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BUILDING BASE ISOLATION DESIGN: QUANTIFICATION OF VIBRATION TRANSMISSION USING POWER FLOW ANALYSIS

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ABSTRACT

This paper reports on ongoing work aimed at developing practical guidance for designing BBI solutions. This includes examining the mechanisms by which ground-borne vibrations from railway activities are transmitted into buildings, in particular, the soil-structure interaction (coupling loss), the role of the isolation system and the influence of structural elements within the building using power flow analysis. Power flow analysis provides valuable insight into the vibration transmission through the system, offering an effective basis for isolation design. This analysis requires estimating the mobility of the substructure (foundation and ground), the isolation system and that of the superstructure. The paper presents a series of experimental measurements of these essential parameters, made at various stages of construction in a recent BBI project. The mobility of the substructure was measured using hammer impact, and vibration levels due to train passages were recorded both at the beginning of construction, before the construction of the superstructure and after the completion of the building. Since the mobility of the superstructure cannot be measured directly, this was estimated by numerical simulation. The characteristics of the isolation system were determined by laboratory tests under loading conditions representative of the operating state of the building.

Keywords: *Ground-borne vibration, Ground-borne noise, Building base isolation, Power flow analysis*

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1. INTRODUCTION

Buildings, especially those near railway or subway networks, can be subjected to ground-borne vibrations that result in unacceptable levels of structure-borne noise and vibration for the occupants of the building. In order to protect a building from such disturbance, it is necessary to decouple the building from the surrounding sources at the foundation level or on the columns or walls in an upper level by introducing a building base (vibration) isolation solution.

A true assessment of any isolation solution requires comparing noise or vibration levels inside the building with and without the isolation system. This indicator is known as the insertion loss. In practice, once a building is isolated, the non-isolated condition is unavailable, making the true insertion loss unmeasurable.

Today, the performance of a Building Base Isolation (BBI) system is often defined solely in terms of transmission loss, where vibration levels are typically measured above and below the isolation 'cut' in the completed isolated building. However, these measurements do not accurately reflect true isolation performance as they focus on the forced response of a limited section of a complex structure. Furthermore, in an isolated building, increased vibration in the foundation (substructure) may lead to an inaccurate assessment of isolation performance compared to a non-isolated building [1]. Transmission loss and insertion loss indicate the same performance only when the building acts as a SDOF mass-spring system.

A comprehensive study of vibration transmission between the ground and a building was conducted by Edirisinghe and Talbot [2]. They investigated the fully coupled three-dimensional behavior of a tunnel–foundation–building system, analysing the effects of

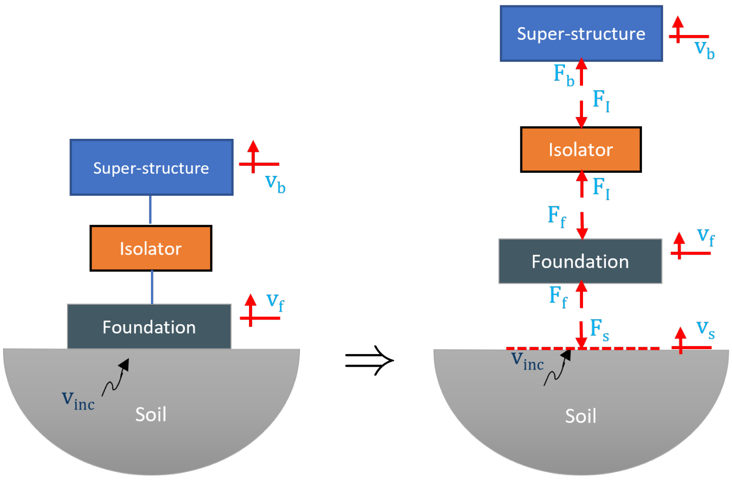

Figure 1. A general overview of the ground-foundation-building interaction.

the source location (the tunnel) relative to the building, the foundation configuration and the flexibility of the building structure. The results showed that simplified models, which capture the fundamental soil-structure interaction (SSI) of the system without including tunnel interaction, can provide sufficiently accurate predictions of vibration transmission through the building.

