ENVIRONMENTAL NOISE CONTROL
The 2005 Congress and Exposition on Noise Control Engineering
07-10 August 2005 - Rio de Janeiro - Brazil

Tools for building acoustics design and experimental performances

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Abstract By issuing the Regulation concerning control and reduction of the acoustic pollution, Umbria Region has imposed the acoustic design for buildings and the check of passive acoustic requirements, defined by Italian national laws. The new Umbria Region legislation considers the acoustic design absolutely necessary to obtain the planning permission. Afterwards it must be attested that the works correspond to the acoustic design in order to obtain the declaration of habitability. Finally the town council, with the technical support of the environmental protection regional agency, carries out sample controls comparing the works with the design evaluations. In this paper the results of acoustic measurements and calculations about different typologies of floors are compared, in order to find a simplified evaluation method for passive acoustic requirements and to provide useful instruments for acoustic design.

1. INTRODUCTION

In the last few decades international standards and local laws have been dedicating growing attention to the definition and the improvement of building acoustics passive requirements, in order to protect indoor activities from noise disturbance. Among the acoustic requirements, the impact sound insulation between rooms assumes particular importance. The present paper aims at determining, by means of field measurements, the acoustic performances of some common typologies of floors. According to ISO standards, measurements on a steel beam floor, a wooden beam floor and two brick-concrete floors, one of which comprehensive of floating floor, have been carried out using a standardized tapping machine placed on each tested structure. From the collected experimental data, the corresponding impact sound insulation of the floors has been extrapolated and then compared with the limits provided by Italian legislation [1]. A comparison between results obtained from field measurements and values estimated by a software, implementing a calculation model defined by EN standards, has been finally carried out. Such a comparison has allowed to test the software in the calculation of impact sound insulation between rooms, thus giving useful tools for building acoustics.

2. BUILDING ACOUSTICS LEGISLATION

2.1 Italian DPCM 5 December 1997

In Italy DPCM 5 December 1997 [1] determine acoustic requirements for indoor sound sources and passive acoustic requirements for the buildings and their parts, in order to reduce the human exposure to noise. Buildings are distinguished in the categories shown in Table 1.

Table 1: Building classification (DPCM 5/12/1997)

Category	Building typology
A	Dwellings and similar
B	Offices and similar
C	Hotels and similar
D	Hospitals and similar
E	Schools and similar
F	Recreational or religious activities and similar
G	Commercial activities and similar

The quantities that characterize passive acoustic requirements of buildings are:
1) reverberation time T, defined in ISO 3382:1975;
2) sound reduction index of partitions between rooms R, defined in ISO 140-5:1996;
3) standardized sound level difference of façades $D_{2m,nT}$;
4) normalized impact sound pressure level of floors L_n, defined in ISO 140-6:1996;
5) A-weighted maximum sound pressure level measured with time weighting S L_{ASmax};
6) A-weighted continuous equivalent sound pressure level L_{Aeq}.

The evaluation indexes that characterize passive acoustic requirements of buildings are:
a) weighted sound reduction index of partitions between rooms R_w calculated according to UNI 8270-7:1987, paragraph 5.1 (see ISO 717-1);
b) weighted standardized sound level difference of façades $D_{2m,nT,w}$ calculated according to the same procedure of the previous point a);
c) weighted normalized impact sound pressure level of floors $L_{n,w}$ calculated according to UNI 8270-7:1987, paragraph 5.2 (see ISO 717-2).

The limits imposed by DPCM [1] for passive acoustic requirements of buildings, building parts and indoor sound sources are shown in Table 2.

Table 2: Building acoustics passive requirements (DPCM 5/12/1997)

Category	R_w	$D_{2m,nT,w}$	$L_{n,w}$	L_{ASmax}	L_{Aeq}
D	55	45	58	35	25
A,C	50	40	63	35	35
E	50	48	58	35	25
B,F,G	50	42	55	35	35

2.2 New Regulation In Umbria Region

In Umbria Region the Regulation 13 August 2004, n. 1 [2] has put into effects the Regional Law 6 June 2002, n. 8 [3] concerning dispositions for the control and the reduction of acoustic pollution. The Regulation provides that the plans of new constructions and those regarding restructurings must be accompanied by the acoustic design, compiled in the respect of the requirements established by DPCM 5 Decembers 1997 [1] and by municipal regulations. The acoustic design, undersigned by competent technicians, is an integral part of the technical documents required to obtain the planning permission: it defines the structural characteristics of the buildings, specifying the geometric and physical requirements, the materials and the technological systems in order to satisfy the limits of DPCM. Afterwards it must be attested that the works correspond to the acoustic design in order to obtain the declaration of habitability. Finally the town council, with the technical support of the environmental protection regional agency, carries out sample controls comparing the works with the design evaluations.

