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Measurement of ground-to-building frequency response functions for assessment of human exposure to vibration from railway vibration

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Abstract

The University of Salford has derived exposure-response relationships for vibration caused by railway construction and operation in residential environments. The exposure assessment methodology for almost 1000 case studies has its key factor in the measurement of synchronized ground-to-building frequency response functions (FRF). The latter is obtained by averaging the spectral content of simultaneous events recorded by two sensors, one outside and one inside the residence of the participant of the survey. In this paper magnitude only methods such as H and cross spectrum methods like H1 and H2 have been considered with the aim of assessing the most suitable way to calculate the FRF for determining the human exposure. However, an assessment of the linearity of the ground-to-building transmissibility measurement is necessary; therefore a coherence average based FRF has been introduced in order to compare the methods listed above. Furthermore, results are illustrated with measured vibration data from railway operation.

1 Introduction

In the exposure assessment methodologies introduced in the framework of the project “Human response to vibration in residential environments” [1], the transmissibility is a key tool that has been used for characterizing the propagation of vibration from outside to inside the property in order to estimate the internal long term exposure. The overall aim of this project was to investigate the relationship between annoyance and exposure to vibration in residential environments. 931 questionnaires were conducted with residents to determine annoyance due to vibration from railway activities posing the significant challenge of determining 24-hour vibration exposure for as many of these case studies as possible.

The use of ground to building transfer functions, or transmissibility, is encouraged in the U.K; for example BS 6472-1:2008 [2], the British Standard for predicting internal building vibration for assessing human exposure to vibration in buildings. However, clear guidelines for its application are not provided. Generally in literature, the use of the transmissibility is “hidden” in measurement methodologies and models for assessing vibration induced in buildings [3] [4] [5] [6] but a few papers [7] [8] treat the problem of the transmission of railway vibration into buildings explicitly.

On the other hand, the problem of the transfer function is mainly approached in the dual channel analysis where different formulations have been introduced [9][10].

In this paper the problem of the ground to building transmissibility is considered with the following aim: to assess which kind of transmissibility formulation is the most useful for the assessment of human exposure from railway vibrations.

2 Exposure Assessment Methodology

To reliably assess annoyance caused by vibration exposure in residential environments, a large sample of participants is needed. In the framework of the study "Human response to vibration in residential environments" the sample of the population annoyed by railway vibration was quantified in 1281 residents of which 931 were subject to railway operation.

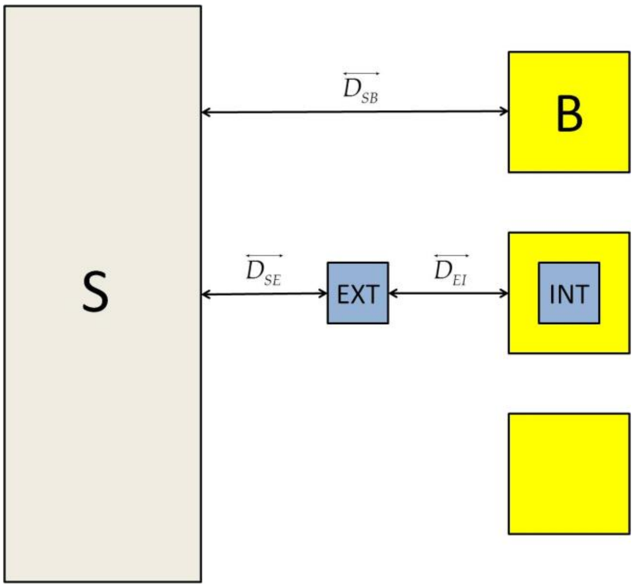

Figure 1: Scheme illustrating the ground to building transmissibility measurement

Considering the large number of case studies, it was impossible to obtain a direct long term internal exposure estimation for each participant as requested by the standard and a new strategy for obtaining the internal exposure was necessary [11] meeting "half way" the needs of both project and standard.

According to BS 6472-1 [2] and ANC guidelines [12], a measurement point other than the point of entry[1] can be used for the long term estimation and a transfer function needs to be declared between this point and the point of entry inside the building.

As a consequence, for each measurement site the exposure assessment methodology relies on two measurements: 24 hour long term monitoring measurement (control position or *EXT* position in Figure 1) in proximity to the residents' properties and synchronized short term monitoring measurement (*INT* position in Figure 1) within the property as close to the point of entry as possible. For the events simultaneously recorded at both measurement positions a ground to building frequency response function can be defined. The latter is used as a filter for propagating the entire vibration time history from the long term monitoring position inside the residence. In this way the entire full time history of the internal activity is provided and the exposure can be calculated using different metrics (See Table 1).

3 Overview of the transmissibility measurements

A key component of the assessment strategy for the long term internal exposure explained in section 2 has is the use of two time synchronized accelerometers, one outside the property and one inside, for measuring the ground-to-building (at the point of entry) frequency response function or transmissibility.

[1] The point of entry is defined as the contact surface between the human body and the vibrating receiver (floor).

The measurement setup is summarized in Figure 1: EXT refers to the accelerometer outside the house[2] whereas INT is the one inside and S stands for the vibration source. The following distances have been defined as well: $\overleftrightarrow{D_{SB}}$ is the distance between the source and the building, $\overleftrightarrow{D_{SE}}$ is the distance between the source and the accelerometer placed externally to the property and $\overleftrightarrow{D_{EI}}$ is the distance between the two sensors.

