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# ON PREDICTING STRUCTURE-BORNE SOUND IN BUILDINGS GENERATED BY GROUND VIBRATION SOURCES

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**ABSTRACT**

Prediction methods are required for designing buildings to protect inhabitants against ground-borne (structure-borne) noise from railway lines or other outdoor ground vibration sources, according to national regulations, guidelines or recommendations. There is no European standard for such predictions yet, but a European task group (CEN/TC126/WG2/TG1) is now doing preliminary work on this subject. A recent standard (EN ISO 20270) on field characterization of vibration sources opens a way for tackling the problem, based on the source-receiver vibration system methodology and using a mobility approach. In this paper, the approach is applied to ground-borne sound in buildings, where the building foundations in contact with ground are considered as the source and the building upper-structure the receiver. Two challenges are identified: one concerns the transmission of vibration power to the building upper-structure not only by flexural waves as with service equipment, for which a standardized prediction method exists, but also by in-plane waves; the second challenge arises from the complexity of the ground vibration field and the coupling between ground and building foundations, leading to difficulties in estimating the source activity.

**Keywords:** *ground-borne sound, source-receiver vibration system, mobility-based approach.*

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## 1. INTRODUCTION

Prediction methods are required for designing buildings to protect inhabitants against ground-borne (structure-borne) noise from railway lines or other ground vibration sources, according to national regulations, guidelines or recommendations. There is no European standard for such predictions yet, but a European task group (CEN/TC126/WG2/TG1) is doing preliminary work on this subject. This technical committee deals with building acoustics and only ground-borne sound (usually of frequency range 16-250 Hz) will be considered.

Other prediction methods have been developed in building acoustics within CEN/TC126/WG2, all using a power-based (SEA) approach, and among them, a method predicting the sound generated by service equipment (i.e. indoor airborne and structure-borne sound sources), recently standardized (EN ISO 12354-5, [1]). Could a similar approach be applied to predicting ground-borne sound? The approach is briefly presented and the question answered in Section 2.

Moreover, a recent standard (EN ISO 20270, [2]) on field characterization of structure-borne sound sources opens a way for tackling the problem of vibration immission to building. Using the source-receiver vibration system methodology, this characterization method could be applied to ground-borne sound immission to buildings, where the building foundations in contact with ground would be considered as the source and the building upper-structure the receiver. The standard and its application to ground-borne sound in buildings are presented and discussed in Section 3, from which the bases of a prediction method are deduced (in Section 4).

## 2. APPROACH USED FOR SERVICE EQUIPMENT

### 2.1 Case of service equipment

In EN 12354-5, three methods are suggested to estimate the sound pressure level generated in buildings by service equipment considered as a structure-borne sound source (SSS):

- Two methods are based on the use of EN ISO 12354-2 [3], which estimates impact sound level in building (see [1]). EN ISO 12354-2 is limited to sources generating flexural waves (SSS located in the middle of the element with applied forces perpendicular to the element) and to sound transmission to nearby rooms only (see Fig.1).

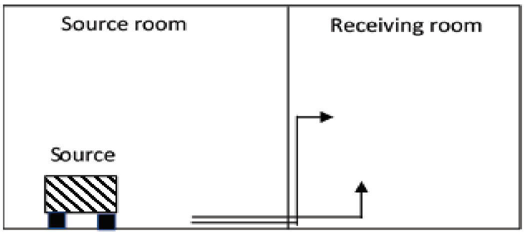


**Figure 1**. Example of configuration in EN 12354-5; the arrows indicate flanking paths.

- A third method suggests to create a data base of measured sound pressure levels transmitted to the room of interest and produced by a unit power SSS connected to the building element of interest. Knowing the power injected by any other source, the corresponding sound pressure level transmitted to the room can then be deduced. The receiving room can be far away from the excited building element and the method potentially applicable to a building excited at his base by outdoor ground vibration, assuming the power injected is known (see Section 4).

### 2.2 Case of outdoor ground vibration sources

In this case, structure-borne sound is generated in the building by ground-borne vibration transmitted first to the building structures in contact with ground (building foundations) and then to the building upper structure, which radiates sound in rooms (called ground-borne sound). The ground/building configurations are usually not simple (see Fig.2) nor is the ground vibration field exciting the building, which depends on the source type (point or line source in particular) and its location (at ground surface or underground in particular). Fortunately, a solution for handling this quite complex problem has been given in a recent ISO standard dealing with field measurement of complex SSS (EN ISO 20270, [2]). This standard is explained in Section 3.