3. IMPACT SOUND

In a closed room the sound is propagated via air and solid paths. The noise transmitted through the constructions is caused by dynamic forces that act on the structures; the excitation can be stationary (pump, air-conditioners, washing machine, etc.), due to impact (slammed doors, persons who walk, etc.) or induced by the sound.
The most common source of impact sound consists in the tapping of the steps, but actually any machine, device or household appliance that acts mechanically on the floor surface can directly produce in the below room a sound of similar impact nature.
Impact sound is propagated through the floors from the upper to the lower levels, without meeting great resistance, since the typical horizontal structures in the buildings don't offer high insulation against this modality of noise transmission. In order to reduce the impact sound level between rooms, it is necessary to interrupt the structural continuity, for instance by means of resilient coverings and floating floors [4] [5].

4. EXPERIMENTAL METHOD

4.1 Field Measurements Of Impact Sound Insulation

Field measurements of impact sound insulation of floors have been carried out according to ISO 140-7 [6]. This international standard specifies a field method for measuring the impact sound insulation properties of building floors by using a standardized tapping machine [6].
The hammer connecting line of the tapping machine has been oriented at 45° to the direction of the beams, in order to involve a heterogeneous structure.
The impact sound pressure levels at the different microphone positions have been averaged on an energy basis for all positions of the tapping machine. Four microphone positions have been used, distributed throughout the room, respecting the minimum separating distances according to ISO 140-7. The sound pressure levels have been measured using one-third-octave band filters having centre frequencies from 100 Hz to 5.000 Hz.
The noise levels have been corrected in order to make them independent from the particular sound absorption of the receiving room. The reverberation time has been measured according to ISO 354 [7]. To ensure that the observations in the receiving room have not been affected by extraneous sound, background noise levels have been measured and compared with the

ones of signal and background noise combined, then producing any possible correction required by ISO 140-7.
All tests have been carried out using the signal acquisition unit SYMPHONIE [8] and the software of analysis and elaboration dB BATI 32 [9].
Finally the following quantities have been determined:

1) normalized impact sound pressure level:

$$L'_n = L_i + 10 \log \frac{A}{A_0} \quad \text{(dB)} \qquad (1)$$

   with $A_0 = 10\ m^2$;

2) standardized impact sound pressure level:

$$L'_{nT} = L_i - 10 \log \frac{T}{T_0} \quad \text{(dB)} \qquad (2)$$

   For dwellings T_0 equals 0.5 s.

4.2 Evaluation Of Weighted Impact Sound Pressure Levels

The field measurements of impact sound insulation of floors, standardized in ISO 140-7 [6], give frequency-dependent values. Single-number quantities characterizing the acoustic performance of floors are defined by ISO 717-2 [10], in order to rate impact sound insulation and simplify the formulation of acoustic requirements in building codes.
The international standard ISO 717-2 gives rules for determining these quantities from the results of measurements carried out according to ISO 140-7. The values obtained have been compared with reference values at measurement frequencies within the range 100 Hz to 3.150 Hz for measurements in one-third-octave bands. To evaluate the results of measurements of L'_n or L'_{nT} in one-third-octave bands, the reference curve has been shifted in steps of 1 dB towards the measured curve until the sum of unfavourable deviations has been as large as possible but not higher than 32.0 dB. The value in decibels of the reference curve at 500 Hz, after shifting it according to this procedure, is $L'_{n,w}$ or $L'_{nT,w}$ respectively.

5. EXPERIMENTAL DATA

In order to estimate the impact sound insulation between rooms in real operating conditions, three main typologies of floors have been examined, carrying out field measurements on a steel beam floor with sheet, a wooden beam floor and a brick-concrete floor. Further measure has involved a second brick-concrete floor, provided with a floating floor made by means of a soundproofing material placed under the concrete casting.
According to the previously described method, field measurements of reverberation time, background noise and impact sound pressure levels have been carried out in the receiving rooms below the examined floors. These measurements have been made between February and March 2005 and the selected floors are set in dwelling buildings situated in the municipal district of Assisi and Bastia Umbra (Perugia).