Using numerical modelling and experimental measurements, Kuo et al. [3] studied the coupling loss of a building subjected to railway-induced vibrations. Their field measurements and numerical studies also showed that a simplified SSI model, which does not include the track or tunnel, provides a sufficiently accurate estimation for the purposes of design. Additionally, their results showed that ground conditions significantly influence coupling loss, whereas the building geometry and foundation type have a more limited impact.

Disregarding the effect of any source-building interaction, the vibration transmission through the system can therefore be decomposed into three main parts: (1) vibration transmission from the ground to the building foundation, (2) vibration transmission through the isolation system and (3) vibration transmission through the building floors above the vibration cut.

One approach to quantifying the vibration transmission process between the different domains (the substructure, the isolator and the superstructure) is to evaluate the vibration energy flux using structural power flow analysis [1,4]. In this paper, theoretical expressions of this analysis are first presented, and the essential parameters governing the interaction between the domains are described. A recent building base isolation project is then used to illustrate how these quantities may be derived from experimental in-situ measurements and then used to estimate the power flow into the building.

1.1 Application of structural power in Building Base Isolation

Focusing on vibration levels at the ground-building interface accounts for transmission at only one location and in one direction. In contrast, power flow analysis can provide a global measure of isolation performance by evaluating the vibrational power at multiple locations and in several directions, leading to a more accurate evaluation of the transmissibility process.

Figure 1 shows the two main coupled domains with the intermediate isolation system, where the substructure (the foundation) has been excited by an incident wave $\mathbf{v}_{\text{inc}}$. The interaction force between the domains depends not only on the excitation but also on the dynamic characteristics of each domain, which can be represented by the mobilities of the coupled domains.

To analyse vibrational/structural power transmission through a building, we need to determine the power in terms of the interaction forces (F) and velocities (v) at each domain's interface. Based on the domain decomposition shown in Fig. 1 for the isolated building, these can be expressed in terms of the 'free' velocities of either the foundation or the soil, that is, the velocities measured at the interface between either the foundation and the future superstructure before the superstructure is constructed, or the velocities measured on the ground surface before the future foundation is constructed (Fig. 2):

$$\begin{aligned} \mathbf{v}_\mathrm{f} &= \mathbf{v}_\mathrm{f,free} - \mathbf{Y}_\mathrm{f} \cdot \mathbf{F}_\mathrm{f} \\ \mathbf{v}_\mathrm{b} &= \mathbf{Y}_\mathrm{b} \cdot \mathbf{F}_\mathrm{b} \\ \mathbf{v}_\mathrm{b} - \mathbf{v}_\mathrm{f} &= \mathbf{Y}_\mathrm{I} \cdot \mathbf{F}_\mathrm{I} \end{aligned} \tag{1}$$

where, $\mathbf{v}_\mathrm{f,free}$ is the foundation's free vibration, and $\mathbf{Y}_\mathrm{f}$, $\mathbf{Y}_\mathrm{b}$, and $\mathbf{Y}_\mathrm{I}$ are the mobility of the foundation, the building and the isolator, respectively.

Since the mobility of the superstructure cannot be measured directly, it is estimated through numerical simulation. In contrast, the mobility of the substructure (the foundation-soil system) can be obtained via either numerical simulation or measurement using a conventional hammer impact test. For a complex substructure, an averaged mobility can serve as a representative value for varying mobilities at different points. The mobility of the isolation system is defined by the bearing dynamic stiffness, which is determined through laboratory tests under load conditions representative of the building's operational state.

Since the isolator is assumed to be massless, $\mathbf{F}_\mathrm{b} = \mathbf{F}_\mathrm{f} = \mathbf{F}_\mathrm{I}$, and the interaction forces and velocity responses can be obtained from Eqn. 1 as follows:

