24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

# PREDICTING GROUND-BORNE NOISE FROM VIBRATION OF RADIATING BUILDING ELEMENTS USING POWER BASED BUILDING ACOUSTICS THEORY

Michel Villot

*CSTB, Health and Comfort Department, Grenoble France*
*email: Michel.jean.villot@gmail.com*

Philippe Jean

*CSTB, Health and Comfort Department, Grenoble France*

Loïc Grau

*ACOUPHEN, Pusignan, Lyon France*

Noise measured inside buildings close to railway lines is often a mixture of ground-borne noise and airborne noise. Predicting ground-borne noise from vibration measurements and comparing the result to noise measurements may be useful to identify ground-borne noise. In this paper the prediction is done using building acoustics theory and a power based parameter called radiation efficiency. Due to the low frequency range of ground-borne noise where both building elements and rooms have strong modal behavior, the usual values of radiation efficiency either measured or calculated under diffuse field conditions cannot be used anymore. However, this parameter can still be measured or calculated using numerical models. In this paper, values of radiation efficiency are calculated and the spectra obtained discussed. Safe upper limits are then proposed, thus leading to simplified formulae, useable at engineering level for prediction but only valid under certain assumptions.
Keywords: Railway vibration, ground-borne noise

## 1. Introduction

Noise measured inside buildings close to railway lines is often a mixture of ground-borne noise and airborne noise, the former being vibration induced noise and the latter often generated outdoors by the same railway source if on ground surface, and/or by other sources (usually road traffic), and transmitted through the building façade. This paper is focused on predicting ground-borne noise from vibration measurements. Ground-borne vibration from railways is generally measured vertically at one location on floors at mid span and ground-borne noise generally measured at one location near room center [1]. Generally, only audible ground-borne noise is considered and measured in the range 16 – 250 Hz [1]; predicting ground-borne noise from vibration requires therefore vibration measurements performed in the same frequency range. Such point to point relationship between ground-borne vibration and noise, has been used in empirical models [2], [3], the output being a frequency dependent relationship expressed statistically in 1/3 octave bands in terms of mean values calculated over numerous often different situations; the standard deviation is of the order of 5 dB [3] thus showing the variability of this point to point relationship. This rather high variability has also been theoretically shown in [4] using a deterministic calculation model; the conclusions in [4] highlighted the high variability of the two primary quantities themselves (floor vibration and room noise at one location) due to pronounced modal responses of floors and rooms and the high variability of their relationship, depending on the relative position of the resonant frequencies of both floor and room modes.

Building acoustics uses a different approach where measurement and prediction methods are based on an energy approach (Statistical Energy Analysis, SEA), which involves space average quantities and power based parameters, and which is rather robust, but usually limited to mid and high frequencies, where vibrational and acoustic fields are diffuse [5]; the SEA parameter dedicated to acoustic radiation of vibrating plates is called radiation efficiency (notation $\sigma_s$). “Could radiation efficiency be used (with care) at lower frequencies to predict ground-borne vibration induced noise?” is the question addressed in this paper. It should be noted that the use of radiation efficiency at low frequencies has already been addressed in other existing studies, of which results are also discussed in this paper.

The paper is divided in four parts:

- First, the energy approach used (SEA) is briefly explained
- The next section is focused on low frequencies, where radiation efficiency is more variable
- The variability of $\sigma_s$ is then studied using ‘exact’ numerical models
- Finally, simplified formulae are given, only valid under certain assumptions

It must be added that this paper is a reduced version of a more detailed paper under submission [6].

## 2. The energy approach used (SEA)

Statistical Energy Analysis (SEA) was developed in the late sixties (see [5] for example). The word “statistical” means that some averaging is involved, as well as some randomness in excitation (time and space) and in frequency distribution of resonant modes. The energy stored in rooms or in building elements (walls and floors) is characterized using both space and time averaged (rms) quantities expressed in rather broad frequency bands (usually 1/3 octave bands, sometimes octave bands); such quantities are indicated by brackets <> in this paper. Interactions between building elements and rooms are also expressed as power flows using power based parameters. Diffuse field assumption is made, thus limiting the use of SEA usually down to 100 Hz in building acoustics.