5.1 Steel Beam Floor With Sheet

The first test floor consists of the following elements (Figure 1):

- type HEA steel beams and a sheet having a height of 5.5 cm;
- gypsum false ceiling;
- reinforced-concrete slab having a thickness of 3.5 cm;
- concrete having a thickness of 7 cm;
- tile covering of 1 cm (Figure 2).

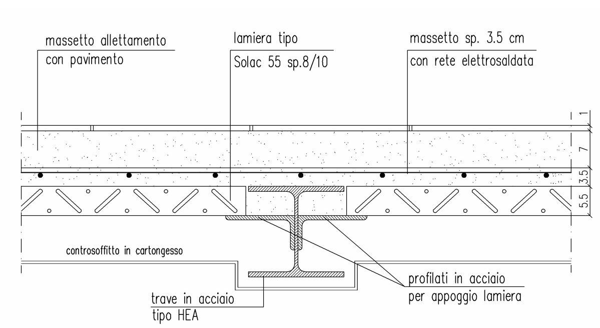

Figure 1: Steel beam floor with sheet
Section

Figure 2: Steel beam floor with sheet
Tapping machine on the floor

The receiving room has a volume of 50.30 m³ and the obtained values are shown in Table 3.

Table 3: Values concerning steel beam floor with sheet

Frequency (Hz)	Background (dB)	L'_{SB} (dB)	L' (dB)	T (s)	A (m^2)	L'_n (dB)	$L'_{n,w}$ (C_I) (dB)	L'_{nT} (dB)	$L'_{nT,w}$ (C_I) (dB)
100	43,4	63,5	63,5	1,27	6,34	61,5	**71 (-12)**	59,5	**69 (-12)**
125	32,2	69,5	69,5	2,16	3,73	65,2		63,1	
160	29,2	69,0	69,0	1,77	4,55	65,6		63,5	
200	31,9	63,1	63,1	2,01	4,00	59,1		57,1	
250	28,6	64,5	64,5	2,49	3,23	59,6		57,5	
315	27,1	62,3	62,3	2,69	2,99	57,1		55,0	
400	27,3	62,1	62,1	2,79	2,88	56,7		54,6	
500	26,2	62,3	62,3	2,73	2,95	57,0		54,9	
630	26,0	63,3	63,3	2,70	2,98	58,0		56,0	
800	26,4	64,9	64,9	2,70	2,98	59,6		57,6	
1000	26,8	65,3	65,3	2,66	3,03	60,1		58,0	
1250	27,6	66,1	66,1	2,54	3,17	61,1		59,0	
1600	28,4	71,0	71,0	2,45	3,28	66,2		64,1	
2000	29,2	70,2	70,2	2,29	3,51	65,7		63,6	
2500	30,0	69,2	69,2	2,09	3,85	65,1		63,0	
3150	30,9	66,7	66,7	1,89	4,26	63,0		60,9	
4000	31,8	63,0	63,0	1,72	4,68	59,7		57,6	
5000	33,0	59,0	59,0	1,51	5,33	56,3		54,2	

5.2 Wooden Beam Floor

The second test floor consists of the following elements (Figure 3):

- wooden main beams (20 x 25 cm) and wooden rafters (8 x 8 cm), shown in Figure 4;
- flat tiles of 3 cm;
- reinforced-concrete slab having a thickness of 4 cm;
- concrete having a thickness of 8 cm;
- tile covering of 1 cm.

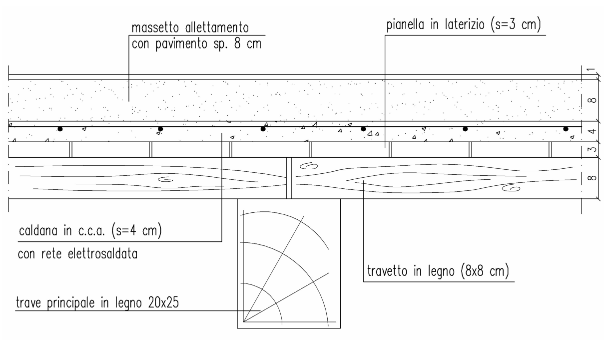

Figure 3: Wooden beam floor
Section

Figure 4: Wooden beam floor
Particular of wooden beams

The receiving room has a volume of 42.46 m³ and the obtained values are shown in Table 4.

