METHODOLOGY FOR THE EXPERIMENTAL EVALUATION OF FREQUENCY RESPONSE FUNCTIONS IN THE FRAME OF RAILWAY-INDUCED OR CONSTRUCTION-INDUCED GROUNDBOURNE VIBRATION

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Abstract
In this paper, a methodology for the experimental evaluation of mechanical vibration frequency response functions in the framework of groundbourne railway-induced and construction-induced vibration predictions is presented. This methodology is based on a device specifically designed for the excitation of railway superstructures. The device can be used also to excite the ground with the aim of obtaining ground/building frequency response functions. The resulting frequency response functions can be used to feed prediction empirical models with specific in situ results or to characterize the system by performing an inversion process over a theoretical model of it, among other applications. Two examples of this methodology applied for the experimental determination of frequency response functions and subsequent system characterization are presented.

Keywords: vibrations, building, railway infrastructures, construction works.

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1 Introduction

Noise and vibration induced by transport infrastructures, industrial or construction activities and other sources of vibration are an important issue of concern regulated by current legislation in most countries around the world. This regulations aims to control the maximum levels of noise and vibration to ensure structural safety of the buildings and tolerable annoyance levels on the surrounding workers and inhabitants, among other factors [1]. In this context, groundbourne railway-induced and construction-induced vibrations to the nearby buildings are one of the most problematic issues [2]. Thus, accurate modelling of this problem is of great interest for designers of new railway infrastructures and construction companies. Existing semi-analytical and numerical models devoted to simulate these problems have a significant uncertainty associated to their results due to the huge amount of subsystems that are involved in the problem and the uncertainty associated to their geometrical and mechanical parameters [3]. In particular, the soil is one of the most important sources of this uncertainty, because of its inherent inhomogeneity and the consequent complexity on its characterisation [4,5]. Empirical models, although they are based on experimental measurements, are not able to ensure better accuracy (quite the opposite, in fact) than semi-analytical and numerical models when the system to be studied is not exactly one of the empirical model database, because of the huge amount of combinations of subsystems to cover, the differences in the coupling of different subsystems and the large variability of their parameters. To increase the accuracy on the resulting predictions of computational models, hybrid models are a very interesting engineering tool [6]. They are based on the combination between experimental data, measured on the existing subsystems of the specific case to be studied, with a computational model, i.e. semi-analytical, numerical or empirical models. In hybrid models, the experimental data can be included on the computational prediction tools in the form of mechanical vibration Frequency Transfer Functions (FTF), for the case of empirical models, and in the form of a set of mechanical parameters, for the case of semi-analytical and numerical models. The only problem of using hybrid models is the increasing of the engineering costs associated to the measurements.

Experimentally evaluated Frequency Response Functions (FRF) between an excitation point and a set of accelerometers on the system under study can be efficiently used for feeding hybrid models in two ways. On the one hand, they can provide FTF between particular points of the system, which can be directly used in prediction empirical models. On the other hand FRFs can be employed to characterize the measured part of the system by performing an inversion process over a theoretical model of this part, providing the mechanical parameters of this part of the system which can be used in semi-analytical or numerical models of the whole system. In railway-induced vibration problems, FRF of at least some significant part of the system can be always measured for the specific case under study. For example, for an environmental groundbourne noise and vibration assessment of a new underground urban railway line to be constructed, the FRF that relate an excitation on the ground surface and significant buildings floors vibration can be measured previously to the tunnel perforation, feeding a hybrid model that could be used to accurately include the noise and vibration pollution legal restrictions in the design of the new underground line in terms of his path and superstructure characteristics. In a more advanced stage of the project, after the tunnel perforation, the FRF that relate an excitation on the tunnel invert and significant buildings floors vibration can be used to improve the accuracy of the previously used hybrid method, allowing the designers to a more accurate selection of the railway superstructure. In construction-induced vibration problems, FRF between the ground surface and nearby building floors can be combined with empirical or numerical models of construction machines vibration generation to set an accurate hybrid model of the problem.