In the case of radiation in a room of a vibrating building element structurally excited, the power based parameter characterizing the interaction between building element vibrational field and room acoustic field is called radiation efficiency and denoted $\sigma_s$; the subscript $s$ stands for structural excitation. This parameter relates the sound power $\Pi_{rad}$ radiated by the element to the vibrational energy stored in the element according to:

$$\Pi_{rad} = \rho c.\sigma_s.S<v^2> \quad (1)$$

where $S$ is the element surface area and $<v^2>$ its space average rms velocity. $\Pi_{rad}$ can be estimated from the space average rms sound pressure $<p^2>$ measured in the room and the room absorption area $A$ using the following energy balance equation, which indicates that the radiated power is absorbed in the room:

$$\Pi_{rad} = (<p^2> / 4\ \rho c)\ A \quad (2)$$

Equations (1) and (2) are frequency dependent, usually expressed in 1/3 octave bands and lead to the following relationship between the space average sound pressure level $Lp_{av}$ in the room and the space averaged velocity level $Lv_{av}$ of any wall or floor mechanically excited and radiating in the room:

$$Lp_{av} - Lv_{av} = 10\ lg\sigma_s + 10lg\ (4S/A) \quad (3)$$

The reference 2 $10^{-5}$ Pa is used for sound pressure levels and ref. 5 $10^{-8}$ m/s is commonly used in building acoustics for velocity levels, thus leading to the above simple formulae; if ref. $10^{-9}$ m/s is used for velocity levels as recommended in ISO standards, -34 dB should be added on the right-hand side of equation (3).

*A* is related to the room reverberation time *Tr* and the room volume *V*, using the well-known Sabine's formula:

$$A = 0.16\ V\ /\ Tr \tag{4}$$

$\sigma_s$ can be measured in laboratory using equation (3); it should be noted that no standard exists on laboratory measurements of the radiation efficiency; but this topic is about to be worked on at ISO level (TC43 SC2).

Under diffuse field conditions, $\sigma_s$ is close to 1 at and above the so-called critical frequency of the building element considered and decreases with decreasing frequency below. Heavy elements have rather low critical frequencies (typically around 100 Hz for a 20cm concrete floor) and radiate well at low frequencies, more than lightweight elements, which have higher critical frequencies (typically around 1600 Hz for a lightweight wood floor on joists and up to 4000 Hz for a single leaf gypsum wall on studs). In the case of heavy homogeneous building elements, $\sigma_s$ can be calculated [7]. Figure 1 gives the radiation efficiency of two typical building elements.

In case of several building elements radiating in a room, the sound fields generated individually by each element can then be added energetically to obtain the total sound field.

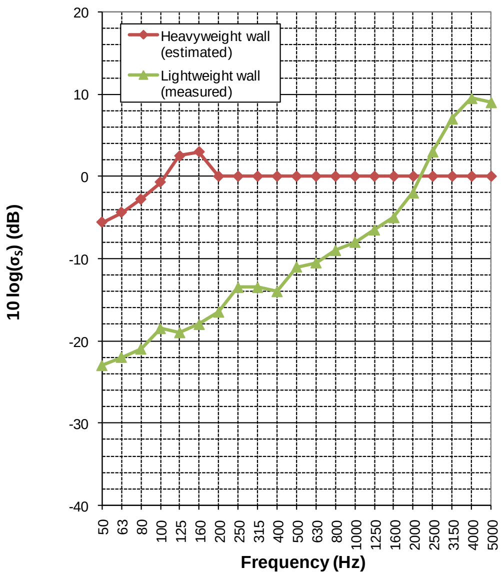


Figure 1: Typical radiation efficiencies: red curve, 16 cm concrete wall (calculated according to [6]); green curve, single leaf gypsum wall on studs (measured).