Table 4: Values concerning wooden beam floor

Frequency (Hz)	**Background (dB)**	**L'_{SB} (dB)**	**L' (dB)**	**T (s)**	**A (m^2)**	**L'_n (dB)**	**$L'_{n,w}$ (C_I) (dB)**	**L'_{nT} (dB)**	**$L'_{nT,w}$ (C_I) (dB)**
100	36,6	66,6	66,6	2,02	3,36	61,9		60,5	
125	23,5	72,0	72,0	1,93	3,52	67,5		66,1	
160	25,2	71,5	71,5	1,87	3,63	67,1		65,8	
200	26,6	76,0	76,0	1,60	4,25	72,3		70,9	
250	25,8	79,5	79,5	1,78	3,82	75,3		74,0	
315	23,7	81,0	81,0	1,55	4,38	77,4		76,1	
400	23,3	79,7	79,7	1,66	4,09	75,8		74,5	
500	24,0	80,3	80,3	1,68	4,04	76,4		75,0	
630	24,9	80,3	80,3	1,56	4,35	76,7	**84 (-11)**	75,4	**83 (-11)**
800	25,4	80,8	80,8	1,29	5,27	78,0		76,7	
1000	26,3	82,1	82,1	1,15	5,91	79,8		78,5	
1250	27,3	81,5	81,5	1,07	6,35	79,5		78,2	
1600	28,2	80,9	80,9	1,11	6,12	78,8		77,4	
2000	29,1	81,1	81,1	1,14	5,96	78,9		77,5	
2500	30,0	80,1	80,1	1,11	6,12	78,0		76,6	
3150	31,0	77,8	77,8	1,03	6,60	76,0		74,7	
4000	31,9	75,1	75,1	0,96	7,08	73,6		72,3	
5000	33,2	70,7	70,7	0,90	7,55	69,5		68,1	

5.3 Brick-Concrete Floor

The third test floor consists of the following elements (Figure 5):
- bricks (20 cm) and reinforced-concrete slab (4 cm);
- plaster on the lower surface of 1.5 cm;
- concrete having a thickness of 10 cm;

– tile covering of 1 cm (Figure 6).

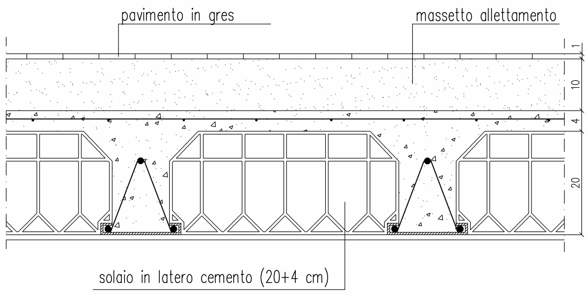

Figure 5: Brick-concrete floor
Section

Figure 6: Brick-concrete floor
Tapping machine on the floor

The receiving room has a volume of 38.43 m³ and the obtained values are shown in Table 5.

Table 5: Values concerning brick-concrete floor

Frequency (Hz)	Background (dB)	L'_{SB} (dB)	L' (dB)	T (s)	A (m^2)	L'_n (dB)	$L'_{n,w}$ (C_I) (dB)	L'_{nT} (dB)	$L'_{nT,w}$ (C_I) (dB)
100	29,0	56,8	56,8	2,67	2,30	50,4	**70 (-9)**	49,5	**69 (-9)**
125	29,2	65,3	65,3	3,35	1,84	57,9		57,0	
160	28,5	66,4	66,4	3,62	1,70	58,7		57,8	
200	30,8	71,4	71,4	3,78	1,63	63,5		62,6	
250	29,2	71,4	71,4	3,82	1,61	63,5		62,6	
315	28,3	71,1	71,1	3,76	1,64	63,2		62,3	
400	28,1	73,0	73,0	4,21	1,46	64,6		63,7	
500	26,8	72,3	72,3	3,48	1,77	64,8		63,9	
630	26,2	73,5	73,5	3,40	1,81	66,1		65,2	
800	26,6	74,3	74,3	3,70	1,66	66,5		65,6	
1000	27,5	74,1	74,1	3,73	1,65	66,3		65,4	
1250	28,0	72,0	72,0	3,44	1,79	64,5		63,6	
1600	29,1	71,0	71,0	2,89	2,13	64,3		63,4	
2000	29,7	70,0	70,0	2,89	2,13	63,3		62,4	
2500	30,1	69,7	69,7	2,89	2,13	63,0		62,1	
3150	30,7	68,2	68,2	2,69	2,29	61,8		60,9	
4000	31,6	63,9	63,9	2,32	2,65	58,1		57,2	
5000	32,5	57,2	57,2	2,00	3,07	52,1		51,2	

