall (purple line) is approximately

10 cm thick and the wooden floors (green line) are supported on wooden joists. Case ‘C’ the ceiling revealed to be very responsive going down to 8 Hz. However, it ceases to respond to the incoming vibration within the 31.5 to 63 Hz region; this can be due to the combination of the structures modal behaviour, along with the transducer placement (being placed at an anti-node).

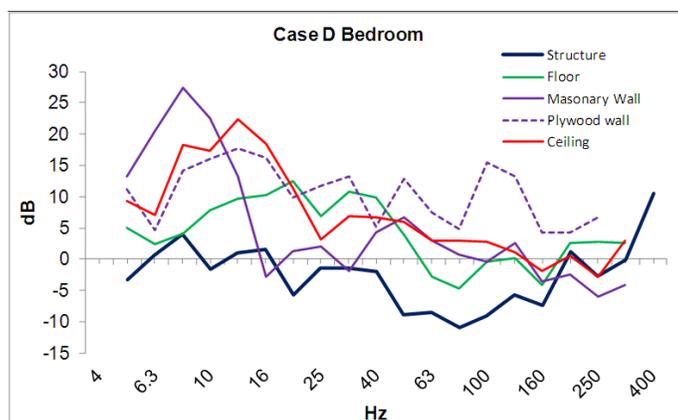


Figure 4.3: Structural response of a terraced building (blue line) along with its bedroom structural elements response.

Figure 4.3 exhibits the building foundations response along with the bedroom main partition response located in the first floor of a terraced dwelling (next to underground track). As before, the Figure show that the incoming vibration reduces at the foundation (structure) and amplifies at all other internal structures. Here the wooden ceiling response is similar to the wooden wall, and in contrast to Figure 4.2 the floor does not respond sharply at a distinctive frequency.

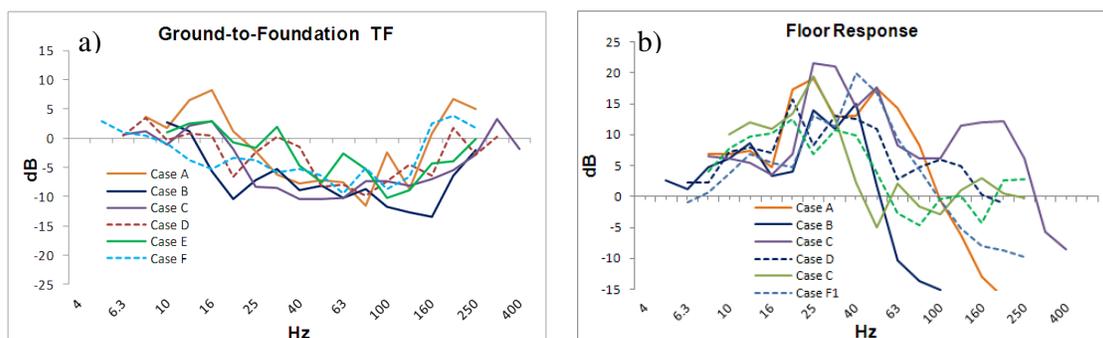


Figure 4.4: Response comparison, where the dash lines represent terraced dwellings and the solid line represents detached dwellings. a) comparing foundation response; b) comparing bedroom floor response;

Figure 4.4a presents a direct comparison of free field-to-foundation TF, here a general trend can be observed even when including both terraced and detached houses. All TF presented in Figure 4.4b correspond to wooden floor of similar size of bedrooms (approximately from 3 by 4 metres to 4 by 5 meters (case A) measured slightly off centre). Although Figure 4.4b shows some spread of data there is a spectral trend which can be used to infer a generalised empirical curve reflecting the potential vibration that the bedroom floor can be subjected too. As can be seen in Figure 4.1 through to 4.4, the wall’s response varies significantly independently of the construction type, not only in magnitude but also on its resonant frequency, suggesting a

significant degree of unreliability when attempting to map its response to any proposed generalised curve.