Although the use of the ground-to-building transfer functions is suggested by BS 6472-1 for the prediction of building vibration, especially for planning purposes, in the standard there is not any guidance about its definition. Instead, suggestions are provided in BS ISO 4866 [13] for the definition of soil-to-foundation transfer functions caused by ground-borne sources highlighting the difficulty to measure ground-to-building transfer functions correctly in residential areas like the ones surveyed by the project "Human response to vibration in residential environments".

Generally, the EXT accelerometer should not be installed too close to the excitation point such as the railway line because the ground motion will be influenced by the source mechanisms. This means that an ideal position of the transducer should be outside the near field of the source where compression and surface waves are generated. Even if it's difficult to evaluate the extent of the near field, some indications are available in the literature: Madshus et al. [14], for soft soil, quantified the effect of the near field as 15 meters from the source whereas Hannelius (in Bahrekazemi [15]) suggests 20 meters. On the other hand, the EXT transducer cannot be too close to the building as suggested by With and Bodare [8] who also advise that the transducer on the ground should not be in close proximity to large objects like cellars or boulders. The 'close proximity' of the building can be quantified as less than 2 meters from the building or 1/10 of the dominant wavelength, generated by the source, away from the building as reported in the ANC guidelines [12].

Furthermore, the amplitude of vibration may be affected by reflection at the front of the foundation (with respect to the travelling wave) and decreased at the rear side by dissipation and front side reflection [13].

All the observations mentioned above have been taken into consideration for the installation of the long term monitoring position with some constraints experienced during the field work. Primarily, the need to put the instrumentation in a secure place created some limitations in choosing a position not too close to the source or to the building. Another difficulty experienced was when the distance $\overleftrightarrow{D_{SB}}$ was too close to the source: in this way both EXT transducer and buildings were likely to be in the near field of the source.

The installation of the INT accelerometer is generally done at one point: on the mid floor of the room where a complaint originates or where the greatest adverse comment can be predicted according to BS 6472-1:2008. Of course, the accessibility to the best measurement point is related with the resident's interest in, and cooperation with the study.

4 Analysis tools

In this section, theory is provided regarding the tools used for conducting the transmissibility analysis. First of all, a hypothesis on the nature of the process involved is needed; we are going to consider our vibration signals X_n as a weakly stationary process [16], where the index n denotes the time $t = n\Delta t$ at which the observation is made and Δt is the sampling interval quantified as 200 Hz.

4.1 Coherence

The coherence function between the two signals E_n and I_n is equal to the cross spectrum $G_{EI}(f)$ divided by the square root of the product of the two auto spectra [17]:

[2] In this framework the control position is considered as an external measurement.

$$\gamma_{EI}(f) = \frac{G_{EI}(f)}{\sqrt{G_{EE}(f) G_{II}(f)}} \tag{1}$$

The coherence is a normalized cross-spectral density function and the magnitude-squared coherence (MSC) defined as

$$MSC_{EI}(f) \equiv |\gamma_{EI}(f)|^2 \tag{2}$$

lies in range $0 \le MSC_{EI}(f) \le 1$. For a single estimate the MSC would always be unity [9], therefore its calculation is based on average functions. Carter et al. [18] suggested a moving average approach with a 50 % overlap with a Hanning window function. In this framework the window dimension is 200 point in order to achieve a 1 Hz spectral resolution.

Randall [9] identified the following reasons for having a MSC less than unity: the presence of uncorrelated noise in E_n and/or I_n, a non linear relationship between E_n and/or I_n and leakage due to insufficient resolution, and/or wrong choice of window function.

4.2 Transfer function of frequency response function

The most important use of the dual channel analysis is the measurement of frequency response functions (FRFs), transfer functions or, as called in the framework of this work, transmissibilities. Throughout the text these terms will be used interchangeably.

The transmissibility is a sort of "black box" which represents the ratio of the output-to-input of the system in the frequency domain. In our case the output is the vibration I_n inside the property measured at the *INT* position whereas the input is the incoming vibration E_n recorded at the *EXT* position as represented in Figure 1. Therefore the system considered is the portion of soil which interacts with the building foundation and the sub-structures linked with the foundation like floors, walls and cellars.

The FRF provides a correct description of the system considered if the latter is stable, linear, time-invariant and noise free. Therefore in our case, the FRF will provide an approximation of the behavior of the system.

Several estimators exist in literature for calculating the FRF. Considering the system described in 3, the first estimator $H(f)$ can be obtained from:

$$H(f) = \sqrt{\frac{G_{II}(f)}{G_{EE}(f)}} \tag{3}$$

where $G_{II}(f)$ and $G_{EE}(f)$ are the auto spectra of I_n and E_n. This estimator has been used in the project "Human response to vibration in residential environments" for calculating the soil to building transmissibility. A similar approach has been used by Hunaidi and Tremblay [4] and Jakobsen [7] with the difference that their analysis were carried out in octave bands. In [6] and [19] the equation (3) is referred as total transmissibility. The second estimator is defined as $H1(f)$

$$H1(f) = \frac{G_{EI}(f)}{G_{EE}(f)} \tag{4}$$

where $G_{EI}(f)$ is the cross spectrum between E_n and I_n. The noise at the input contaminates $H1(f)$: its effect is significant in the vicinity of the resonances [10]. The $H1(f)$ estimator, also called direct transmissibility in [6] and [19], was used by With and Bodare [8]. The latter evaluated ground-to-building transfer functions using a stationary source. The last estimator considered is $H2(f)$:

$$H2(f) = \frac{G_{II}(f)}{G_{IE}(f)} \tag{5}$$

$G_{IE}(f)$ is the cross spectrum between I_n and E_n. This formulation was introduced by Mitchell: it is sensitive to the noise at the output and its effect is pronounced in regions of anti-resonance [10]. It can be seen that the ratio between $H1(f)$ and $H2(f)$ is equal to the MSC.

