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Analysis of the aspects affecting sound radiation efficiency based on numerical simulations

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ABSTRACT

The sound radiation efficiency of a vibrating structure is an acoustic descriptor, used both to compare and optimise products, and as input data in prediction models based on statistical energy analysis. Although a published standard for the measurements of the radiation efficiency is not yet available, the proposal ISO/CD 10848-5, regarding laboratory measurement methods to characterise the acoustic radiation of a building element, is currently under evaluation. The radiation efficiency of certain elements clearly depends on their dimension, on the type of excitation, the boundary conditions and the orientation of the baffles surrounding the sample. Moreover, evidence from different studies suggests that several factors related to the test arrangement strongly influence the results. These include the positions over which the vibration response of the tested element is measured, and, when the diffuse sound field approach is used to evaluate the radiated sound power, the number and the arrangement of the positions over which sound pressure levels are measured. The aim of this study is to analyse those aspects which strongly affect the experimental evaluation of the radiation efficiency, based on numerical simulations. To this purpose a homogeneous concrete wall was investigated by means of an FE vibro-acoustic analysis.

Keywords: Radiation Efficiency, Vibro-acoustics, average vibration velocity, average sound pressure levels
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1. INTRODUCTION

The sound radiation efficiency of a vibrating structure, which quantifies its capability to convert the vibrational energy into sound radiated within a surrounding fluid, is a widely used acoustic parameter, required in many prediction models based on the Statistical Energy Analysis (SEA), like, for example, the computation of the sound reduction index in buildings, according to the ISO 12354-1 standard [1]. The radiation efficiency is defined as the ratio between the total sound power W radiated by the structure and the sound power that would be theoretically radiated by an ideal piston source having the same surface area S and vibrating with the same mean square velocity of the surface $\left\langle v^2 \right\rangle$. Several models to predict the radiation efficiency of a given structure have been developed in the last year, considering homogeneous rectangular plates and strip [2–5], ribbed and orthotropic panels [6–8] and multilayer systems [9]. The experimental evaluation of the radiation efficiency requires the knowledge of the sound power radiated by the vibrating structure and the vibration velocity averaged over its surface. Since the radiated sound power cannot be directly measured, but needs to be derived from other quantities, such as sound pressure, sound intensity or vibration velocity, different approaches can be applied to experimentally evaluate the radiation efficiency. Even though an official standardised method to evaluate the radiation efficiency is not currently available, the draft ISO/CD 10848-5 has been completed by the Technical commitee ISO/TC 43, subcommitee 2 Building Acoustics, concerning the laboratory measurements of the radiation efficiency of building elements. According to this draf, the radiation efficiency is evaluated, as described in the next section, from the velocity levels measured on the surface of the partition and the sound pressure levels measured in the receiving room, assuming a perfectly diffuse sound field. Alternatively, as specified in Annex A of the draft ISO/CD 10848-5, sound intensity measurements, performed according to ISO 15186-1 standard, can be used. However, well-established hybrid approaches, based on the discretisation of the radiating surface in a number of rigid pistons [10, 11] have not been included in the draft. These methods, which only require the measurement on the complex velocity on a grid of points uniformly distributed on the vibrating surface and analytical calculation, are widely used to evaluate the radiation efficiency of planar structures, which it is assumed have been inserted in a rigid baffle and radiate in the free field. In this study, a homogeneous concrete wall was investigated by means of an FE vibro-acoustic analysis. The radiation efficiency of the partition is computed from the sound pressure levels and the velocity levels evaluated in a different number of positions throughout the solid and the acoustic domains. The results obtained using the diffuse filed apporach (DFA) are also compared with the radiation efficiency obtained by using the hybrid approach known as discrete calculation method [10].