## 3. Application to ground-borne noise

In the case of ground-borne noise from railways, only audible ground-borne noise is usually considered and measured in the range 1/3 oct. 16 – 250 Hz, as said in the introduction. This frequency range can be roughly separated in two parts: (i) the range from 50 to 250 Hz, with a lower limit approximately corresponding to the first acoustic resonant modes for small building rooms, and which has been considered in several newly revised standards in building acoustics in order to measure and predict building performances down to 50 Hz (see [7] to [9]); and (ii) the range from 16 to 40 Hz, which is not addressed in any existing standard in building acoustics.

### 3.1 Frequency range 50 to 250 Hz

In the frequency range 50 to 250 Hz, the diffuse field conditions assumed in section 2 are not present on site, particularly in small rooms, where vibrational and sound fields are dominated by modal responses [4]. However, according to [7] to [9], the modal responses of rooms or building elements can still be represented by spatially averaged levels measured or calculated in 1/3 octave bands, and equation (3) can still be used to estimate $\sigma_s$. However, according to [9], the room reverberation time which leads to the room equivalent absorption area *A*, shall be measured in octave bands; the corresponding values *A* in octave bands are then used in equation (3), the same value being attributed to each 1/3 octave in the octave band considered. This solution is numerically checked in section 4, from measurement simulations using deterministic 'exact' models.

The spatial variation of the sound pressure level must also be determined, which is done through standard deviation (*SD)*, which according to [7] can be approximated from the room modal density *n(f)* as:

$$SD(dB) \approx 1 + 0{,}2 \,/\, n(f) \qquad (5)$$

$$n(f) = 4\pi V f^2/c^3 + \pi S f/2c^2 + L/8c \qquad (6)$$

where *f* is the center frequency of the octave band considered in Hertz, *c* is the sound speed in air in m/s (c=340m/s), *V* the room volume in cubic meter, *S* the total surface of the room boundaries in square meter and *L* the total length of the room edges, in meter.

Another similar expression of *SD* can be found in [10]:

$$SD(dB) = \frac{4{,}34}{-0{,}22 + \sqrt{1 + 0{,}319 . B . n(f)}} \qquad (7)$$

where *B* is the bandwidth considered, which is frequency dependent as well. Formula (7) has been successfully validated experimentally in [10], down to a frequency range where the first room modes are located.

### 3.2 Frequency range 16 to 40 Hz

This range is not addressed in any existing standard in building acoustics. However, in the experimental work described in [10], the spatial variation in sound pressure level of different rooms excited by loudspeakers has been measured down to 20 Hz, below the first room modes, and expressed in terms of standard deviation *SD*. The results show a maximum of *SD* of about 5 dB at the first room resonance frequency and a continuous decrease of *SD* with decreasing frequency below. Measured reverberation time spectra [14] show continuity in room absorption down to low frequencies, thus validating referencing radiation efficiency to sound absorption and using equation (3); however the validity of Sabine's formula (4) might be questionable.

## 4. Numerical validation

The aim of this section is to check the validity of equation (3) for predicting sound radiation of vibrating floors or/and walls in small rooms down to 16 or 20 Hz. Different situations are simulated, using deterministic 'exact' numerical models.

## 4.1 Existing studies

- In [11], equation (3) was used to estimate the radiation efficiency of a concrete plate excited by a point force and radiating into a rather large room (20 $m^2$ and $60m^3$) using an FEM model. The plate damping was similar to the one of in situ building elements, and the room surface acoustic impedance was chosen to lead to a 1s reverberation time. The radiation efficiency was calculated down to the first room mode (1/3 octave 31,5 Hz) and averaged over 5 force locations, showing its specificity to the modal responses of the plate and the room, which lead, below the floor critical frequency, to a spectrum showing isolated peaks, absent in the smooth spectra usually obtained under diffuse field conditions see (Figure 1).

- In [12], equation (3) was used to estimate the radiation efficiency of a concrete plate radiating in a room, but with differences (compared to [11]) in the form of excitation (plate connected to a source plate), in the rooms considered ($20m^2$ living room and $10m^2$ bedroom with varying room size and plate size, thickness and boundary conditions), in the calculation method (use of a Green function) and in the room absorption (empty rooms). The results showed, like in [11], peaks below the plate critical frequency, located at different frequencies, mainly depending on the room size considered (living room or bedroom) and not much on the floor; varying room and plate dimensions lead to a standard deviation from 3 to 5 dB.