$$\begin{aligned} \mathbf{F}_\mathrm{I} &= \|\mathbf{Y}_\mathrm{b} + \mathbf{Y}_\mathrm{I} + \mathbf{Y}_\mathrm{f}\|^{-1} \cdot \mathbf{v}_\mathrm{f,free} \\ \mathbf{v}_\mathrm{b} &= \|\mathbf{Y}_\mathrm{b}\| \cdot \|\mathbf{Y}_\mathrm{b} + \mathbf{Y}_\mathrm{I} + \mathbf{Y}_\mathrm{f}\|^{-1} \cdot \mathbf{v}_\mathrm{f,free} \\ \mathbf{v}_\mathrm{f} &= \|\mathbf{Y}_\mathrm{b} + \mathbf{Y}_\mathrm{I}\| \cdot \|\mathbf{Y}_\mathrm{b} + \mathbf{Y}_\mathrm{I} + \mathbf{Y}_\mathrm{f}\|^{-1} \cdot \mathbf{v}_\mathrm{f,free} \end{aligned} \tag{2}$$

For the non-isolated case, the free velocity of the foundation can be expressed in terms of the free-field velocity measured on the ground surface before the future foundation is constructed (Fig. 2):

$$\mathbf{v}_\mathrm{f,free} = \|\mathbf{Y}_\mathrm{f}\| \cdot \|\mathbf{Y}_\mathrm{f} + \mathbf{Y}_\mathrm{soil}\|^{-1} \cdot \mathbf{v}_\mathrm{inc} \tag{3}$$

The transmitted vibrational power to the foundation, and that transmitted through the building's columns and floors, is given by:

$$\begin{aligned} \Pi_\mathrm{f} &= \frac{1}{2}\Re\left\{\mathbf{F}_\mathrm{f}^\mathrm{H} \cdot \mathbf{v}_\mathrm{f}\right\} \\ \Pi_\mathrm{b} &= \frac{1}{2}\Re\left\{\mathbf{F}_\mathrm{b}^\mathrm{H} \cdot \mathbf{v}_\mathrm{b}\right\} \end{aligned} \tag{4}$$

where the superscript "H" denotes to the Hermitian transpose operation.

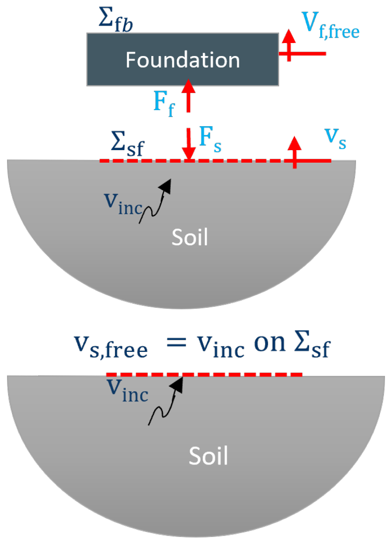

Figure 2. An overview of (bottom) the ground free vibration and (top) the free foundation vibration.

Introducing Eqn. 2 to Eqn. 4, the transmitted power can be written in terms of the measurable free vibration velocity and the mobilities:

$$\Pi_\mathrm{b} = \frac{1}{2}\Re\left\{\mathbf{v}_\mathrm{f,free}^\mathrm{H}.\mathcal{H}^\mathrm{-H}.\mathbf{v}_\mathrm{f,free}\right\} \tag{5}$$

with

$$\mathcal{H}^\mathrm{-H} = \|\mathbf{Y}_\mathrm{b} + \mathbf{Y}_\mathrm{I} + \mathbf{Y}_\mathrm{f}\|^\mathrm{-H}.\|\mathbf{Y}_\mathrm{b}\|.\|\mathbf{Y}_\mathrm{b} + \mathbf{Y}_\mathrm{I} + \mathbf{Y}_\mathrm{f}\|^{-1} \tag{6}$$

It is worth noting that, since the mobility of the foundation is independent of that of the superstructure, the total mobility is often approximated as the sum of the individual mobilities, i.e.,$\|\mathbf{Y}_\mathrm{b}+\mathbf{Y}_\mathrm{I}+\mathbf{Y}_\mathrm{f}\|^2 \approx \|\mathbf{Y}_\mathrm{b}+\mathbf{Y}_\mathrm{I}\|^2+\|\mathbf{Y}_\mathrm{f}\|^2$. This approximation neglects the phase interaction between the mobility terms but does not introduce significant errors in the calculation under the assumption of weak coupling.