2. DRAFT ISO/CD 10848-5: RADIATION EFFICIENCY EVALUATION

The draft ISO/CD 10848 prepared by the committee ISO/TC43 SC 2 specifies laboratory measurement methods to characterise the radiation efficiency of building elements mechanically or acoustically excited. The sound pressure level L_p in the receiving room and its reverberation time T are required, together with the the velocity level L_v averaged over the surface of the vibrating element, in order to evaluate the radiation efficiency of the tested structure. The average sound pressure level measured in

n fixed microphone positions when a stationary source is used, is defined as:

$$L_p = 10 \log \left(\frac{\sum_{i=1}^{n} p_i^2}{n p_0^2} \right) \tag{1}$$

where p_i is the root-mean-square (rms) sound pressure measured at the i^{th} position and $p_0 = 20\ \mu$ Pa is the reference sound pressure. The space and time averaged sound pressure levels, determined according to Equation 1, should be measured within the receiving room volume avoiding those areas where the direct radiation and the near acoustic field have a significant influence. In fact, sound pressure measurement should be performed according to paragraph 7.1.2 of ISO 10840-1 standard [12]. A minimum number of 5 microphone positions must be used, randomly distributed throughout the volume, fulfilling the following distance requirements:

- 0.7 m between microphone positions;
- 0.7 m between any microphone positions and room boundaries or diffusers;
- 1.0 m between any microphone positions and the tested partition.

Alternatively, a continuously moving microphone with a sweep radius of at least 1 m can be used, conveniently tilted in order to not lie within 10° of a room surface.

The spatial average velocity level, measured in m positions on the element surface when a stationary source is used, is analogously defined as:

$$L_v = 10 \log \left(\frac{\sum_{i=1}^{m} v_i^2}{m v_0^2} \right) \tag{2}$$

where v_i is the rms vibration velocity measured at the i^{th} position, while $v_0 = 10^{-9}$ m/s is the reference velocity. Vibration measurement, usually carried out by using accelerometers, shall be performed according to the requirements given in paragraph 7.2.3 of ISO 10848-1 standard. At least 2 non-simultaneous excitation positions, using one steady-state acoustic source according to paragraph 7.1.1.1 of ISO 10848-1, are required. For each excitation position, the vibration velocity should be measured in a minimum of 6 points, randomly distributed over the surface, if the tested partition is a Type A element and a minimum of 9 points if it is a Type B element. The definition of Type A and Type B elements is provided in standards ISO 10848-1:2017 and 12354-1:2017. When the test element is mechanically excited, either by using a stationary or transient signal, the number of non-simultaneous excitation positions is increased to a minimum of 3 for Type A elements, and at least 6 for Type B elements; while the vibration velocity should be measured in at least 3 points over the radiating surface for each source position. As for sound pressure measurements, distance requirements should be fulfilled according to paragraph 7.2.5 ISO 10848-1:2017:

- 0.25 m between measurement positions and test element boundaries;
- 0.50 m between excitation positions and test element boundaries;
- 0.50 m between individual measurement positions associated to each excitation position;
- 0.70 m between the different excitation positions (for Type B elements);

– 1.00 m between the different excitation positions (for Type A elements);

– 1.00 m between each excitation position and the associated measurement partitions.

The radiation function L_{RF} is computed as the difference between the average sound pressure level measured in the receiving room and the average velocity level measured on the test element surface. In the case of stationary excitation, by only one source at the time, the radiation function should be averaged over the number of source positions n_S:

$$L_{RF} = \frac{1}{n_S} \sum_{i=1}^{n_S} \left(L_p - L_v \right)_i \tag{3}$$

The radiation efficiency of a vibrating element, generally defined as the ratio of the sound power W radiated by the structure and the one that would be theoretically radiated by a rigid piston with the same surface area S, vibrating with equal mean square velocity $\left\langle v^2 \right\rangle$, can be expressed as:

$$\sigma = \frac{W}{\rho_0 c_0 S \left\langle v^2 \right\rangle} \tag{4}$$

where ρ_0 and c_0 are the air density and the speed of sound respectively. Assuming a perfectly diffuse field in the receiving room, the sound radiated power can be evaluated from the average sound pressure as:

$$W = \frac{p^2}{4\rho_0 c_0 S} A \tag{5}$$

where A is the equivalent sound absorption area in the receiving room, evaluated from the measured reverberation time T according to paragraph 7.1.3 of ISO 10848-1 standard. After simple algebraic manipulation the radiation efficiency, given in Equation 7, can be expressed as a function of the radiation function as:

