In-situ performance prediction of base-isolated buildings

Trévisan Benjamin, Grau Loïc & Bozzetto Denis
Acouphen-acoustic design office, France.
Villot Michel, Jean Philippe
Health & Comfort Department, CSTB, France.

Summary
Noise is one of the main causes of disturbance in buildings. Indeed, the acoustic comfort is clearly linked to the insulation of any receiving room from the other rooms and from the outside. Railway traffic can generate structure-borne noise, i.e. noise induced by vibration of floors, walls and ceilings. Between source and building rooms, such vibration propagates through soil, building foundation and building structures. Separating the foundation from the rest of the building with a resilient material constitutes a good solution to reduce structure-borne noise. The European BIOVib project (Building Insulation against Outdoor Vibrations) aims at quantifying and predicting the *in-situ* performance of such isolators in term of an isolator performance indicator based on the structural power transmitted (called Power Flow Insertion Gain, PFIG), and a building performance indicator based on the building floor responses (called Building Insertion Gain Indicator, BIGI). In this paper, these two indicators are estimated and compared in the simple case a 2D ground/building configuration: the PFIG is estimated using a simplified vibrational model based on mobility, taking into account isolator, source (building foundation and ground) and receiving structure dynamic properties, and limited to vertical vibrations only; the floor velocities and the BIGI are numerically estimated using the CSTB ground/structure interaction software MEFFISTO. The results show that the simplified vibrational model based on mobility leads to an acceptable estimation of the building performance.

PACS no. 43.30.+s

1. Introduction

This paper is focused on noise induced by vibration of building structures due to railway traffic. Such ground-borne noise can be reduced by inserting isolators at the base of the building. The isolator performance is usually simplistically estimated through the dynamic transmissibility of a single degree of freedom mass-spring oscillator, which overestimates the performance [1, 2]. Expressing the performance in terms of Power Flow Insertion Gain (PFIG), based on power [1], is more correct and useful, particularly if several wave types are involved.
A first study on this subject was performed at CSTB a few years ago and presented at a conference [2]. In this study, a simplified method for quantifying and predicting the PFIG was proposed, using a vibrational model based on mobility, taking into account isolator, source (building foundation and ground) and receiving upper-structure dynamic properties, and limited to vertical vibration only. The principle of this method is briefly presented in section 2 of the present paper.
Since, more work has been done in the frame of BIOVib, an on-going Eurostar project [3] on ground-borne noise mitigation measures in buildings. In this project, one of the main ideas consists of: (i) expressing the (treated) building performance as an insertion gain (BIGI, Building Insertion Gain Indicator) defined from the building floor velocity responses (without and with isolators), which are closely related to the human response to railway vibration and vibration induced noise according to ISO 14837-31 [4], and (ii) predicting the above performance from the *in-situ* isolator performance expressed as PFIG and estimated using the simplified method based on mobility and proposed in [2].
In the present paper, this simplified performance prediction method is validated in the simple case of a 2D ground/building configuration (the same

as the one used in [2]) numerically calculated using the CSTB ground structure vibration interaction software MEFISSTO [5]. First the 2D numerical model is described (section 3) and then, the performances of the isolators (PFIG) and the building (BIGI) are calculated and compared (section 4).

2. Principle of the mobility method

2.1. Isolator performance definition

The mitigation measure consists in inserting an isolator between source (building foundation) and receiver (building upper-structure). Assuming one contact between source and receiver and a dominant vertical vibration transmission, the system can be dynamically modelled as shown in Figure 1. The performance can be expressed [1, 2] as a Power Flow Insertion Gain (PFIG) in dB defined from the ratio between the vibration power flows transmitted to the receiver with and without the isolator:

$$PFIG = 10\ log\left(\frac{\Pi_{isol}}{\Pi_{unisol}}\right) \qquad (1)$$

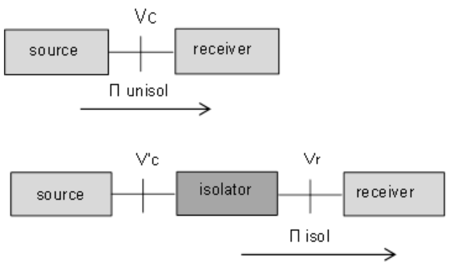

Figure 1. Source-receiver isolated system.

2.2. Isolator performance calculation

Source, receiver and isolator can be characterized by their mobility Y (ratio between velocity response and force applied) as show in Figure 2.