1.2 Application in SSI impact and coupling loss estimation

Power flow analysis is helping to further our understanding of SSI and its significance in the response of buildings to ground-borne vibration. By analysing the mean vibrational power input to a building, it is clear that SSI must be accounted for to avoid over-predicting building vibration levels. The constraining of the soil by foundation and building structures, and the radiation damping provided by the soil to the building, all act to limit vibration levels in the building to below those predicted when SSI is neglected.

SSI should therefore be accounted for in any assessment of building base isolation. However, there is growing evidence that this may be achieved by using either simplified models or limited site measurements to estimate the coupling loss introduced by constructing a building and its foundation [2].

1.3 Application in building isolation performance evaluation

The isolation performance of a BBI system can be defined in terms of power-flow insertion gain as the ratio of the power transmitted by the isolator to the superstructure to that transmitted by a rigid connection for the non-isolated building [1]:

$$\text{PFIG [dB]} = 10\,\log_{10}\left(\frac{\Pi_{\text{b, iso}}}{\Pi_{\text{b, non-iso}}}\right) \tag{7}$$

where $\Pi_{\text{b, iso}}$ and $\Pi_{\text{b, non-iso}}$ are the total mean power flows entering an isolated and non-isolated building, respectively.

The power flow transmitted through the non-isolated building can be determined by setting the mobility of the isolator to zero in Eqn. 5, ensuring a rigid contact between the foundation and the building.

In the frequency range from 16 to 250 Hz, BIOVIB [5, 6] proposed an approximation to the PFIG formulation and justified a new performance indicator that may be more easily evaluated via in-situ measurements. Assuming that the vibration transmission is dominated by vertical vibration, and that the isolator mobility is large compared to that of the foundation, this is expressed in terms of the transmission loss (TL) through the isolator and the mobilities of the building and foundation:

$$\text{PFIG [dB]} \approx \text{TL} + 10\,\log_{10}\left(\frac{\|\mathbf{Y}_{\text{b}} + \mathbf{Y}_{\text{f}}\|^2}{\|\mathbf{Y}_{\text{b}}\|^2}\right) \tag{8}$$

The first term of Eqn. 8, the transmission loss, is defined as the ratio of the vibrational input power to that transmitted to the isolated building:

$$\text{TL [dB]} = 10\,\log_{10}\left(\frac{\Pi_{\text{b, iso}}}{\Pi_{\text{f, iso}}}\right) \tag{9}$$

This approximation offers the advantage that the vibrational power transmission into an isolated building can be obtained either through in-situ measurements or from the mobilities of the isolator and the building:

$$\text{TL [dB]} = 10\,\log_{10}\left(\frac{\|\mathbf{Y}_{\text{b}}\|^2}{\|\mathbf{Y}_{\text{b}} + \mathbf{Y}_{\text{I}}\|^2}\right) \tag{10}$$

The application of this performance indicator (Eqn. 8) within the framework of the BIOVIB project has been validated through laboratory and in-situ measurements [7, 8].

2. CASE STUDY: PERFORMANCE ASSESSMENT OF AN ISOLATED BUILDING

In the following, a hybrid experimental-numerical methodology is used to determine the parameters necessary for assessing the performance of an isolated building by means of power flow analysis. The proposed methodology has four steps:

1. Determine the mobility of the building (superstructure) using numerical calculation, such as Finite Element Analysis (FEA) in the frequency domain.

2. Determine the isolator mobility based on the dynamic characteristics of the bearings, $\mathbf{Y}_{\text{I}} = |i\omega/K^*_{\text{iso}}|$. The complex dynamic stiffness of the isolation bearing ($K^*_{\text{iso}} = K_{\text{iso}}(1 + i\eta)$) and the bearing loss factor η are defined under the specific bearing design load by a dynamic test following the procedure described in ISO 4664-1 [9].

3. Determine the substructure mobility through an in-situ hammer impact test at the bearing locations before installing the building (superstructure), following the measurement procedure described in ISO 7626 [10].

4. Measure train pass-bys at the substructure (i.e., the free vibration of the foundation) before the building (superstructure) is installed, following the measurement procedure described in ISO 14837-31 [11].