In railway-induced vibration problems, the experimental evaluation of FRF on the railway track is normally performed using hammer testing. In hammer testing, the rail is excited by a mechanical impact (instrumented hammer) and the response is measured by accelerometers at different points of the rail structure. The measured FRF can be compared to an analytical model of the superstructure, for example a 2-DOF systems [7], or to a numerical model of a track section [8–10], in order to obtain the data required. The main drawbacks of this method are: its limited capability to excite not only the upper components of the superstructure (rail, fastener and sleeper) [11]; the absence of low frequency content (below 50 Hz) in the dynamic load applied by this excitation system; the fact that the test cannot be done under preload conditions which implies that the nonlinear behaviour of some of the elastomeric or rubber-based components of the track cannot be studied properly [9,12]. Testing methodologies that are able to excite the whole railway track are the Track Loading Vehicle (TLV) and the Rolling Stiffness Measurement Vehicle (RSMV) [13,14]. However, both of them have a drawback: they cannot measure directly the force applied to the superstructure and they need to indirectly calculate it from vibration measurements.

In the point of view of construction-induced vibration problems, methods used in earthquake engineering for the assessment of building dynamics can be employed. This methods, typically based on large eccentric mass shakers [15,16], are also unable to determine by a direct measurement the applied force on the system.

In this paper, a methodology for the experimental evaluation of mechanical vibration FRF in the framework of groundbourne railway-induced and construction-induced vibration predictions is presented. It is based on a device specifically designed for the excitation of railway superstructures. Basically, it is an eccentric mass shaker mounted over four supports which are specifically designed to rest over railway superstructure rails. A force transducer is located at each support to measure the input forces to the system and different accelerometers are located at the points at which the transfer functions are required. A complete description of the device is presented in Section 2. Thus, this device is able to excite the whole system, producing significant levels of vibration in nearby soil surface or even nearby buildings at the desired range of frequencies (up to 80 Hz [2]), with the particularity that is giving a direct measurement of the force applied to the system. The device can be used also to excite the ground with the aim of obtaining ground/building frequency response functions. The resulting frequency response functions can be used to feed prediction empirical models with specific in situ results or to characterize the system by performing an inversion process over a theoretical model of it, among other applications. Two examples of this methodology applied for the experimental determination of frequency response functions and subsequent system characterization are presented in Section 3.

2 Methodology definition

The methodology presented in this paper is based on the excitation device shown in Figure 1. It is an eccentric mass shaker which has been specifically designed for the excitation of railway superstructures.

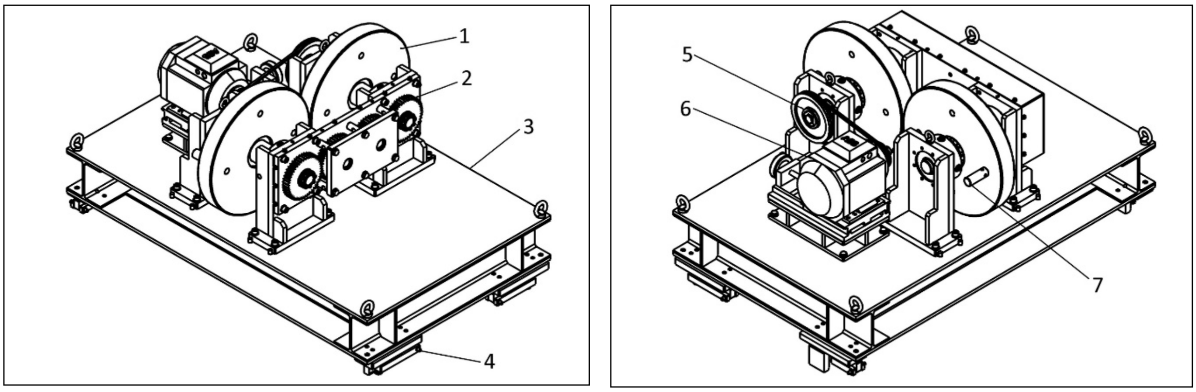

Figure 1 – Excitation device.

The device consists on a bench (3 in Figure 1) in which an electric motor (6 in Figure 1), a main transmission (5 in Figure 1) and a secondary transmission (2 in Figure 1) are installed. The main and secondary transmissions transmit the rotation movement to two disks (1 in Figure 1) which are rotating in synchronised counter phase thanks to the secondary transmission. Both disks are exactly equal and have a female screw thread in which different masses can be attached (7 in Figure 1). This masses are the ones that create the eccentricity of the disks and, consequently, the dynamic excitation force. To ensure that the horizontal component of this force is practically null, the female screw threads are symmetrically located on the disks and the attached masses are selected to be exactly equal. To excite the system in the desired range of frequencies, up to 80 Hz, the electric motor is controlled by a frequency converter and different attached masses are designed to keep a significant dynamic force all along the frequency range. The device is mounted over four supports (4 in Figure 1) which are specifically designed to rest over railway superstructure rails. In Figure 2, the supporting system is shown.