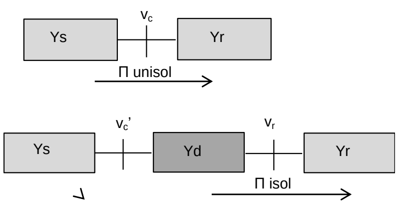

Figure 2. Source-receiver isolated system; mobilities.

The powers $\prod_{isol}$ and $\prod_{unisol}$ can be written as:

$$\Pi_{isol} = v_{r,rms}^2.\mathrm{Re}(Y_R)/\left|Y_R\right|^2 \qquad (2)$$

$$\Pi_{unisol} = v_{c,rms}^2.\mathrm{Re}(Y_R)/\left|Y_R\right|^2 \qquad (3)$$

which leads to:

$$PFIG = 10.\lg(v_{r,rms}^2 / v_{c,rms}^2) \qquad (4)$$

The PFIG can be simply estimated from the ratio of the receiver contact velocities with and without isolators. Of course, this formula cannot be used in reality since the un-isolated configuration does not exist; but in the case of a numerical model, both un-isolated and isolated configurations can be modelled and the velocities numerically determined.

3. Numerical model

3.1. Ground building configuration

A 2D ground/building numerical model has been used for validation; the calculations were fast and the 2D configuration assumed realistic enough.

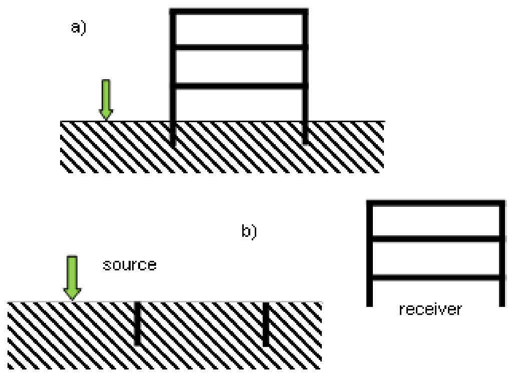

Figure 3. 2D ground building configurations considered

The 2D ground/building configuration is given in Figure 3-a. The building is excited by a vertical force at the ground top surface and mitigated by inserting an elastic layer at the two contacts. The system is now a two-contact source/receiver system, where the velocities at each contact can be numerically determined. Moreover, the floor velocities can also be numerically determined and the Building Insertion Gain Indicator (BIGI), defined as the ratio between the un-isolated and isolated floor velocities, calculated as:

$$BIGI = 10\ log\left(\frac{v_{floor,rms,isol}^2}{v_{floor,rms,unisol}^2}\right) \qquad (5)$$

The system can be separated into a source and a receiver as indicated in Figure 3-b where:

- the source (ground-foundation) configuration allows numerically estimating the source point mobility Y_S (ratio velocity/force when a force is applied on top of the foundation)
- the disconnected building upper-structure allows numerically estimating the receiver point mobility Y_R (ratio velocity/force when a force is applied at the foot of the upper-structure).

However, both longitudinal and bending waves are present and the system is a two-contact source/receiver system. Equations (2) to (4) can be considered in two ways: (i) a simplified way where only vertical vibration transmission is considered and the coupling between the two contacts ignored; (ii) an exact (reference) modelling where both the three degrees of freedom (two translations and one rotation) present at each contact and the coupling between contacts are considered.

3.1.1. Simplified way

In this case, only the vertical velocities $v_{c,rms}$ and $v_{r,rms}$ are numerically determined at each contact (configuration in Figure 3-a), the source point mobility Y_S (source configuration in Figure 3-b) is reduced to vertical vibration transmission by only considering vertical force and vertical velocity response, the receiver point mobility Y_r (receiver configuration in Figure 3-b) is also reduced to vertical vibration transmission and equation (4) can be used at each contact, thus leading to two "local" simplified PFIG.

3.1.2. Exact (reference) modelling

In this case, the PFIG, thanks to its power-based definition, can be estimated from the total power transmitted to the building upper structure with and without isolators.

Any power is now obtained through a matrix equation:

$$\mathbf{\Pi} = \frac{1}{2}\mathrm{Re}\left(\boldsymbol{Y_R^{-1}}\right)|\boldsymbol{v}|^2 \qquad (6)$$