$$\sigma = \frac{A}{4S} 10^{\left(\frac{L_{RF}}{10} + 34\right)/10} \tag{6}$$

The radiation index L_σ, expressed in dB, is defined as:

$$L_\sigma = 10 \log (\sigma) \tag{7}$$

Annex A of the draft ISO/CD 10848-5 provides an alternative experimental procedure to evaluate the radiation index of a building partition based on sound intensity measurements, performed according to ISO 15186-1 standard. Even though such standard, which describes an experimental procedure to measure the sound insulation of a building element, only takes into account airborne sound source, the sound intensity method can be also applied to a steady state mechanical excitation. The intensity radiation function $L_{RF,I}$ is defined as:

$$L_{RF,I} = \frac{1}{n_S} \sum_{i=1}^{n_S} \left(\overline{L_{I_n}} - L_v \right)_i \tag{8}$$

The average normal sound intensity level $\overline{L_{I_n}}$ is computed as ten times the logarithm to base 10 of the ratio of the unsigned sound intensity component in the direction normal to the measurement surface I_n to the reference sound intensity $I_0 = 10^{-12} \mathrm{W/m^2}$. The radiation index is computed from the intensity radiation function as:

$$L_\sigma = L_{RF,I} + 34 \tag{9}$$

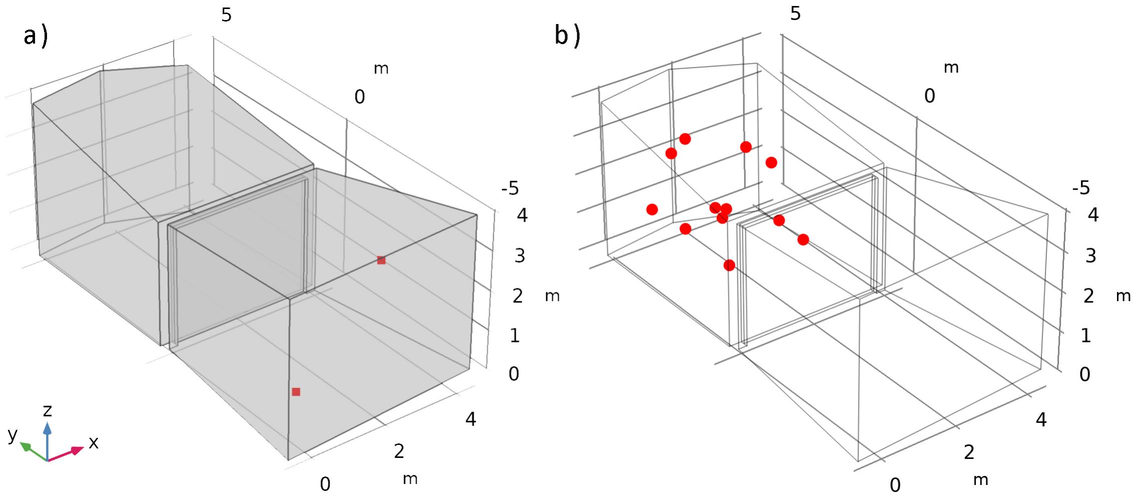

Figure 1: FE model: a) 3D geometry of the tested wall inserted into the sound transmission test facility. The red squares represent the two airborne sound source positions; b) the red dots represent the points where the sound pressure is evaluated in the receiving rooms.