Figure 2 – Excitation device supporting system for one of the four supports and example of transducers setup (Force transducer denoted in red and accelerometers in the rail denoted in yellow).

The measurement setup consists on four force transducers located at the device supports, which are able to measured the force applied to the railway track or the system to be excited. A set of accelerometers is in charge of getting the response of the system by means of acceleration of vibration in significant locations of the system. If the engineer is looking for FTF of the system between several specific points, the significant locations where the accelerometers should be placed are the required ones for the FTF. However, if a detailed characterization of the system is desired, this set accelerometers should be accurately designed to properly understand the dynamic behaviour of the system or subsystem under study. In this last case, FRF of the system have to be used to perfom an inversion process over a theoretical model. These measured FRF can be stored in a matrix FRF matrix $\mathbf{H}_{\text{exp}}$, related to a set of measument points $\mathbf{x}_u$ and a set of excitation points $\mathbf{x}_f$. A theoretical model can be defined as

$$\mathbf{H}_{\text{theo}} = \Phi(\mathbf{p}, \mathbf{x}_u, \mathbf{x}_f), \tag{1}$$

where $\mathbf{H}_{\text{theo}}$ are the FRF evaluated by the theoretical model Φ and $\mathbf{p}$ are the unknown parameters of the system. Selecting the same $\mathbf{x}_u$ and $\mathbf{x}_f$ than the experimental setup of a particular experimental measurement campaign, the output FRF of the theoretical model $\mathbf{H}_{\text{theo}}$ should match with the experimental ones $\mathbf{H}_{\text{exp}}$ if the $\mathbf{p}$ parameters are correct. With the aim of obtaining the correct $\mathbf{p}$ parameters, which are the parameters of the system in the basis of the theoretical model used, a optimization process must be performed.

3 Application of the methodology

In this section, two examples of the application of the described methodology are presented. First, a measurement campaign performed in the frame of the project VIBRO-IMPACT is described. The VIBRO-IMPACT project has aimed to develop a methodology for the prediction of construction-induced vibration [17], being a ground/building theoretical model and its validation one of the most important parts of the project. Second, a measurement campaign performed in the frame of the RECYTRACK project is also described. The RECYTRACK project has aimed to develop a new elastomeric material, based on end-of-life recycled tires, to be used for different vibration abatement solutions to be applied in the track in railway-induced vibration problems [18]. One of the most important parts of the project is the assessment of the vibration isolation efficiency of these new solutions, being the measurement campaign presented here part of the assessment of the under-ballast mat solution.

3.1 Construction-induced vibration problem

To validate the ground/building theoretical model of the VIBRO-IMPACT project, a measurement campaign in an eight-storey building with two underground parking levels was performed. In Figure 3, some images of the measurement setup are shown. As shown, the measurements were developed when only the structure of the building was constructed. The excitation device was placed on the surrounding ground at the level of the first parking floor (not underground at this stage of the construction process) and the setup of the measurement points was basically two accelerometers per floor, one located in the floor centre and another one close to a central column.

Figure 3 – Excitation device placed in the surface of the nearby ground of a building in Sant Adrià del Besòs (Barcelona).

In this case, the distance between the excitation point and the receivers is significantly large. To ensure that the mechanical vibration energy generated by the excitation device can be higher enough than the background vibration in the receivers in the point of view of the frequency spectrum, the rotating speed of the excitation device is set to a value or to a small range of values for each measurement. An example of this is shown in Figure 4, where frequency spectrums for accelerometers located in floors one, two and eight when the excitation device is rotating at 17 Hz are presented. One can observe that, near to 17

Hz, the frequency content is mainly induced to the excitation device, which makes these values valid to be used for the construction of the FRF of the system between the different points in the measurement setup. An efficient procedure is to develop excitation frequency sweeps in a limited range of frequencies, changing the range of frequencies for each measurement to eventually complete all the desired range of frequencies. For a case like this, where the receivers are far from the excitation device, the range of frequencies for each measurement should be small to concentrate the mechanical vibration energy.