This equation takes into account two translations (horizontal and vertical, respective notations: x and y), one rotation (notation: α) and the two contacts (notations: 1 (left) and 2 (right)). Power and velocity become the following six-component vectors and the receiver mobility becomes the following (6 x 6) simplified matrix, assuming the receiver response to wave types other than the one excited uncorrelated:

$$\mathbf{\Pi} = \begin{pmatrix} \Pi_x^1 \\ \Pi_y^1 \\ \Pi_\alpha^1 \\ \Pi_x^2 \\ \Pi_y^2 \\ \Pi_\alpha^2 \end{pmatrix}; \qquad \boldsymbol{v} = \begin{pmatrix} v_x^1 \\ v_y^1 \\ v_\alpha^1 \\ v_x^2 \\ v_y^2 \\ v_\alpha^2 \end{pmatrix} \qquad (7)$$

$$\boldsymbol{Y_R} = \begin{pmatrix} Y_{11}^{xx} & 0 & 0 & Y_{12}^{xx} & 0 & 0 \\ 0 & Y_{11}^{yy} & 0 & 0 & Y_{12}^{yy} & 0 \\ 0 & 0 & Y_{11}^{\alpha\alpha} & 0 & 0 & Y_{12}^{\alpha\alpha} \\ Y_{21}^{xx} & 0 & 0 & Y_{22}^{xx} & 0 & 0 \\ 0 & Y_{21}^{yy} & 0 & 0 & Y_{22}^{yy} & 0 \\ 0 & 0 & Y_{21}^{\alpha\alpha} & 0 & 0 & Y_{22}^{\alpha\alpha} \end{pmatrix} \qquad (8)$$

Note that the $\boldsymbol{Y_R}$ matrix is symmetrical, like the 2D building studied. The total power flow for the i[th] contact point is given by adding energetically the contributions of each degree of freedom (two translations and one rotation):

$$\Pi^i = \Pi_x^i + \Pi_y^i + \Pi_\alpha^i \qquad (9)$$

And the total power flow transmitted to the building is given by energetically adding the contributions of each contact:

$$\Pi_{tot} = \Pi^1 + \Pi^2 \qquad (10)$$

The transmitted power flow for the un-isolated case is calculated as:

$$\mathbf{\Pi}^{unisol} = \frac{1}{2}\mathrm{Re}\left(\boldsymbol{Y_r^{-1}}\right)|\boldsymbol{v_c}|^{\mathbf{2}} \qquad (11)$$

and for the isolated case:

$$\mathbf{\Pi}^{isol} = \frac{1}{2}\mathrm{Re}\left(\boldsymbol{Y_r^{-1}}\right)|\boldsymbol{v_r}|^{\mathbf{2}} \qquad (12)$$

Equations (10) to (12) allow calculating the reference PFIG:

$$PFIG_{ref} = 10\ log\left(\frac{\Pi_{tot}^{isol}}{\Pi_{tot}^{unisol}}\right) \qquad (13)$$

3.2. BEM FEM numerical model

The CSTB BEM-FEM ground structure vibration interaction model (MEFISSTO software, [5]) has been used. With the FEM (Finite Element Method) the entire domain considered is meshed whereas with the BEM (Boundary Element Method) only the domain boundaries are meshed which in 2D leads to meshing simple contours. The basic configuration consists of a half space ground

(BEM approach) and a building (FEM) with building elements either underground or above ground. Although the ground surface is of infinite extend, in practice only a limited portion of it is meshed beyond the area of interest; this is possible because of the strong absorption in the ground. Continuity of displacement and stress is assumed at common boundaries between domains.

FEM and BEM calculations are performed in narrow frequency bands, but all the frequency spectra given in this paper are expressed in a more robust way in 1/3 octave bands, compatible with common vibration or noise measurement results in buildings.

3.3. Geometry and material characteristics

Details of the geometry of the ground-building configuration studied are given in Figure 4.

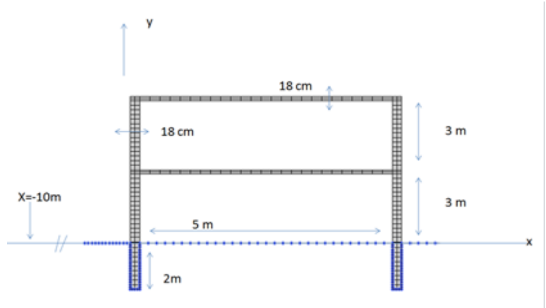

Figure 4. Ground building configuration: geometry

The material characteristics [2] for ground, concrete and the 6 cm thick elastic layer are given in Table I. The excitation force is located at 4m from the building.

Table I. Material characteristics from [2].