## 4.2 Estimation of $\sigma_s$

### *4.2.1 Situation considered and numerical model used*

The building / excitation situation studied in [13] (see Figure 2) as well as the numerical method used in [13] (3D Finite Elements for structural vibration and integral method for acoustic radiation) were reused here. The ground is roughly simulated by a concrete slab (in yellow on Figure 2) with high internal loss of 50%, representing a slab on a medium ground (not too stiff and not too soft) and the excitation is a single vertical point force applied next to one building façade (purple arrow on Figure 2). The building is made of 27 rooms of different dimensions (values in red on figure 2) from $25m^3$ to $50m^3$ made of different building elements: 20cm concrete floors and concrete walls and façades of different thicknesses (values in black on Figure 2). The 27 rooms/volumes are denoted volume (i,j,k) according to the (x,y,z) axis indicated in Figure 2; for example volume (1,2,1) is the one on ground floor directly facing the excitation force.

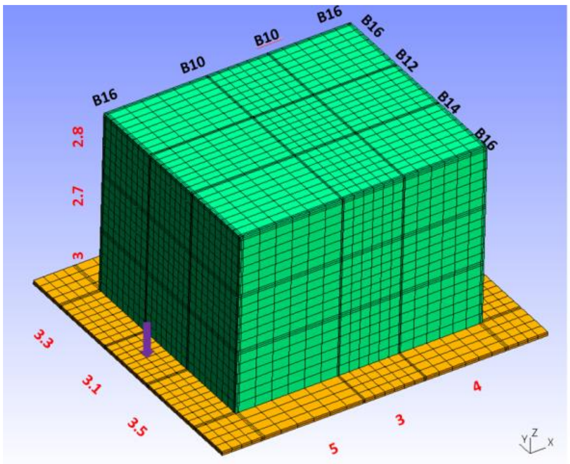


Figure 2. View of the 27 rooms: point force excitation represented by blue arrow; room dimensions in centimeters (in red); building element thicknesses in centimeters (in black)

Narrow band vibration fields are calculated and sound fields generated individually by each building element in each room are calculated and added (correlated complex summation) to obtain the total sound fields generated in each room. 1/3 octave values are then calculated, leading to the results presented in this paper. The wall and floor internal damping is about 1%, thus leading to total damping values similar to the ones of in situ building elements. Room absorption is expressed by the Sabine absorption coefficient of each building element composing the room, the same for each element and leading to the reverberation times given in Table 1 and obtained experimentally in furnished rooms of similar size [14].

Space average value and standard deviation (SD) of both building element vibration fields and room sound fields are calculated from 100 locations randomly distributed, in order to estimate $\sigma_s$ using equation (3) and to validate formulas (5) and (7).

Table 1: Typified frequency average reverberation time used in (1/3 octave) calculation

| Oct. (Hz) | 16 | 31,5 | 63 | 125 | 250 |
|---|---|---|---|---|---|
| *Tr* (s) | 1,5 | 1 | 0,5 | 0,5 | 0,5 |

### *4.2.2 Results*

First, the following degree of indetermination in the building parameters is assumed: only the 9 volumes (2,j,k) are considered, corresponding to small rooms (bedrooms) of the order of 10 m$^2$ and of height in the interval 2,7-3m. And in these rooms, only the radiation of the 14 cm and 16 cm walls are considered. The radiation efficiencies obtained are given in Figure 3. The results show that the radiation efficiency spectrum shape is the same, mainly driven by the room size. The standard deviation is about 3 dB, representing the expected uncertainty if the building configuration is not exactly known (uncertainty of a few cm on the room dimensions and the building element thicknesses).