5.4 Brick-Concrete Floor With Floating Floor

The fourth test floor is very similar to the third (20 + 4 cm brick-concrete floor, Figure 7). The substantial difference consists in the presence of a floating floor made with a sheet of thermal-acoustic insulating material, type THERMOLIVING [11], laid on the floor and covered with the concrete casting. Besides, the floor has a wooden covering (parquet) of 1 cm (Figure 8).
The receiving room has a volume of 44.70 m³ and the obtained values are shown in Table 6.

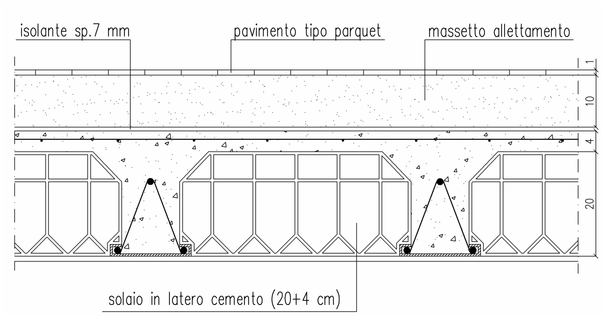

Figure 7: Brick-concrete floor with floating floor Section

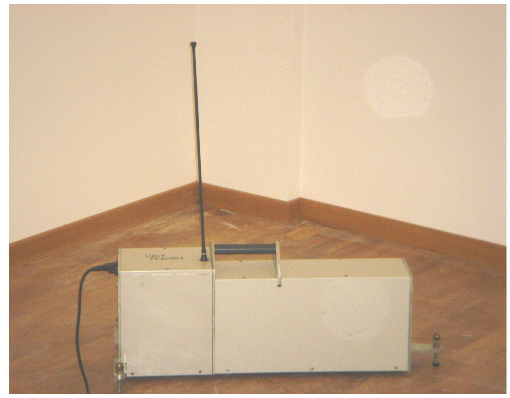

Figure 8: Brick-concrete floor with floating floor Tapping machine on the floor

Table 6: Values concerning brick-concrete floor with floating floor

Frequency (Hz)	Background (dB)	L'_{SB} (dB)	L' (dB)	T (s)	A (m^2)	L'_n (dB)	$L'_{n,w}$ (C_I) (dB)	L'_{nT} (dB)	$L'_{nT,w}$ (C_I) (dB)
100	24,0	57,2	57,2	3,15	2,27	50,8	54 (-2)	49,2	53 (-3)
125	30,1	62,9	62,9	4,39	1,63	55,0		53,5	
160	29,6	62,8	62,8	4,51	1,59	54,8		53,2	
200	32,3	65,0	65,0	3,69	1,94	57,9		56,3	
250	29,1	63,9	63,9	3,70	1,93	56,8		55,2	
315	30,3	65,0	65,0	3,57	2,00	58,0		56,5	
400	30,9	65,9	65,9	3,53	2,03	59,0		57,4	
500	30,7	64,1	64,1	3,45	2,07	57,3		55,7	
630	28,6	63,3	63,3	3,59	1,99	56,3		54,7	
800	27,8	62,9	62,9	3,88	1,84	55,6		54,0	
1000	28,1	60,7	60,7	3,48	2,06	53,8		52,3	
1250	28,4	57,9	57,9	3,35	2,13	51,2		49,6	
1600	29,3	53,3	53,3	3,09	2,31	46,9		45,4	
2000	29,7	49,8	49,8	3,11	2,30	43,4		41,9	
2500	30,3	45,6	45,6	2,90	2,47	39,5		38,0	
3150	31,1	40,3	39,7	2,58	2,77	34,2		32,6	
4000	31,9	33,0	31,7	2,22	3,22	26,8		25,2	
5000	33,5	33,0	31,7	1,84	3,89	27,6		26,0	

6. TOOLS FOR BUILDING ACOUSTICS DESIGN

The possibility of using theoretical models which forecast the acoustic performances of different structures is essential for building acoustics design. The planner is aided by solutions based on experimental data, formulas included in Technical Literature and EN 12354 European standards [12], which supply simplified models of calculation.