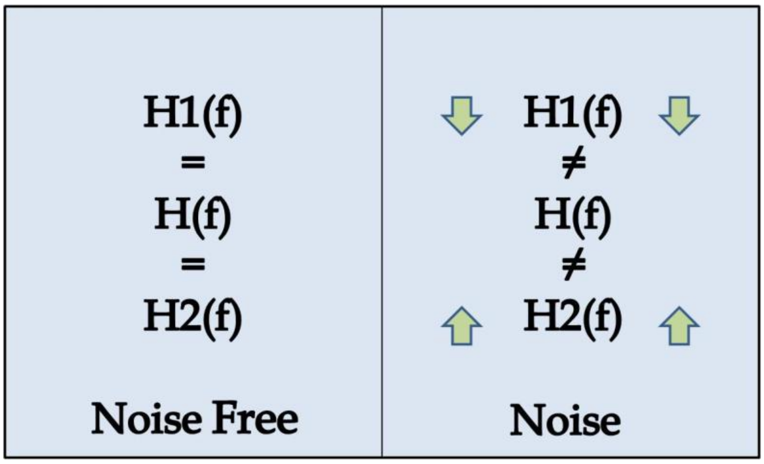

Figure 2: Effect of noise on the different FRF formulations.

In a noise free scenario all the FRF formulations provide the same result; however, the presence of noise corrupts the results. In fact in a noisy environment, for a given frequency *f*, the cross spectrum tends to decrease therefore $H1(f)$ will decrease whereas $H2(f)$ will increase (See right side Figure 2) considering (4) and (5).

The application of these "tools" will be presented in the next section for analyzing ground-to-building transmissibility for the assessment of human exposure.

5 Analysis of transmissibility

Considering the scenario depicted in section 3, the analysis steps necessary for evaluating the transmissibility between two synchronized accelerometers, one placed outside the house called *EXT* and one placed internally as close as possible to the point of entry named *INT*, are considered.

The measurement is realized considering several train passages: a minimum of five.

First of all, the events are identified using the LTA/STA algorithm as shown in 5.1, then in 5.2 the propagation time between the events is removed. In 5.3 a method for assessing the linearity of the measurement is presented based on the coherence whereas the issue of the averaging is considered in 5.4. Finally the use of transmissibility for assessing the human exposure is presented in 5.5.

5.1 Event identification

The identification of the event (a single train pass) simultaneously recorded at the two measurement positions is mainly based on the LTA/STA algorithm. The latter is one of the possible trigger algorithms used in seismology for automated event detection [20]: it consists of an estimation of the signal to noise ratio along the time history evaluating the ratio of short-to-long-term energy density. In detail, the STA/LTA algorithm processes the signal in two moving time windows: a short-time average window (STA) and a long-time average window (LTA). The STA measures the 'instant' amplitude of the signal and watches for the train passes while the LTA takes care of the current average background noise amplitude. When the ratio of both exceeds a pre-set value, an event is 'declared'. Then, the duration of the event is found identifying the 10 dB [3] down points of the envelope.

5.2 Alignment

Once the events have been identified, an intermediate step is needed before performing the dual channel analysis. To obtain a better definition of the coherence and transmissibility measurements, the propagation time between the waveforms has been removed. An estimation of the propagation time is obtained by evaluating the time lag corresponding to the maximum of the cross correlation function between the two signals: the reference signal of the *EXT* accelerometer and one component of the *INT* accelerometer. The waveform alignment is conducted using the Z component of the *EXT* accelerometer as reference.

5.3 Linearity of the measurement

The FRF formulations provided in section 4.2 can be used under the assumption that the system is time-invariant, stable and linear. This last characteristic can be identified using the coherence, which gives a measure of the degree of linear dependence between the two signals as a function of frequency [9].

The higher the linear relation between the signals detected by the *INT* and *EXT* receivers, the higher the coherence [21]. High values of coherence, generally close to 1, identify frequency ranges with a high signal to noise ratio [21] whereas low coherence values, as already stated in section 4.1, are generally associated with noise or non linearity in the system. Moreover, according to Price & Bernard [22] if the coherence is less than 0.8 the system should be modeled as having more than one input, i.e. a multiple input single output (M.I.S.O.) model should be used for describing the system. Using the MSC as tool for our analysis, a requirement needs to be satisfied for assessing the linearity of the dual channel measurement.

A practical example of setting a coherence threshold for indentifying linearity in dual channel measurements is given in Nazai and Desai [23]. In order to select frequency ranges where the phase between the two instruments had a linear behavior, they chose, based on their experience, a frequency threshold above 0.9.