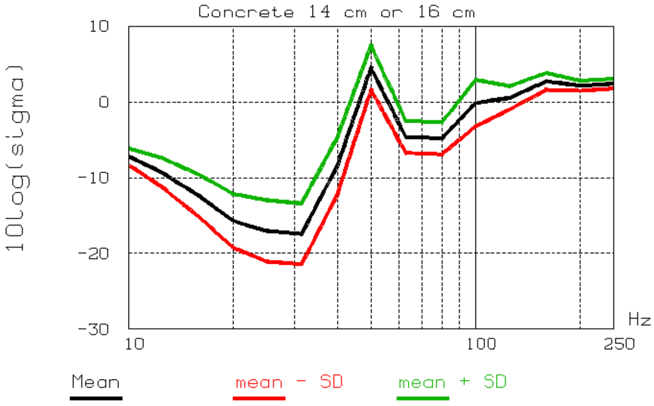


Figure 3: Radiation efficiencies of 14-16 cm concrete walls radiating in small bedrooms in terms of mean value and SD

Secondly, the spatial variation in sound pressure levels is studied in the case of volume (2,2,2) (size of a bedroom) from sound levels calculated at 100 positions randomly located in the room. The standard deviations (*SD*) corresponding to the sound fields generated individually by each building element composing the room, and the one corresponding to the total sound field generated by the 6 elements together have been calculated and are compared in Figure 4. The results show that for each element individually, *SD* increases with decreasing frequency from around 3 dB at 250 Hz up to 6 dB at 30-40 Hz, and then decreases; however, for the total sound field, *SD* increases all the way up to about 8 dB at 10 Hz. This shows that in the low frequency range below 30-40 Hz, phase is important in recomposing the total sound field and generates probably interferences leading to an increase in the sound spatial variation. This also means that recomposing energetically (incoherently) the sound fields radiated by each element, as mentioned in the last paragraph in section 2, is wrong in that frequency range. *SD* values obtained using formula (7) slightly underestimates the calculated values (within 1 dB) down to 30 Hz; formula (5) is less accurate.

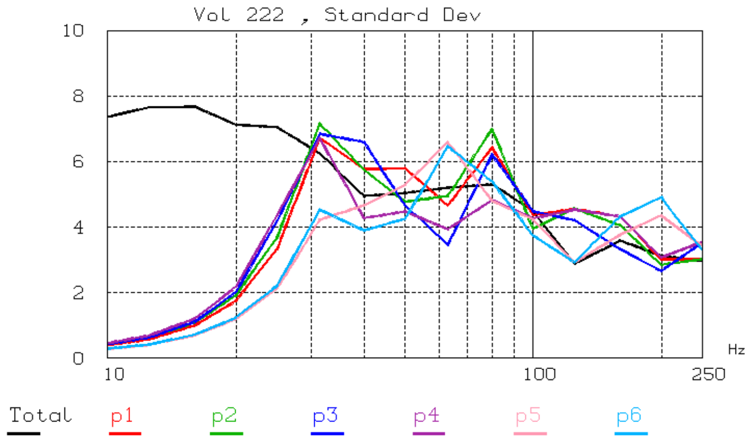


Figure 4: Spatial variation of sound field: Standard deviations in Volume (2,2,2) for each element radiating individually (in color) and for the total sound field (in black).

## 5. Conclusion and further simplifications

The results presented in section 4 show that predicting ground-borne noise from vibration of a building element radiating in a room is possible using equation (3), assuming the radiation efficiency of the element in the room considered is correctly estimated, using a model taking into account the strong modal behavior of the room at low frequencies. The results obtained will lead to a useful catalogue (not done yet) of radiation efficiencies for a limited number of categories of rooms and building elements. Moreover, the sound fields radiated by each element can be added energetically to obtain the total sound field in the room down to a frequency corresponding to the first room modes.

The numerical model of geometrically perfect empty rooms used in section 4 probably amplify this modal behavior, and the peaks observed on the radiation efficiency below the critical frequency are likely to be close to 0 dB ($\sigma_s = 1$) in reality. If the first room modes can be localized, or at least if a frequency range likely to contain these modes can be identified, then a value of 0dB can be assumed at these frequencies, without the use of a sophisticated model. At the extreme, a value of 0dB can be given over the frequency range below the critical frequency, leading to a constant value $\sigma_s = 1$ over the whole frequency range.