3. NUMERICAL INVESTIGATION OF THE RADIATION EFFICIENCY

In order to analyse the different aspects which may influence the experimental evaluation of the radiation efficiency of a building element, according to the procedure described in the draft ISO/CD 10848-5, a vibro-acoustics numerical analysis was performed on a homogeneous isotropic wall, inserted in the testing window of the sound transmission test facility of the university of Ferrara. The sound transmission test facility consists of two reverberant rooms. The emitting room has a net volume of about 80.3m^3, while the receiving room is smaller with a volume of 71.2m^3. Both the emitting and the receiving room were modelled in the finite element FE software COMSOL Multiphysics®, as a fluid domain. The tested element, a concrete homogeneous wall 10mm thick, with fixed boundary conditions, was modelled as a solid domain inserted between the two air volumes. On the wall surface exposed to the incident sound field and on the radiating surface continuity equations are applied in order to couple the acoustic and the structural domains. In Figure 1 a), a 3D view of the implemented model is provided. The boundary conditions of the fluid domain geometry should represent the surface impedance of the walls, the floor and the ceiling of the two reverberant rooms. An impedance boundary condition was used in the model, assumed to be equal for all the surfaces, except the one of the test element. The surface impedance was computed from the room reverberation time, according to Annex F of ISO 10534-2. Due to the significant computational cost of such simulation, it is possible to investigate a limited frequency range. For this reason a concrete wall 100mm thick, with density $\rho = 2300$kg/m^3, complex elastic modulus $E = 3.7E10(1 + j0.05)$Pa and Poisson ratio $\nu = 0.23$, was chosen as test element, in order to have its critical frequency fall within the investigated frequencies. The geometry assigned to the fluid domain was meshed with tetrahedral elements, while for the solid domain the nodes generated at the interface surface with the emitting room volume were swept through the wall thickness, in order to reduce the number of elements and the computational effort required by the simulation. For both

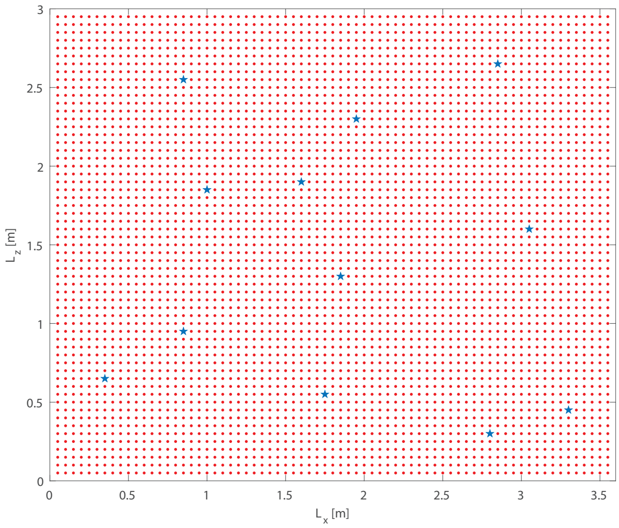

Figure 2: Grid of points equally distributed over the wall surface. The red dots represents the entire data set, while the blue stars are 12 points randomly chosen to compute the velocity level L_v.

the acoustic and solid domain the maximum element size was equal to or smaller than $\lambda_{max}/6$. The wavelength λ_{max} is associated to the higher investigated frequency, which in this case was f_{max} = 560Hz, covering the one-third octave bands between 50Hz - 500Hz with 9 frequency lines for each band. The computational cost required by such FE simulations is significant. In fact, each computation was solved in 98404s using 86.6 GB of virtual memory.

In order to fulfil the requirement of the standard draft described in the previous section, an airborne spherical sound source was used to excite the emitting room, in two different non-simultaneous positions, which are shown as red squares in Figure 1 a). For each source position the rms sound pressure was evaluated in a number of points, randomly distributed within the volume of the receiving room according the requirements described in section 2; an example of 12 random positions is provided in Figure 1 b). The wall surface vibration velocity was evaluated over a uniform grid of points with 50mm spacing, for a total of 4189 values. The velocity level, expressed in Equation 2,was computed by randomly choosing a number of points, among the 4189 evaluated, fulfilling the requirements described in section 2. The diagram of Figure 2 shows the grid of points over which the complex vibration velocity was evaluated. The blue stars represent 12 points randomly chosen among the entire set of data in order to compute the average velocity.