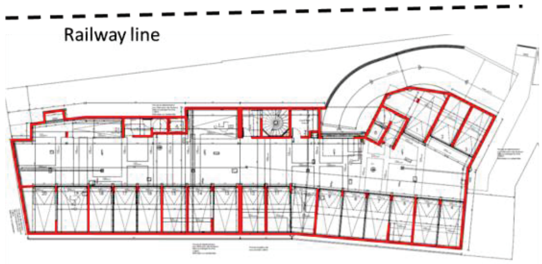


**Figure 2**. Example of building configuration next to a railway line (horizontal layout) [4]

Moreover, an ISO standard dealing with measuring and evaluating ground-borne sound in buildings already exists for the case of railway sources (ISO 14837-31, [5]) and gives useful information on the subject: (i) it defines the quantities for evaluating human exposure in buildings ($L_{pASmax}$ for sound levels in rooms and $L_{vSmax}$ for vibration levels on floors, both being the "preferred" quantities), (ii) it mentions that ground-borne sound measurements can be erroneous because of high back ground noise or the presence of outdoor airborne noise transmitted to the room through the façade, (iii) it recommends estimating ground-borne sound from floor vibration and explains in an (informative) annex how to do it, (iv) it separates vibration immission to building into a "building coupling loss", defined as vertical vibration level difference between the ground surface without building and the building foundations, and a "building transmissibility", defined as vertical vibration level difference between building foundations and floors.

## 3. METHODOLOGY SUGGESTED IN EN ISO 20270

### 3.1 Defining/choosing the interface between the source and the receiver

EN ISO 20270 deals with source-receiver vibration systems and their field characterization. The quantity measured is the source "blocked force", i.e. the contact force applied to the receiver (see Fig.3) when the receiver is rigid and "blocks" the source; this quantity is a source characteristic.
The internal source S shown in Fig.3 is unknown (usually not accessible and/or complex) and the source is characterized at a hypothetical source-receiver interface, chosen in the sake of practicality.

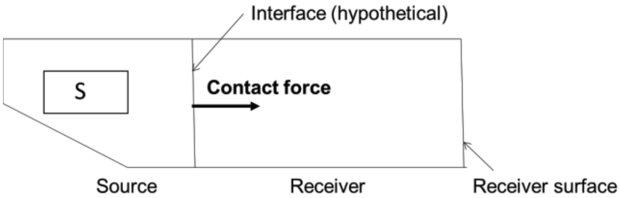


**Figure 3**. Source-receiver vibration system (from EN ISO 20270)

Applying the approach to ground-building configurations leads to choose the interface between building foundations (the source) and building upper-structure (the receiver) on the horizontal surface, where building base isolators would be located if the building were isolated against outdoor vibration, often just below the ground floor (red line in Fig.4). This choice will allow dealing with building base isolators later on. The contact zone is not simple, made of building façades, walls and pillars cut horizontally (structures in red in Fig.3).

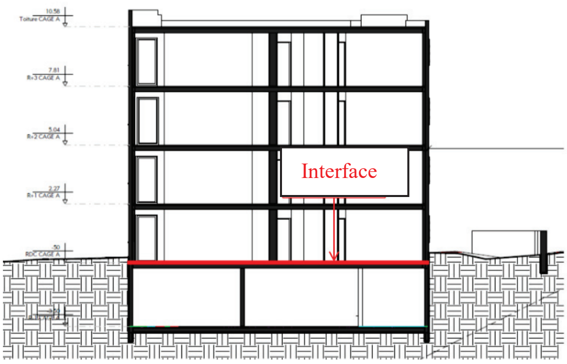


**Figure 4**. Vertical cut of the building in Fig.3 [4].

### 3.2 Method for determining the source blocked force

The principle of the method is the following (see Fig.5): the forces and velocities involved are vectors, taking into account the number of excitation points, the number of measurement points, and the number of degrees of freedom (DOF) at each point considered.