5. Measure train pass-bys on the substructure below the vibration isolation system and on the floors above it, following the measurement procedure described in ISO 14837-31 [11].

Given that the quality of the rail-wheel contact surface (a crucial factor in the induced vibrations) may degrade over time, the measured free vibration levels of the foundation or soil should be normalised using a reference vibration level recorded at a point near the source, before calculating the contact force in the completed building using Eqn. 2.

This methodology is examined for the real case study of a two-story building constructed on footings adjacent a railway station in Barcelona. The building is isolated on elastomeric bearings on top of the foundation footings.

2.1 Mobility of the building (super-structure)

To determine the mobility of the building, a Finite Element (FE) model of the superstructure is developed. Since the building structure exhibits a repeated section along its length, a section of building perpendicular to the track with three supports is modelled (Fig. 3). A unit force is applied at each support, and the building response — both at the same support and at the other supports — is calculated to enable the assembly of the building's $N \times N$ mobility matrix, $\mathrm{Y_{b,ij}} = \mathrm{v_{b,j}}/\mathrm{F_{b,i}}$, where N represents the number of bearing locations.

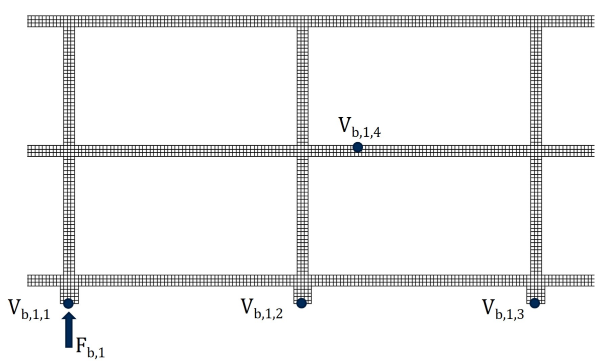

Figure 3. 2D - Finite Element modeling of the building.

Figure 4 shows the direct mobility (the diagonal terms) at each isolator location. Despite the peaks and troughs caused by the bending modes of the structure, the building mobility is primarily dominated by the mass effect, expressed as $\mathrm{Y_b} \approx |1/\omega \mathrm{M_b}|$.

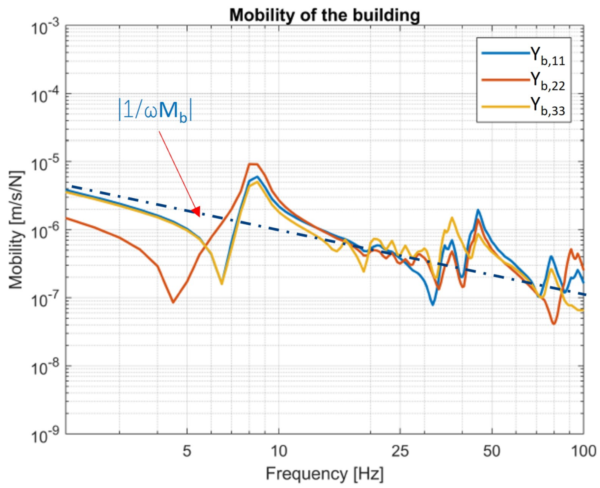

Figure 4. The mobility of the building calculated by FEA.

2.2 Mobility of the foundation (sub-structure)

In the second step, an in-situ measurement campaign is carried out to obtain the foundation mobility using an instrumented hammer, following the measurement procedure described in ISO 7626 [10]. At each bearing location, the mobility of substructure is obtained by applying a hammer impact at each bearing location and measuring the substructure response at the impact location as well as at the other supports. The mobility of the substructure is then assembled as an $N \times N$ matrix, $\mathrm{Y_{f,ij}} = \mathrm{v_{f,j}}/\mathrm{F_{f,i}}$.

In this case study, since the footings are similar, the mobility has been measured only at one of the footings, and only the direct mobility is taken into account. The cross-mobility between the horizontal and vertical foundation responses has been found to be negligible relative to the direct mobility, as illustrated in Fig. 5.