4. RESULTS AND DISCUSSION

In order to verify the reliability of the FE model, the difference between the sound pressure levels evaluated in the emitting and in the receiving rooms was compared with the transmission loss computed by a finite transfer method (TMM) algorithm, a well established wave-based approach to predict sound transmission through different media [13], widely used in building acoustics [14–16]. As shown in Figure 3, consistent results

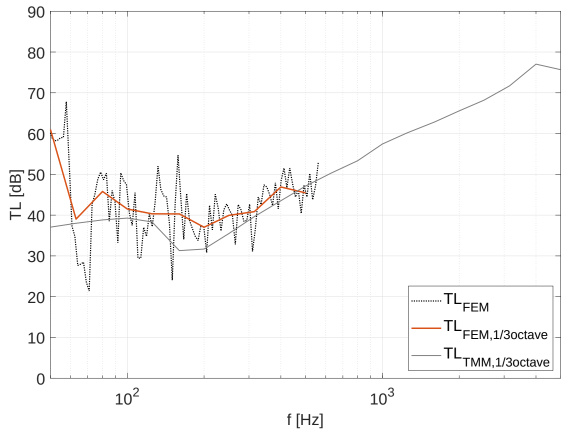

Figure 3: The sound transmission loss of a 100mm *thick concrete wall computed from the FE simulation is compared with the results computed by means of the transfer matrix method.*

were found between the two approaches. The transmission loss obtained from the FEM simulation highlights the influence of modal behaviour of both the rooms and the partition as well, which are not taken into account in the transfer matrix method. The dip in the TL of the 100mm thick concrete wall, between the 160Hz and 200Hz third octave bands, identifies the critical frequency of the partition, consistently with the value expected from the analytical formulation [17].

The radiation efficiency of the concrete wall was computed from the average sound pressure levels, evaluated in the receiving room in a number of positions distributed throughout the volume, and from the average velocity levels, evaluated over different points randomly distributed over the wall surface. In both cases the chosen positions fulfilled the distance requirements given in the standard ISO 10848-1. In Figure 4 the average radiation index is shown together with the curves evaluated for each source position. The radiation indexes reported in Figure 4 a) were computed considering a minimum number of points over which the sound pressure and the vibration velocity were evaluated. In particular for this kind of building element, 5 microphone positions to measure the sound pressure and 6 accelerometer positions to evaluated the vibration velocity are required for each source location. A peak in the radiation index curve, which should occur at the critical frequency, falls within the 315Hz bands. It seems that the critical condition is shifted towards higher frequencies, compared to the expected value. By increasing the number of points over which both the sound pressure in the room and the velocity over the wall surface are evaluated, the fluctuations due to the rooms and the the wall modes are reduced, as shown in Figure 4 b). However, even though the number of evaluation points was doubled and the distance requirements were still fulfilled, the peak of the radiation index curve falls between the frequency bands centred around 250Hz and 315Hz. These findings are consistent with the results of a parametric analysis undertaken on the experimental radiation efficiency of wooden timber partitions, which highlighted that an undersampling of the vibration velocity, neglecting the regions of the plate close to the boundaries, may lead to an inaccurate average velocity level [18]. On the other hand, by further increasing the number of points over which the two fundamental