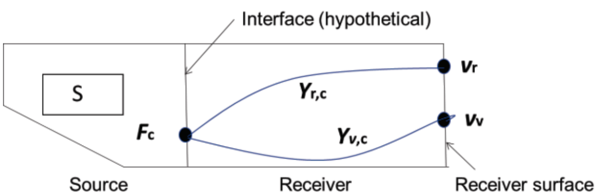


**Figure 5**. Quantities measured in EN ISO 20270.

The measurement procedure is performed in two steps: (i) with the source operating, the indicator velocity vector $\boldsymbol{v}_{\mathbf{r}}$ and the validation velocity vector $\boldsymbol{v}_{\mathbf{v}}$ are measured at different locations on the receiver; (ii) with the source switched off, the transfer mobility matrices $\boldsymbol{Y}_{\mathbf{r,c}}$ and $\boldsymbol{Y}_{\mathbf{v,c}}$ are measured. The blocked force vector $\boldsymbol{F}_{\mathbf{bl,c}}$ is then calculated as:

$$\boldsymbol{F}_{\boldsymbol{bl,c}} = \boldsymbol{Y}_{\boldsymbol{r,c}}^{-1}.\boldsymbol{v}_{\boldsymbol{r}} \tag{1}$$

where the exponent -1 indicates an inversed matrix. The validation consists in estimating the validation vector $\mathbf{v'_v}$ as:

$$\boldsymbol{v}'_{\boldsymbol{v}} = \boldsymbol{Y}_{\boldsymbol{v,c}}.\boldsymbol{F}_{\boldsymbol{bl,c}} \tag{2}$$

and comparing the estimated velocity $\mathbf{v'_v}$ to the measured velocity $\mathbf{v_v}$.

### 3.3 Applying the method to ground-building systems

#### *3.3.1 Excitation and measurement point locations*

The interface being chosen (see Section 3.1), contact lines (walls) and contact points (pillars) are identified (red lines and points in Fig.2), on which excitation contact points must be chosen in order to measure the transfer mobility matrices indicated in Fig.5.

The receiver being the building upper-structure, it seems interesting to choose the velocity measurement points on the floors of the building upper-structure, and measure floor vertical velocities (only one DOF!) corresponding to flexural waves. Such a transfer mobility matrix characterizes indeed the structure-borne sound transmission through the building. In a second step, the ground-borne sound radiated in the room can be estimated from the floor velocity as suggested in ISO 14837-31.

#### *3.3.2 Contact force vector*

In general, both in plane (longitudinal) and flexural waves can be present at the interface, thus leading to both vertical contact forces and flexural contact moments (see Fig.6); indeed, the horizontal contact forces most likely generate little power, because applied near the junction, where a low input mobility is expected, and are therefore neglected.

Wave types at contacts between building foundations and building upper-structure have been numerically studied some time ago in the case of a simplified 2D ground-building system: the in-plane wave power generated by the vertical contact forces seemed to be dominant [6] and the performance of elastomeric mounts or springs inserted between building foundations and building upper-structure were rather well approximated by a power flow insertion gain, calculated from vertical contact forces only [7].

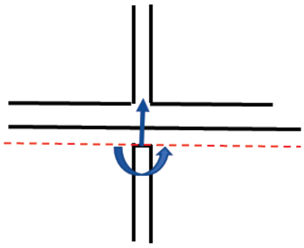

**Figure 6**. Contact force and moment in the case of a wall-floor junction (interface in red).

The contact force vector seems therefore (hopefully) reduceable to vertical forces only, applied at contact points distributed among the contact lines and points indicated in red in Fig.2. Consequently, the blocked force vector estimation (according to Eqn. (1)) becomes easier, the transfer mobility matrices being limited in size to the product (number of excitation points) x (number of velocity measurement points). If the outdoor ground vibration source and the building exist, the source blocked force can therefore be determined according to EN ISO 20270.

## 4. BASES FOR A PREDICTION METHOD

### 4.1 Estimating the building floor velocities

Equation (2) is an interesting way of predicting the floor velocities, if the transfer mobility matrix $\boldsymbol{Y}_{\mathbf{v,c}}$, which characterizes the structure-borne sound transmission through the building is known, as well as the source blocked force vector. But how could the latter quantity be predicted? Estimating the source blocked force from the other source characteristics (i.e. the source free velocity and input mobility [8]) might be the solution, as explained in the next sections.

### 4.2 Source free velocity vector

The source free velocity vector is another source characteristic [8], which corresponds to the contact velocity vector when the receiver is very soft and "frees" the source. It can be measured if the outdoor ground vibration source (or an artificial source) is operational and the building foundations built, but not the building upper-structure on top (see Fig.7, top).