By means of a series of algorithms, EN 12354 norms allow to estimate the acoustic performances of buildings from the ones of their single elements. Unlike other standards, which are instruments of verification, EN 12354 series constitutes a predictive method.

The importance of acoustic design is underlined also by the recent development of softwares based on the formulas contained in EN 12354 norms. ECHO 4.0 [13] is an example of software for the verification and the plan of passive acoustic requirements of buildings, based on a simplified method of calculation that, as far as impact sound, is referred to EN 12354-2 [14]. According to this standard, $L'_{n,w}$ is calculated with the following formula:

$$L'_{n,w} = L_{n,w,eq} - \Delta L_w + K \quad (dB) \tag{3}$$

where:

- $L_{n,w,eq}$ is the equivalent weighted normalized impact sound pressure level of the floor structure, according to ISO 717-2 [10];
- K is the correction for impact sound transmission over the homogenous flanking constructions (see EN 12354-2 [14]);
- ΔL_w is the weighted reduction in impact sound pressure level of resilient coverings or floating floors, according to ISO 717-2 [10].

6.1 Comparison Between Experimental Data And Software Output

The results of field measurements concening the two brick-concrete test floors have been then compared with the software output obtainable for the same structures. The software does not provide for steel or wooden beam floors, instead.
The brick-concrete floor having a height of 20 + 4 cm is included in software database [13] and has $L_{n,w,eq}$ = 68.4 dB. Considering the floor lacking in soundproofing, therefore with ΔL_w = 0.0 dB, and assuming K = 3.0 dB, the value of $L'_{n,w}$ given by the software equals 71.4 dB, while the experimental data drawn from field measurements is 70.0 dB.
For the brick-concrete floor comprehensive of floating floor, instead, ΔL_w equals 18.0 dB, value obtained from laboratory tests carried out on the soundproofing material [11] by an Italian certification institute. In this case the software output is $L'_{n,w}$ = 53.4 dB, in agreement with the value of 54.0 dB deduced from field measurements.
Experimental data and software output are compared in Table 7.

Table 7: Comparison between experimental data and software output

$L'_{n,w}$	Field measurements	Software prediction	Difference
Brick-concrete floor	70.0 dB	71.4 dB	+ 1.4 dB
Brick-concrete floor with floating floor	54.0 dB	53.4 dB	– 0.6 dB

To conclude, the comparison confirms that, as far as impact sound insulation for the two examined floors, the adopted software [13] supplies reliable results, with differences of about 1 dB compared with field experimental data, and can therefore be a useful instrument for the verification and plan of building acoustics passive requirements.

7. CONCLUSIONS

In the present paper passive acoustic requirements for buildings have been examined, with particular attention to impact sound insulation of floors. Field measurements have been executed in order to determine the acoustic performances of different typologies of floors in dwelling buildings and verify whether the corresponding weighted normalized impact sound pressure levels are lower (as required) than the limits provided by Italian DPCM [1].
On the basis of field measurements, the tested steel beam floor, wooden beam floor and brick-concrete floor without floating floor don’t respect the limit of DPCM in dwellings (63 dB) or in the other categories of buildings. Another brick-concrete floor have been then

examined, supplied with a floating floor, to estimate its effective impact sound reduction. In this case $L'_{n,w}$ respects the limit of DPCM [1] for dwellings and every other building destination. The tested floating floor shows that by reducing the vibrations between the structures, with insulating materials, the sound transmission is mitigated.

Field measurements have been carried out also in order to verify the reliability of a predictive software [13], implementing a simplified model of calculation. Weighted normalized impact sound pressure level for the first brick-concrete floor, calculated by the software, has come out of approximately 1 dB higher than the one obtained experimentally: in this case the software has operated in favour of safety. For the brick-concrete floor with floating floor, instead, the software output has come out lower than the value drawn from experimental data, but with an error smaller than 1 dB. On the basis of the present observations, we can therefore conclude that the results obtained with the adopted simulation model [13] for the floors under test are in agreement with the experimental data.

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