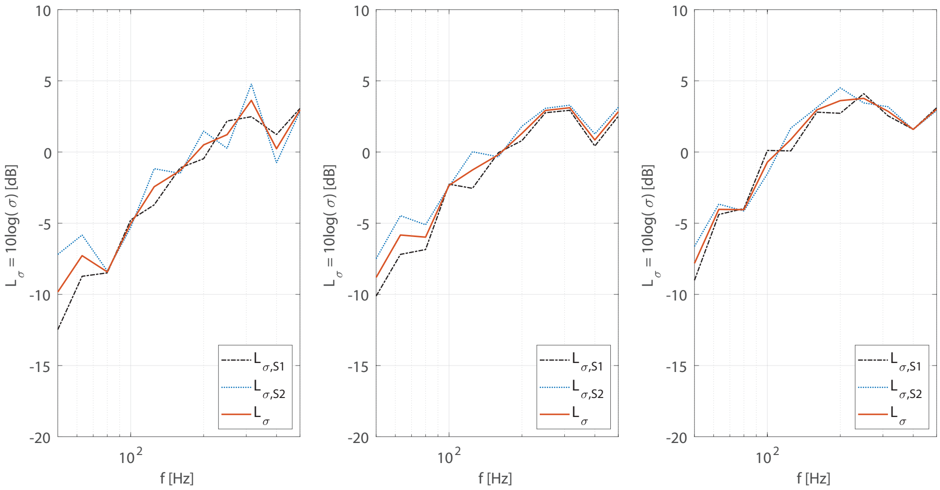

Figure 4: Radiation Efficiency of a 100mm *thick concrete wall evaluated by means of the DFA: a) sound pressure and vibration velocity averaged over 6 points for each source position according to ISO 10848-1; b) sound pressure and vibration velocity averaged over 12 points for each source position according to ISO 10848-1; sound pressure and vibration velocity averaged over grids of points distributed throughout the entire domains.*

quantities are evaluated, also taking into account those regions near the room and the plate boundaries which have to be neglected according to the standard, more reliable results were found. Figure 4 c) shows the radiation index computed by averaging both the sound pressure and the vibration velocity over a grid of points uniformly distributed throughout the considered domain. This larger number of evaluation points and their wider distribution allowed to further reduce the fluctuations due to the modal behaviour of the rooms and the partition. Moreover, the radiation index curve exhibits a wider peak, starting from the band centred on 160Hz up to the 315Hz band. The critical frequency identified by the radiation index is thus consistent with the results of transmission loss presented in Figure 3. Moreover, to further verify the reliability of these results, in Figure 5, this radiation index obtained using the diffuse field approach (DFA) is compared to the radiation index obtained by means of the DCM hybrid approach. This latter method computes the radiation efficiency from the complex vibration velocity, evaluated over a grid of uniformly distributed points, assuming the wall to be inserted into a rigid baffle and radiating in free-field conditions. Therefore, the room influence is completely neglected. Even though some discrepancies are clearly shown, a consistent trend is found between these results.

5. CONCLUSIONS

In this paper the early results of an ongoing study concerning a numerical analysis of several factors that may influence the experimental evaluation of the radiation efficiency of a building partition have been presented. An FE vibro-acoustic model has been implemented considering a concrete wall excited by an acoustic sound field. The building partition, modelled as a solid element, has been inserted into the test window between two air domains, representing the reverberant rooms of a sound transmission test facility. The radiation efficiency has been evaluated according to the ISO/CD 10848-5, a draft

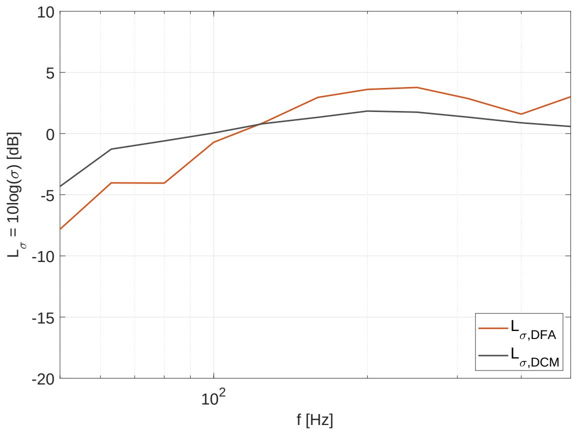

Figure 5: Comparison of radiation index computed from sound pressure and vibration velocity, averaged over grids of points distributed throughout the entire domains, using DFA and the radiation index obtain from the DCM approach.

document regarding the experimental evaluation of the radiation efficiency of building elements. Findings suggest that when a small number of positions are distributed in the receiving room volume, to evaluate the average sound pressure level, an inaccurate radiation efficiency may be computed. Analogously, undersampling the vibration velocity or over the plate surface may lead to inaccurate results. On the other hand, by increasing the number of evaluating positions and also considering the regions close to the boundaries, of both the receiving room and the tested partition, more reliable results can be obtained. To confirm these findings a more detailed investigation is certainly needed in the follow-up of this study, including addition heavy-weight and lightweight partitions and extending the considered frequency range, together with a validation of the numerical results with experimental data.

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