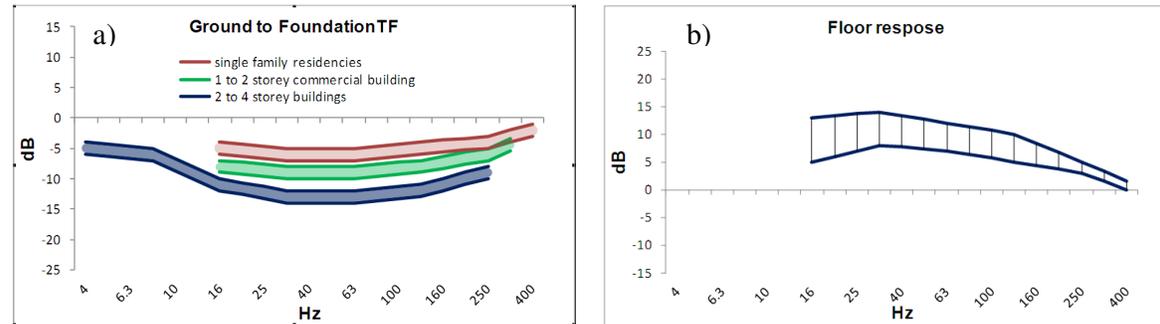


Figure 4.5: Generalised empirical curves; a) taken from Nelson (1987) and proposed in ATF (2006) model building foundation vibration level relative to ground surface vibration level; b) range of amplification of vibration due to floor resonance taken from Nelson (1987).

It can be seen that the measured data representing the ground-to-foundation TF of analysed UK dwellings (Figure 4.4a) follows the same spectral trend as the generalised empirical curves (Figure 4.5a) proposed in both Nelson (1987) and ATF (2006). However, attending to the data spread observed in Figure 4.5a, these typical UK dwellings fail to fit a single class of buildings within the Nelson (1987) classifications. Nevertheless their representation could be referred to the model presented in ATF (2006) by combining both the ‘single family residences’ and ‘1 to 2 storey commercial building’ classes of buildings into one class; or, if adopting a conservative approach, then the upper limit of the ‘single family residence’ (Figure 4.5a) can be used.

Although ATF (2006) claims that floor amplification varies greatly depending on construction it suggests for its model a 6 dB increase which, according to this study, seems to misrepresent the measured UK family dwellings by significant amount as seen in Figure 4.4b which shows a response ranging from approximately 10 to 20 dB in the 16 to 64 Hz frequency range. Moreover, Nelson’s (1987) floor resonance proposed curve (Figure 4.5b), suggesting an amplification ranging from approximately 5 to 15 dB in the 16 to 64 Hz frequency range, also misrepresents (approximately by 5 dB) the floor response of the measured UK family dwellings.

5 CONCLUSIONS

This study analyses the process of evaluating building transfer functions comparing the impact-test (point source) induced to rail induced (line source) TFs from train pass-bys. It was found that the impact-test induced TF can deviate by as much as 20 dB at a 1/3 octave-band in relation to the actual rail induced TFs. However this deviation relieved to be a function of distance between the impact point and the building. As a way of emulating the rail induced transfer function the study suggests that distance between the building and the point of impact needs to be considered in accordance to the building’s footprint so as to generate a plane wave-front at the building’s foundation. However energy of impact can then become an issue. The study also demonstrates the affect that different length of trains have when used as an excitation process when evaluating TFs; concluding that very long pass-bys (i.e. freight trains) yield an atypical TF in comparison with shorter trains (i.e. passenger trains). This

study suggests that the generalised empirical curves given in Nelson (1987), which mainly reflect US buildings, should be adjusted in order to reflect the UK family dwellings. As for ATF (2006) proposed model, this study recommends caution when applying their suggested values for the floor response.

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