For prediction, the (vertical) velocity of the ground surface before constructing the building is usually known (measured or estimated). This quantity takes indeed into account the ground vibration source type and location, as well as the ground type (including the presence of deep hard layers). Measurement positions can be chosen at points where the building foundations will be built (see Fig.7, bottom).

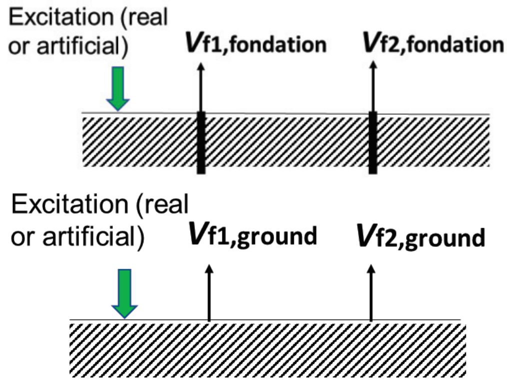


**Figure 7**. 2D schematic example of ground and building foundation velocity measurement configurations; green arrow: ground surface vibration source (real or artificial)

Could the source free velocity vector be estimated from the ground "free of building" velocity? The answer is positive, at least in terms of an averaged value, empirically obtained from a data base of the "building coupling loss" suggested in ISO 14837-31. It could be also obtained more precisely by calculation, based on comparisons between the ground input mobility and the building foundations input mobility (see Section 4.3). Nevertheless, a shape factor, taking into account the shape of the building foundations will probably be necessary, the same way as a shape factor is used in calculating building façade sound insulation, if the façade is not flat (for example with balconies) [9].

### 4.3 Source input mobility matrix

The third source characteristic is the source input mobility matrix $\boldsymbol{Y}_{\mathbf{Sc,c}}$, similar to $\boldsymbol{Y}_{\mathbf{r,c}}$ but measured without the building upper-structure (S means source only) and using a velocity vector, measured at contacts on the interface. The source characteristics are related to each other [8] as:

$$\boldsymbol{v}_{f,c} = \boldsymbol{Y}_{Sc,c}.\boldsymbol{F}_{bl,c} \tag{3}$$

Note that $\boldsymbol{Y}_{\mathbf{Sc,c}}$ can be measured, like $\mathbf{v_f}$, before the building upper-structure is built (see Fig.7, top).

Equation (3) could be a way of estimating $\boldsymbol{F}_{\mathbf{bl,c}}$, knowing the source free velocity and input mobility.

It should be noted, that this relationship can be greatly simplified if the contact points chosen are assumed uncorrelated (therefore not too close from each other) and the quantities involved (forces and velocities) of the same order of magnitude at each contact (case of a wall parallel to a railway source for example). The mobility matrix reduces to an effective mobility [10] at contact $i$ , which includes the influence of the other contacts and can be considered as an independent source.

### 4.4 Source installed power

If the source installed power can be estimated, then the third prediction method indicated in Section 2.1 could be used for estimating ground-borne sound.
If the transfer mobility matrix in Equation (2) is measured with velocity measurements at contacts (with building upper-structure on top), Equation (2) becomes a way of estimating the contact velocity vector $\boldsymbol{v}_{\mathbf{c}}$:

$$\boldsymbol{v_c} = \boldsymbol{Y_{c,c}}.\boldsymbol{F_{bl,c}} \tag{4}$$

Knowing the excitation force vector $\boldsymbol{F}_{\mathbf{bl,c}}$ and the contact velocity vector $\boldsymbol{v}_{\mathbf{c}}$ leads to determining the source installed power:

$$\boldsymbol{W_S} = \boldsymbol{F^T_{bl,c}} \cdot \boldsymbol{v_c} = \boldsymbol{F^T_{bl,c}} .\boldsymbol{Y_{c,c}} \cdot \boldsymbol{F_{bl,c}} \tag{5}$$

Once again, Equation (5) can be greatly simplified, if effective mobilities are used, leading to an independent installed power at each contact.

## 5. CONCLUDING REMARKS

This paper does not define in details a method predicting the ground-borne (structure-borne) sound generated in buildings by outdoor ground vibration sources but gives the basic methodology to reach such a goal. The methodology uses quantities and approaches already defined and even standardized at European or international level. Of course, more work, both theoretical and experimental, is needed to study the feasibility of such an approach and check in details its application and restrictions. Nevertheless, this paper can serve as work document and hopefully help Task Group CEN/TC126/WG2/TG1 do preliminary work on this subject.

## 6. ACKNOWLEDGMENTS

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