	Young modulus	*Loss factor*	*Density*	*Poisson's ratio*
Ground	270 Mpa	0.10	1500 kg/m^{-3}	0.26
Concrete	28 GPa	0.01	2400 kg/m^{-3}	0.15
Resilient	6 MPa	0.10	1100 kg/m^{-3}	0.26

The elastic layer dynamic stiffness K has been chosen as follows:

$$K = E.S/e \qquad (14)$$

where E is the Young modulus given in Table 1, S the layer surface area (0.18 x1 m^2 in the 2D geometry chosen) and e its thickness (6cm), which leads to K=18000 kN/m per meter length for each contact point. The weight of the upper-structure is close to M=4750 kg per meter length, which leads to the following resonance frequency (assuming the upper-structure a lump mass in vertical movement only):

$$f_r = (1/2\pi).\sqrt{K/M} \approx 10Hz \qquad (15)$$

4. Results

4.1. Evaluation of performances in terms of BIGI and PFIG

Five 1/3 octave spectra are represented in Figure 5:

- the building performance (BIGI) in dB, numerically calculated using equation (5),
- the "exact" reference PFIG in dB, calculated using equations (10) to (13), for which the six velocity components of vectors $\boldsymbol{v}_\mathbf{c}$ and $\boldsymbol{v}_\mathbf{r}$ and the nine mobility components of matrix $\boldsymbol{Y}_\mathbf{r}$ have been numerically "measured" using MEFISSTO.
- the two "local" simplified PFIG in dB, calculated according to section 3.1.1, and the mean value of the two corresponding power ratios, expressed in dB.

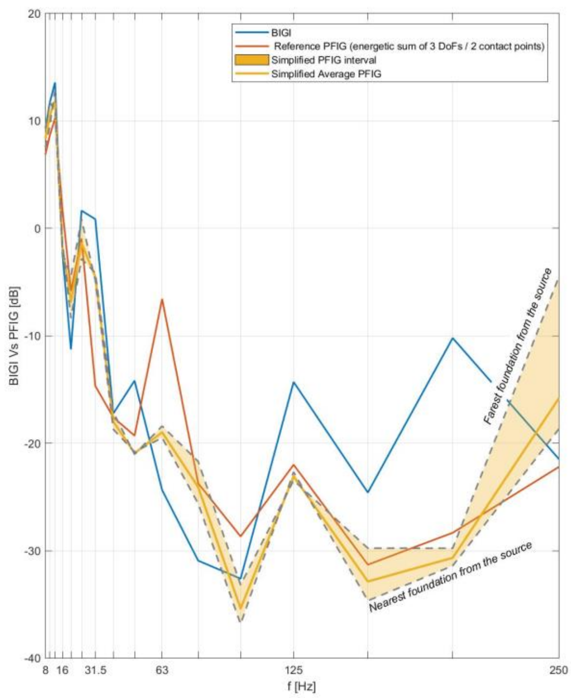

Figure 5. Comparison between the BIGI, the reference PFIG, the two "local" simplified PFIG and their mean value.

The results show that PFIGs and BIGI are around the same order of magnitudes even if differences appear, increasing with frequency.
The following comments can be made:

Firstly, all the spectra agree on a resonance frequency at 1/3 octave 12 Hz, which is close but above the resonance expected at 10 Hz if a simplistic mass spring model is used for prediction.
Secondly, the “local” simplified PFIGs become clearly different at frequencies above 125Hz (yellow area in Figure 5), the local PFIG at the nearest foundation being more performant. As a consequence, the mean simplified PFIG is closer to the local PFIG at the nearest foundation and overestimates the building performance in this frequency range (above 125Hz).
Thirdly, the mean simplified PFIG (yellow curve) is surprisingly rather close to the reference PFIG (red curve) and mainly follow the same tendencies, except at 1/3 octave 63 Hz.
Note that the difference between BIGI and PFIG were expected since the BIGI only represent a local floor performance reduced to bending wave only, and not the entire building vibrational energy.
In order to decide if all these estimations of performance were close enough to be acceptable, their single number values have been calculated in terms of sound pressure level in dB(A), as explained in the next section.

4.2. Performance in terms of single number value

According to [6], ground-borne noise radiated from the floor can be obtained from space average floor velocity using a frequency dependent power-based linear relationship between ground-borne noise level and floor vibration velocity level, the key parameter being the floor radiation efficiency. As a result, the performance spectrum obtained for the base-isolated building in terms of floor velocity using equation (11), can also be applied to the ground-borne noise radiated; and the latter quantity can easily be expressed by a single number value in dB(A).
Let’s consider an un-isolated building, for which the measured noise spectrum (in black in Figure 6) leads to a global sound pressure level $L_{p,A,Smax} = 36.7\,\mathrm{dB(A)}$ from 16 to 250 Hz. Applying the performances plotted in Figure (5) to this noise spectrum leads, after isolating the building, to the noise spectra shown in Figure (6).
The results show the effect of building base isolation on noise perceived in the building, which decreases from 36.7 dB(A) (un-isolated building) to around respectively 22 dB(A) (isolated building, estimated from the BIGI), 21 dB(A) (isolated building, estimated from the reference PFIG) and 19 dB(A) (isolated building, estimated from the mean simplified PFIG).
All these estimated performances lead to global sound pressure values within 3 dB(A). Considering that measurement uncertainties are usually around 3 dB(A), these estimations can be considered as all acceptable, including the simplified one.
Note again that both PFIG estimations overestimate the performance compared to the BIGI.