Therefore, the strategy used will be similar to the one presented before only that, based on the authors' experience, the coherence threshold chosen will be 0.8 in order to satisfy the hypothesis of Price & Bernard as well. In this way the frequency ranges that satisfy this condition can identify a linear Single Input Single Output (S.I.S.O.) system. The set of frequencies for the j dual channel measurement where there is linearity is identified by L_j in (6) (which can be the null set).

$$L_j = f_i \in f \,/\, \left|\gamma_j(f_i)\right|^2 \geq 0.8 \tag{6}$$

If all the events measured at both receivers are considered, for each dual channel measurement j will be associated with an L_j, where L is defined as the set of all L_j

$$L = L_1, L_2 \ldots L_N \tag{7}$$

where N is the number of events. Knowing L, it is possible to build the distribution of the frequency bins above the coherence threshold as a function of the frequency. For each event, it's also possible to count the frequency bins that are above the fixed threshold of coherence. This parameter can be related to the length of the event recorded at the *EXT* position in order to understand which events can provide a good coherence measure.

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[3] re 10^(-6) m/s^2

5.4 Averaging

In framework of the project “Human response to vibration in residential environments”, the ground to building transmissibility estimation is obtained by linearly averaging the transfer function, in its *H* formulation shown in (3), for each event recorded at both measurements positions as explained in section 3. Transmissibility functions can also be obtained with a linear average of cross spectra based transfer functions such as *H1(f)* (4) or *H2(f)* (5).

Since cross spectra based transfer functions, *H1(f)* (4) and *H2(f)* (5), share the same coherence function [9], an alternative way of averaging is considered taking into account the linearity *L* of the dual channel measurement. This method consists of averaging only the frequency bins of the transfer function where the coherence between the two receivers is more than 0.8 creating the transfer functions $H1_L$ and $H2_L$.

$$H1_L = \langle H1(f_i) \rangle \quad f_i \in L \tag{8}$$

$$H2_L = \langle H2(f_i) \rangle \quad f_i \in L \tag{9}$$

In this way, the FRFs are defined only for the frequency bins that belong to *L*. $H1_L$ and $H2_L$ formulations have been proposed as a tool for comparing the transmissibilities obtained with different formulations.

5.5 Transmissibility for exposure assessment

As shown in the section above, the coherence can be used as tool for assessing the linearity of the transmissibility. The absence of coherence implies that noise or several excitation sources might be involved in the propagation process, as a consequence it is difficult to assess the linearity between the two receivers. In this scenario cross spectra based transfer functions can introduce error in the estimation of the ground-to-point-of-entry transmissibility, therefore the latter can be better assessed just using magnitude based transfer function for the evaluation of the human exposure. This hypothesis will be tested in the next section.

In Woodcock et al. [11] the use of the transmissibility for propagating the activity from the *EXT* to *INT* accelerometers in order to assess the internal exposure is explained. If we define $E(f)$ as the double sided “non smoothed” Fourier spectrum of the time history $e(t)$ or E_n recorded at the *EXT* position, prediction of the internal spectrum $I_{pred}(f)$ is carried out by interpolating the double sided transmissibility $H(f)$ to the length of $E(f)$ obtaining $H_{est}(f)$ and multiplying both the quantity according to the expression:

$$I_{pred}(f) = H_{est}(f)E(f) \tag{10}$$

Once $I_{pred}(f)$ is obtained, the prediction of the time history $i_{pred}(t)$ is achieved by applying the inverse Fourier transform and the estimation of the internal exposure metric can be done. In the exposure methodology, equation (10) is repeated for each event recorded at the *EXT* transducer for obtaining the long term estimation of the internal exposure as explained in section 2.

An evaluation of the uncertainty on the exposure estimation can be obtained considering the events recorded simultaneously at both measurement positions. The uncertainty can be defined as the relative error $\varepsilon_{\exp}$ between the ‘true’ value of the internal exposure e_r and the one predicted e_p by the method expressed in (10).

$$\varepsilon_{\exp} = \frac{e_p - e_r}{e_r} \tag{11}$$

Exposure Metric	Definition
Peak Particle Acceleration (PPA)	Maximum deviation of the time series from the mean
Root Mean Square (RMS 1 sec)	$\ddot{x}_{rms} = \sqrt{\frac{1}{K}\sum_{n=1}^{K}\ddot{x}(n)^2}$
Vibration Dose Value (VDV)	$\ddot{x}_{VDV} = \sqrt[4]{\frac{T}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$
Root Mean Quad (RMQ)	$\ddot{x}_{rmq} = \sqrt[4]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$

Table 1: Summary of vibration exposure descriptors considered. Where $\ddot{x}(n)$ an acceleration time series, N is the number of samples in the acceleration time series, K number of samples for the RMS and T is the duration of the event in seconds.

The relative error in percentage will be calculated for the following exposure metrics (See Table 1): Weighted Peak, Weighted 1 sec RMS, VDV and Weighted RMQ. The metrics are calculated, for the Z component of the acceleration W_b weighted [2].

6 Results

In this section results for the transmissibility analysis are presented. The method developed for the project "Human response to vibration in residential environment" is going to be tested to a set of measurements done in the framework of the European project Cargovibes [24] by the University of Salford.

Figure 3: Measurement Site.

The measurement site is shown in Figure 3. According to the scheme presented in Figure 1, $\overleftrightarrow{D_{SE}}$ is 20 m, $\overleftrightarrow{D_{SB}}$ is 29 m and $\overleftrightarrow{D_{EI}}$ is 8 m. The *EXT* was installed in a garage whereas the *INT* was placed at the first floor of a semidetached house in a room, close to its center. Both instruments were acquiring for 43 hour.