This extreme simplification has been used in the European project RIVAS [15]; however, the goal in RIVAS was not the development of a prediction method but of a practical tool for quickly indicating the change in indoor ground-borne vibration and noise obtained by the mitigation measures developed in the project, using typified ground/building categories.

Further simplifications were suggested in RIVAS, detailed now in an annex of a draft ISO technical specification [16] and leading to the following simple frequency dependent approximation:

$$Lp_{av} \approx Lv_{meas,floor} + 7 \text{ dB} \quad (8)$$

This simple formula applies to frequencies equal or above 40-50 Hz, relates the room averaged ground-borne noise level $Lp_{av}$ to the floor velocity level $Lv_{meas,floor}$ measured at mid span, but is only valid under the list of assumptions given is [16].

It should finally be noted that, assuming the space average ground-borne noise level about 3dB higher than the sound level $Lp_{meas}$ usually measured near the room center [1], formula (8) becomes:

$$Lp_{mes} \approx Lv_{meas,floor} + 4 \text{ dB} \quad (9)$$

which is close (within 3dB) to the statistical vibration to noise factor obtained in [2] and close to the statistical relationship obtained in [3], which proves that average values obtained using energy based models represent quite well measured values averaged statistically over different sites.

## REFERENCES


1 ISO 14837-1:2006, Mechanical vibration – Ground-borne noise and vibration arising from rail systems – Part 1: General guidance.

2 A. Said et al. Ermittlung des sekundären luftschalls aus dem Schienenverkehr, *Zeitschrift für Lärmnbe-kämpfung*. **53** (2006) Nr.1.

3 H. Kuppelwieser, A. Ziegler A tool for predicting vibration and structure-borne noise immission caused by railways, *Journal of Sound and Vibration* **193**, 261–267 (1996).

4 R. Thornely-Taylor The relationship between floor vibration from an underground source and the airborne sound pressure level in the room, *International Journal of Rail Transportation*, 2016, Vol. **4**, N° **4**, 247-255M.

5 L. Cremer, M. Heckl, and E. E. Ungar *Structure-borne sound: Structural vibrations and sound radiation at audio frequencies*. Springer, Berlin, 2. edition 1988.

6 M. Villot, P. Jean and L. Grau Predicting ground-borne noise from vibration of radiating building elements using power based building acoustics theory, submitted to *International Journal of Rail Transportation*.

7 Revised EN ISO 12354-1 to -4 (expected in early 2017): Building Acoustics – Estimation of acoustic performance of buildings from the performance of elements.

8 Revised ISO 10848-1 to -4 (expected in early 2017): Acoustics – Laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms.

9 Series ISO 16283-1 to -3: Acoustics – Field measurement of sound insulation in buildings and of building elements.

10 C. Hopkins and P. Turner Field measurement of airborne sound insulation between rooms with non-diffuse sound fields at low frequencies, *Applied Acoustics*, **66**, 1339-1382 (2005).

11 C. Hopkins, M. Filippoupolitis and N. Ferreira Prediction of low frequency radiation efficiencies using the normal mode approach and Finite Element methods, *Proceedings of the 18th International Congress on Sound and Vibration*, Florence Italy, (2015).

12 G. Coquel *Propagation and radiation of structure borne sound generated by railways - Application to nearby buildings*. PhD work (in French) performed at Paris-Est University France, June 2009.

13 P. Jean Computing vibration transfer from trains to buildings by means of 2D ½ and 2D ¾, *Proceedings of the Inter-noise congress*, Hamburg Germany, (2016).

14 L. Grau and D. Bozzetto Reverberation time and spatial variation of sound field in dwellings: Experimental data, *Internal report RAP_2016_0*, ACOUPHEN, 2017 (in French).

15 M. Villot, S. Bailhache, C. Guigou and P. Jean: Prediction of railway induced vibration and ground-borne noise exposure in buildings and associated annoyance. *Proceedings of the IWRN workshop*, Uddevalla, Sweden (2013), published in Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Springer (2014)

16 pr ISO TS 14837-31: 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; Annex A: Predicting ground-borne noise from vibration (document under ISO enquiry).