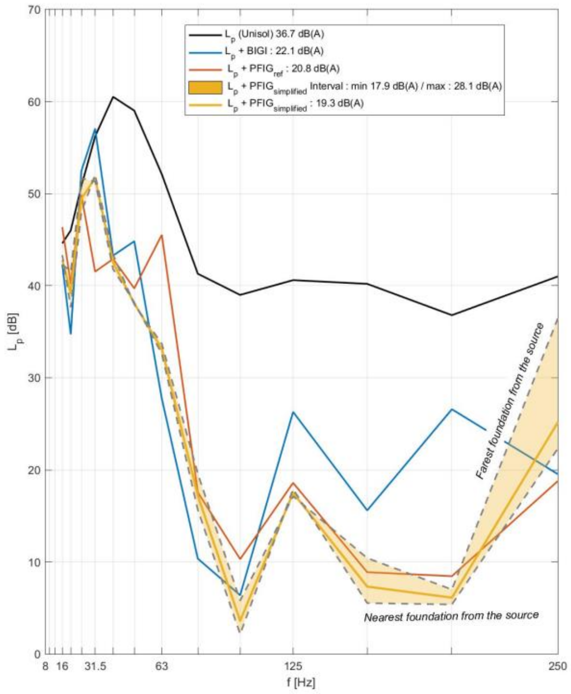

Figure 6. Measured noise level Lp in the un-isolated building (in black) and estimated noise levels after base isolation.

5. Conclusions

This paper shows that the performance of building base isolation can be estimated using either an onsite building performance expressed as frequency dependent insertion gain in terms of floor velocity (BIGI), closely related to the human response to vibration or to vibration induced noise, or an onsite isolator performance expressed as frequency dependent insertion gain in terms of vibrational power transmitted to the building upper-structure (PFIG). Applying this approach numerically to a simple 2D ground/building configuration has shown that the BIGI and the exact PFIG lead to single number values of ground-borne noise in isolated building within 1dB(A) and that even a PFIG reduced to "local" vertical vibration and averaged over the contact points between source (embedded building foundation) and receiver (isolated building upper-structure) could be acceptable, leading to single number values within 3dB(A).

The next step consists in applying this approach to real buildings, i.e. in measuring onsite local simplified PFIGs at several locations where the isolators are installed and averaging them over in order to obtain an estimate of the building performance. Of course, there are too many contact points in reality to measure them all, but a limited number of representative locations could be chosen. These simplified PFIGs could be indirectly obtained from the isolator transmissibility locally measured on site and knowledge of the local point mobility of the building structures on both sides as proposed in [2]. A paper on this subject will soon be submitted to a journal.

Acknowledgement

The authors thank BPI France and the Eurostar program for financially supporting the BIOVib project [3].

References

[1] Talbot, J.P., Hunt, H.E.M.: "On the performance of base-isolated buildings". *Build. Acoust.*, **7** (3), 2000, p. 163–178.

[2] Villot, M., Jean, P.: "Railway vibration: Predicting the field performances of mitigation measures in buildings". In: Eurodyn 2014, International Conference on Structural Dynamics. Porto, 2014.

[3] Eurostars BIOVib project, 'Building Insulation against Outdoor Vibration', Sept 2017. - March 2019. Partners: Belgian manufacturer CDM and French consultancy company ACOUPHEN. EUROSTARS call 17 number 11 420 - BIOVib agreed by the European Union.

[4] ISO/TS 14837-31:2017 - Mechanical vibration -- Ground-borne noise and vibration arising from rail systems -- Part 31: Guideline on field measurements for the evaluation of human exposure in buildings.

[5] Jean, P.: "Boundary and Finite Elements for 2D Soil-Structure Interaction Problems". *Acta Acust. United Acust.*, **87** (1), 2001, p. 56–66.

[6] Villot M., Jean P., Grau L. and Bailhache S., "Predicting railway-induced ground-borne noise from the vibration of building elements using power-based building acoustic theory", International Journal of Rail Transportation, 2018, Vol. 6, N° 1, 38-54.