For the field work were used gps time synchronized tri axial[4] force feedback strong motion accelerometers: The Guralp CMG 5TD [25].

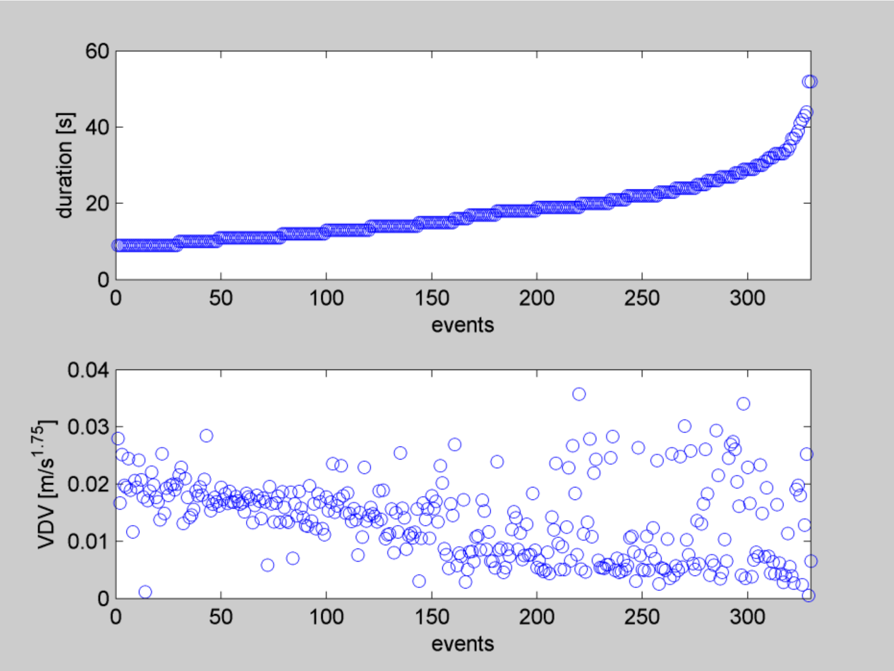

Figure 4: Upper panel: Duration of the events sorted in ascending order. Lower panel: Internal exposure expressed in VDV W_b weighted for each event.

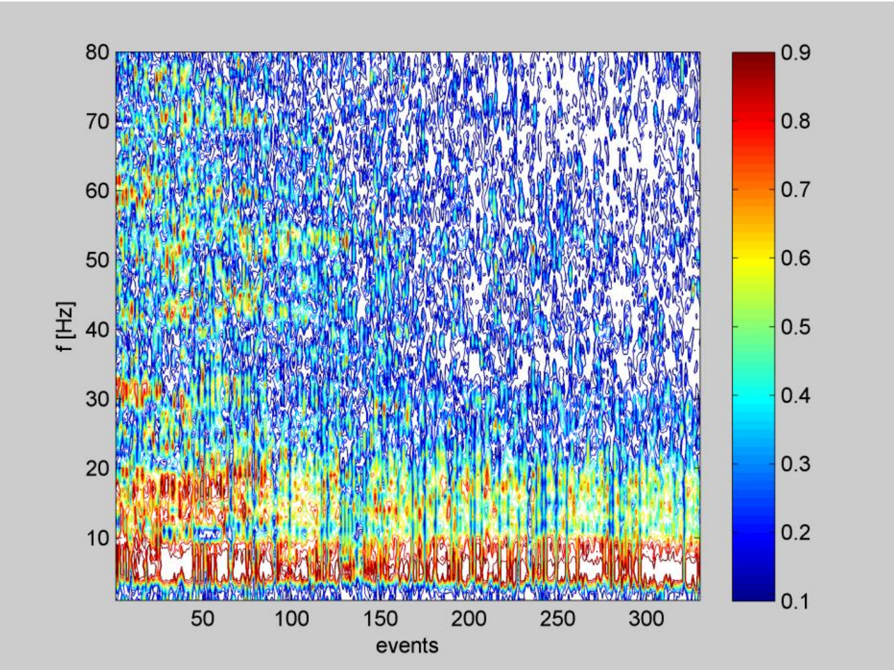

Figure 5: Contour map of the coherence function between the Z components for all the events simultaneously recorded at the *EXT* and *INT* position. Events are sorted by the duration in ascending order.

[4] Vertical component is identified with Z whereas the planar components with N and E.