The building is isolated using steel reinforced rubber bearings (type Stravibase VHS) installed between the concrete distribution beams of the superstructure and the footings, as shown in Fig. 6. The measured dynamic stiffness, including the loss factor of the bearings (under the design load), has been used to determine the mobility of isolator at each support. The isolation bearings are designed to exhibit a rigid-body resonance frequency of 10 Hz under the Acoustic design load (in an equivalent SDOF system). Figure 7 shows the averaged vertical mobility of the foundation, as well as that of the building and isolator at each

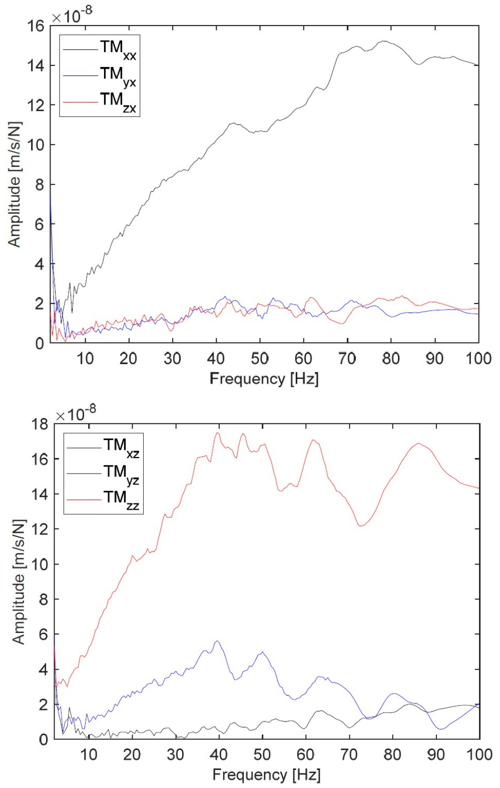

Figure 5. (Top) The three components of the foundation mobility measured under horizontal impact; (Bottom) The three components of the foundation mobility measured under vertical impact.

Figure 6. The isolation bearing, type Stravibase VHS, installed between the concrete distribution beams and the footings.

bearing location. The comparison clearly shows that, at frequencies above 30 Hz, the building and isolator mobilities dictate the foundation-isolator-building behavior that governs the transmission mechanism.

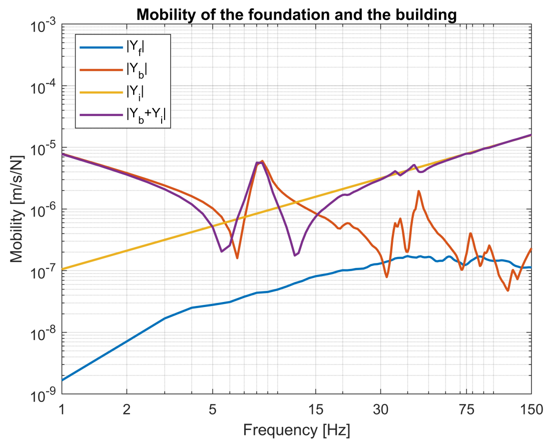

Figure 7. The average measured vertical mobility of the foundation (blue line) compared with the calculated mobility of the building superstructure (red line) and the measured isolator mobility (orange line).

2.3 The building and foundation responses due to train pass-bys

Train pass-bys were measured at different stages of construction, following the measurement procedure described in ISO 14837-31 [11]:

1. After the foundation construction and before the building superstructure installation, on the foundation, to measure the foundation's free vibration.

2. After the building construction, to measure the isolated building response at both the substructure and superstructure levels.

In the first phase, train pass-bys were measured on top of the foundation. The vibration level on the free foundation is used, to evaluate the coupling loss considered in the early-stage vibration study, and to apply any final adjustments to the isolation design before installation, if required.

In the second phase, the building and foundation vibration levels were measured after the building was completed and furnished, once the bearings had received their intended design load, for which their performance was optimized.

During each phase, train pass-bys were recorded simultaneously at a reference point near the railway, to normalize the building's performance, making it independent of any changes in the source strength.

Figure 8 displays the spectra of the train pass-by vibrations measured on the foundation before the installation of superstructure and those measured at the end of construction on the ground floor (above the vibration cut) and on top of the foundation (below the vibration cut).