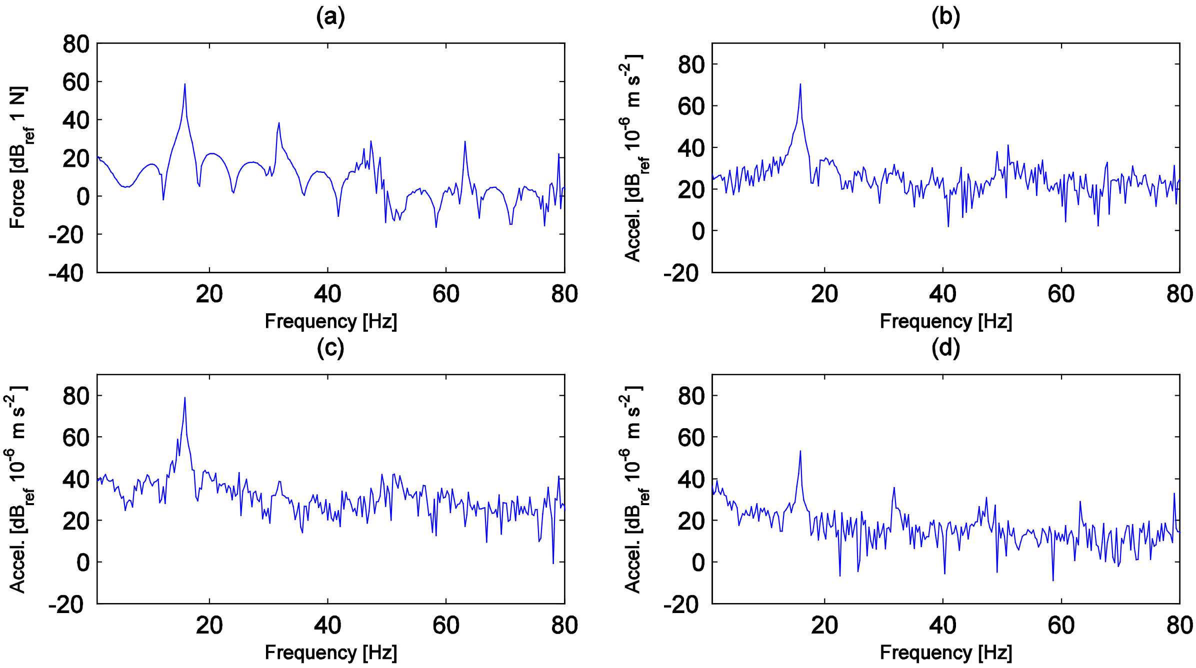

Figure 4 – Frequency spectra for one of the force transducer (a) and the accelerometers placed in the centre of the floors one (b), two (c) and eight (d) when the excitation device is rotating at approximately 17 Hz.

3.2 Railway-induced vibration problem

To assess the vibration isolation efficiency of the elastomeric under-ballast mat solution developed in the RECYTRACK project, a measurement campaign in a ballasted railway track with and without the aforementioned mat is performed. The setup for these measurements is 5 accelerometers located at the railhead (two of them, one over the fastener and another one in the mid-span), the sleeper are the surrounding ground (one close to the track and the other one at 8 meters from the centre of the railway track).

Figure 5 – Excitation device placed in the ballasted railway track under study in Aranda de Duero (Burgos).

For this experimental setup, all the measurement points were very close to the excitation device, therefore, no problems about low signal-to-noise ratios are expected. Thus, the sweeps of excitation frequency can cover all the desired frequency range, since, even without eccentric masses, the vibration levels along all the range of rotating frequencies are high in all the measurement points. To study the nonlinear behaviour of the elastomeric or rubber-based components of the track, the excitation device was loaded with steel sheets to measure the response of the system at different preloads.

The FRF obtained by the application of the presented methodology in the ballasted track with and without the elastomeric mat has been used in the RECYTRACK project to asses about the vibration isolation efficiency of the elastomeric mat, by characterising both railway tracks and couple the resulting models to a train passage model, constituting a hybrid model of the whole system.

4 Conclusions

In this paper, a methodology for the experimental evaluation of mechanical vibration FRF in the framework of groundbourne railway-induced and construction-induced vibration predictions is presented. The excitation device in which this methodology is based is able to excite the whole system, producing significant levels of vibration in nearby soil surface or even nearby buildings at the desired range of frequencies, with the particularity that is giving a direct measurement of the force applied to the system. To achieve this objective, different measurement methodologies can be used depending on the distance between the measurement points and the excitation devices, in order to avoid that the background vibration could affect the FRF or FTF evaluation. Basically, the idea is to concentrate the mechanical vibration energy in small frequency ranges to ensure that, at this frequencies, the signal-to-noise ratio is large enough. This idea and its application based on the methodology presented is experimentally validated for the case of a ground/building problem.

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