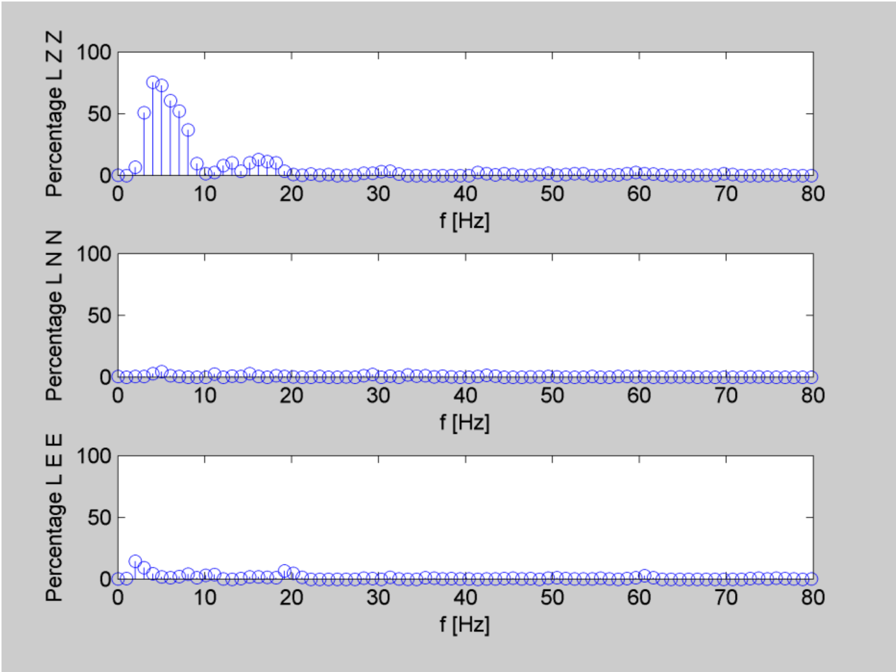

Figure 6: Percentage of frequency bins with a coherence value above 0.8 (Linearity) as a function of frequency. In the upper panel the linearity between the Z component in *EXT* and Z component in *INT* is considered. Middle panel linearity between N and N components. Lower panel linearity between E and E components.

The number of train passages identified by the event identification procedure explained in 5.1 was 330. The durations of the events recorded are in a range between 9 to 52 seconds and they are reported in the upper panel of Figure 4 sorted in ascending order. In the second panel of Figure 4, the internal exposure, expressed in Vibration Dose Value (VDV, see Table 1) for the Z component of the acceleration, for each event is reported showing a wide spread among the exposure values with the increase of the duration.

Once the events have been aligned, a coherence analysis among the events recorded at both receivers has been performed in order to assess the linearity of the dual channel measurement. A contour map of the coherence between the Z components as a function of frequency for all the events recorded at both receivers is shown in Figure 5 and even in this case the events have been sorted by their duration: from the smaller to the bigger value. Therefore, when the number of events increases from 1 to 330 (the x-axis in Figure 5) the higher values of coherence, with a red color in Figure 5, are more focused in the frequency ranges below 10 Hz. On the other hand, events with durations between 9 and 12 seconds, events from 1 to 100 in Figure 4, have their highest coherence values below 20 Hz with some scattered values between 30 and 80 Hz. Therefore, it is likely that short events express a higher linearity L_j, equation (6), in comparison with long events.

Considering the L_j of all the events, the set L, equation (7), can be created and the percentage of frequency bins above the 0.8 coherence threshold is reported in Figure 6 for the Z, N and E components of the acceleration. It can be seen, from Figure 6, that for the Z components the percentage of linearity is above 50 % just in the frequency range between 3 and 7 Hz whereas for the other components the percentage of linearity is below 15 %. According to the data presented above it can be said that the system soil-building can be assumed as a linear S.I.S.O. system just for a certain frequency range. Below, it can be seen how this characteristic can affect the different transfer function formulations.

Figure 7 shows the different transfer function formulations of the transmissibility averaging 330 trains between the Z, E and N components of the two receivers. Each frequency bin belonging to L is highlighted with a circle and its dimension is proportional to the number of the bins, as shown in Figure 5, used for building $H1_L$ and $H2_L$ at that specific frequency.

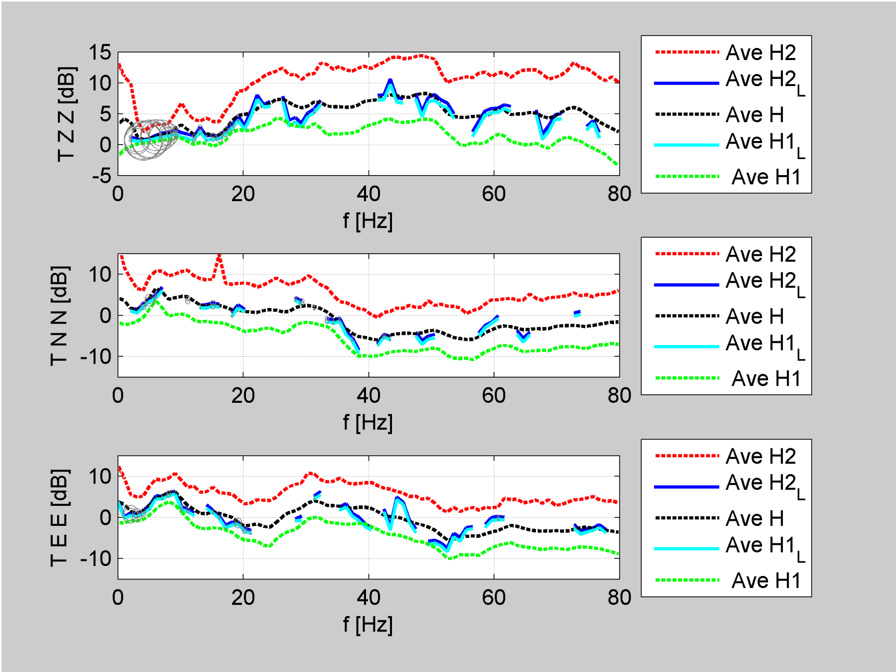

Figure 7: Transmissibility as a function of frequency. From the upper panel: Transmissibility between Z, N and E components of the acceleration. In each panel from the top curve: H2, $H2_L$, H, $H1_L$ and H1 formulation.