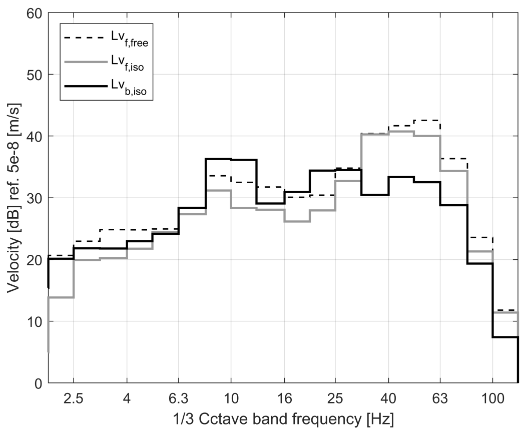

Figure 8. The average train pass-by vibrations measured on top of the free foundation (dashed line), and those measured after completion of the building at the foundation (grey line) and on the ground floor (black line).

A comparison is presented in Fig. 9 between the estimated power flow transmitted to the non-isolated building (i.e., on rigid supports) and that of the building supported by the designed isolation bearings. The power flow is calculated using Eqn. 4, while the interaction force is obtained from Eqn. 2 using the measured foundation free vibration $\mathbf{v}_{f,free}$. Since the non-isolated building is not physically available, Equation 2 has also been used to estimate the building vibration for the non-isolated case.

In Fig. 10, the direct PFIG, defined in Eqn. 7, is compared with the performance indicator established by BIOVIB (Eqn. 8). Despite a reasonable correspondence

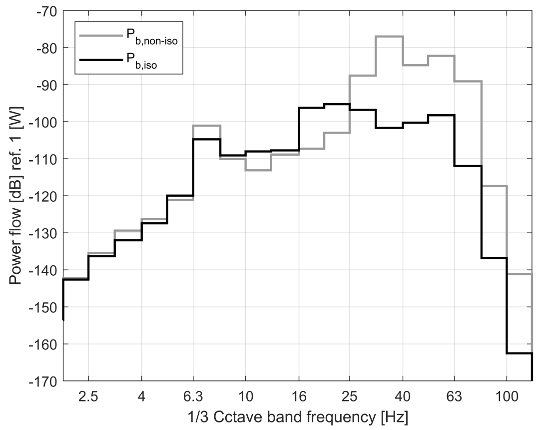

Figure 9. The power flow transmitted through the non-isolated building (gray line) and isolated building (black line).

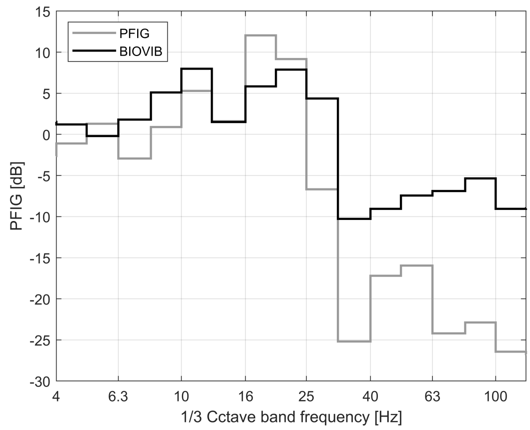

Figure 10. The power flow transmitted through the non-isolated building (gray line) and isolated building (black line).

at frequencies below 25 Hz, reflecting the isolation system's resonance around 10 Hz and the dominant bending modes of the building floors at 20–25 Hz, at higher frequencies, the direct PFIG indicates a higher level of isolation than the BIOVIB indicator. This discrepancy appears to be due to an overestimated vibration level for the non-isolated building, calculated (rather than measured) using Eqn. 5, which may be due to an inaccurate estimation of the building mobility at higher frequencies.

3. CONCLUSIONS

This paper has illustrated the use of power flow analysis for quantifying the vibration transmission into a building, as an effective basis for isolation design. The analysis is based on a hybrid approach that estimates the mobility of the substructure (foundation and ground) and isolation system via measurement, and that of the superstructure via calculation (Finite Element Analysis). The work is part of ongoing research aimed at developing practical guidance for designing building base isolation solutions.

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