On the other hand, when the circles are small, see Figure 7 upper panel in the frequency range 9-25 Hz, not all the frequency bins contribute to the average and the $H1_L$ and $H2_L$ values are generally included between the *H1* and *H2* values.

It is worth noting that, in this situation the discrepancy between the transmissibility formulation is larger than the case when the majority of the frequency bins contribute to $H1_L$ and $H2_L$. When there is no coherence, see Figure 7 upper panel in the frequency range 25-40 Hz, $H1_L$ and $H2_L$ don't exist. In these areas, there is a large discrepancy between the transfer function formulations and this observation is confirmed in the other panel of Figure 7 where the transmissibility for the other components is presented.

As consequence, cross spectra based transfer functions may introduce error in the estimation of the ground-to-point-of-entry transmissibility; therefore the latter can be better assessed just using magnitude based transfer function for the evaluation of the human exposure. This hypothesis will be tested estimating the internal exposure, expressed in different metrics, using the three different transfer function approaches. The long term internal exposure will be obtain using equation (10).

On the other hand, the "real" value of the long term internal exposure is known since both the receivers were recording for the same period of time. Therefore, the uncertainty evaluated using equation (11) expresses the error on the propagation of the activity from the *EXT* to the *INT* using the transmissibility between the two measurement points calculated for all the train passages identified in the monitoring period. The relative error in percentage is calculated for the exposure metrics in Table 1 for the different transfer formulations (3), (4) and (5).

The results are shown in Figure 8. From Figure 8, it can be seen that the error on the internal exposure is less than 10% using the *H* formulation whereas the *H1* formulation provide an underestimation of the metrics around – 50%. The *H2* formulation provides the largest overestimation of the internal exposure: above 250 %.

The hypothesis introduced at the beginning of section 5.5 is confirmed: cross spectra based transmissibility measurement can introduce a greater error in the evaluation of the long term internal human exposure as compared with magnitude only estimator. The latter is more suitable for assessing human exposure to vibration.

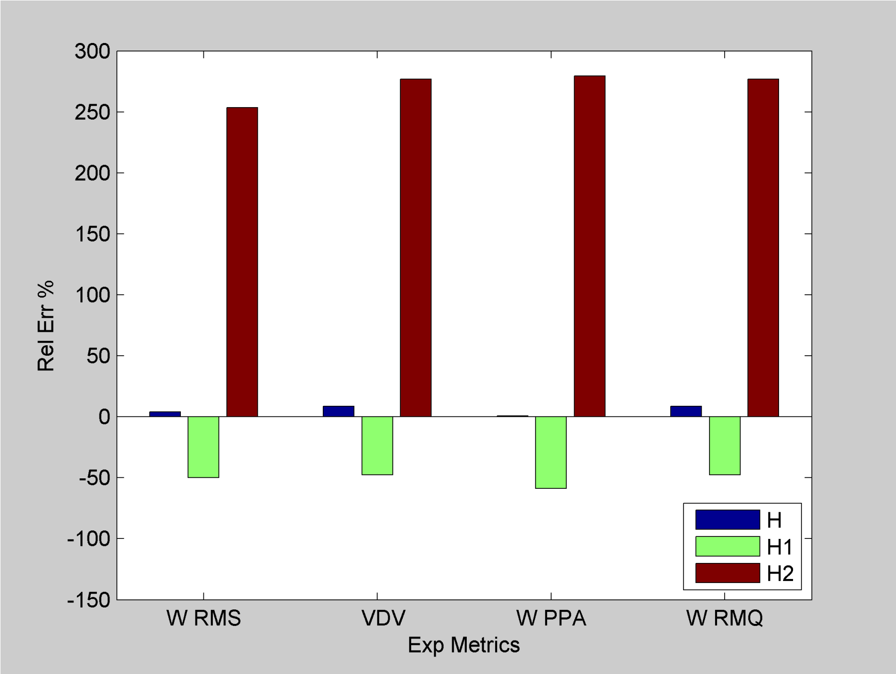

Figure 8: Relative error in percentage on the exposure metrics for different transfer function formulation: H, H1 and H2. Metrics considered: W RMS (1 sec), VDV, W Peak and W RMQ.

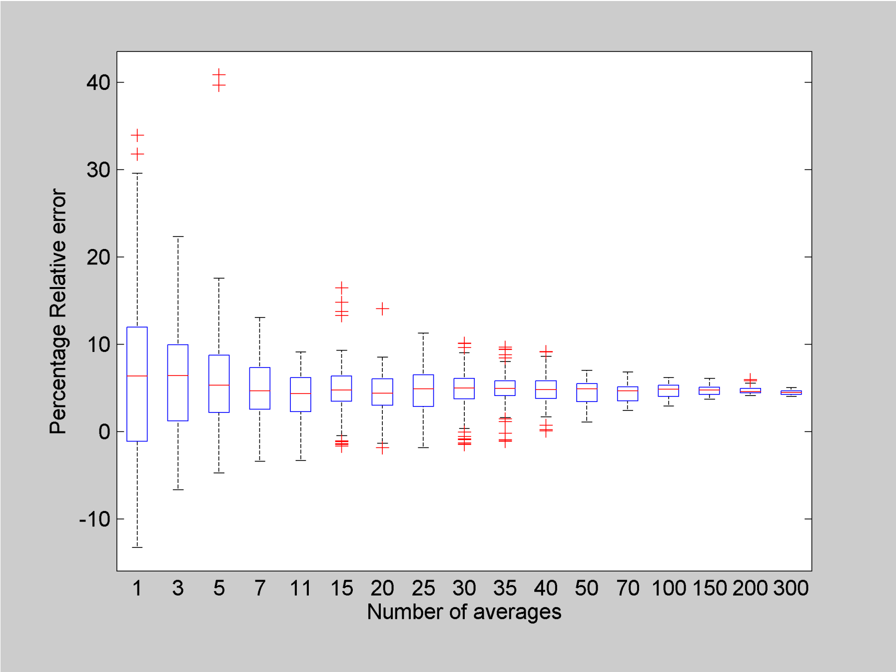

Figure 9: Percentage relative error on the internal long term exposure estimation, express in VDV W_b weighted of the Z component of the acceleration signal, against the number of averages for building the transmissibility function. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considering outliers, and outliers are plotted individually.

The advantage of taking internal long term measurements is that the exact value of the long term internal exposure is known, but it can be considered unpractical especially if a survey with a large number of respondents is undertaken, like the one performed by the University of Salford. In this scenario, the “pragmatic approach” proposed in this paper makes possible to assess human exposure on a large scale using the transmissibility as a filter for propagating the entire activity from the *EXT* to *INT* position.

As said in section 5.4, the transmissibility is obtained by averaging at least 5 train passages and the set of measurements analyzed in this paper can be used for understanding how the number of averages is related with the error on the internal long term exposure estimation.

In fact, a transmissibility function, *H* formulation, with a fixed number of trains *N* can be created randomly picking *N* consecutive train passages during the monitoring time at both measurement positions. Then equation (10) can be applied at each train acquired at *EXT* position for obtaining an estimation of the long term internal exposure. This process has been iterated 100 times for creating a statistical ensemble of estimated internal exposure considering different values of *N*. In Figure 9 the percentage relative error on the long term internal exposure, expressed in VDV, is shown against the number of averages for building the transmissibility function as a box plot. Of course the error on the prediction of the long term internal exposure decrease with the number of averages, and it can be noted that after 30 averages even the outliers can produce an error that is below 10%. Using 5 train pass bys for building the transmissibility function, an error comprised between 10 and 1 %, considering the edges of the box, can be obtained. Considering that 5 trains can be measured in 20-30 minutes of short term monitoring, this error can be considered acceptable in a strategy for a large scale evaluation of the human exposure. Therefore according to the results shown above and considering the measurement site characteristics, the number of train passages for building the transfer function, *H* formulation, can be chosen between 5 and 30 train passages with a measurement time that goes from 30 minutes to 3 hours.

7 Conclusion

In this paper the ground-to-building transmissibility has been considered, based on measurement from two time synchronized receivers, one on the ground and one inside the property, in order to assess human exposure caused by railway vibration.

Magnitude-only and cross spectrum transfer function formulations have been compared for understanding which is the most suitable method for the evaluation of the human exposure. For doing so, the concept of linearity for the dual channel measurement has been defined as the set of frequency bins where the coherence function is above 0.8.

Analyzing the linearity of 330 train passages, for a continuous monitoring period of 43 hour at both measurement positions, it has been found that train events with durations between 9 and 11 seconds exhibit higher linearity than other trains. Considering that the railway line can be seen as a mixture of point and line source [14], it may possible that short trains have a more point like behavior whereas long trains act more as a line generating different responses in the building. In this sense, algorithms for the classification of the train traffic, like [26], can help to understand how the response of the building changes under different train loads. Further research is needed for understanding, through measurement, how the propagation characteristics of the source change with the different train traffic. In fact, a better knowledge of the propagation characteristics may lead to a better understanding of the building response.

Considering all the train passages, the linearity of the dual channel measurements is useful for identifying the frequency ranges where the soil-to-point-of-entry system can be described as linear S.I.S.O. The latter, for the measurement site considered, is an appropriate description of the system in the frequency ranges where the sensitivity of the human body to vibration is high: between 3 and 9 Hz.

Cross spectrum averaging transfer functions based on the linearity of the dual channel measurements have been used for comparing the different transmissibility formulations. When the linearity is high then all the transmissibility formulations are close to each other like in the noise free case, on the other hand in absence of coherence a big discrepancy of several dB can be found between the methods. For this reason, cross spectra based transfer functions can introduce error in the estimation of the ground to point of entry transmissibility which can be better assessed just using magnitude based FRFs for the evaluation of the human exposure.

The error in the estimation of the internal exposure has been evaluated using the transmissibility approach as a filter for propagating the vibration activity, for the entire monitoring period, from the ground to inside the property. It has been found that magnitude only transfer functions provide the lowest error, below 10%, for all the exposure metrics considered confirming the analysis based on the linearity approach.

For the measurement site considered, a number of train pass-bys comprise between 5 and 30 for building magnitude only transmissibility function between the external and internal measurement position has been found to provide an acceptable error on the estimation of the internal exposure. Therefore, this approach it can be considered very valuable for the assessment, on a large scale, of human exposure to railway vibration.

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