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Sound Insulation and Flanking Transmission: from U.E. Directive 89/106 to the flanking transmission loss experimental measurement

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Sound insulation in buildings is strongly affected by flanking transmission due to the structural links of walls, floors and ceilings. The acoustic performance of a single partition evaluated in a standard laboratory can not describe his effective behaviour in a real situation due to the contribution of this additional amount of energy to the sound level in a receiving room. Previsional evaluation of the energy transmission in buildings was always one of the main problems in architectural acoustics due to the difficulty to modelize complex structures, but the new approach described in the EN 12354 define a simplified model that require the knowledge of some coefficient, usually not so well known, to be determined with empirical formulas or experimentally in the field. In any case, the sound insulation loss must be evaluated on the basis of frequency bands. This lecture will give a panoramic overlook to the development of sound insulation theory from the sixties, when a new standardisation work, based on the needs of inhabitants better than on the performances of the construction elements started, to the actual standards and experimental facilities needed. The preparatory working group for issuing the European Directive 89/106 was anxious to simplify the usual approach to the acoustical problems, more troublesome than the energetic, structural and fire-saving ones, due to the frequency spectrum. When ISO and CEN began their work towards new standards stating how it was possible to reach good performances of a building starting from the performances of individual components, they faced also the problem of summarizing a complex of data in a single number, so loosing the clarity of the frequency detail in favour of a misleading index: this lecture will examine also this problem putting in evidence that both researchers and acoustical consultants cannot forget that sound is a frequency dependent physical phenomenon.

1. INTRODUCTION

Sound insulation is a peculiar characteristic of buildings whose interest has grown during the years after the second world war, starting from the fundamental works of Cremer [1,2] and London [3,4] and following quite an exponential law, supported by enhanced knowledge of mathematics and computer science, but also by the growing request of comfort from people living inside buildings.

Nowadays, people is living in an environment more and more polluted and made unfriendly chiefly from its own activities, so, not only coming back at home but also at workplace, people requires protection from the products of others' life: homes, and in general buildings, must keep out hot, cold, moist air, radioactive gases like Radon, organic volatile components like benzene and so on, smog in general, and also noise.

Designers and building manufactures are asked to produce walls that can protect from noise coming from traffic, working and amusement activities, heating and air conditioning plants and so on, having in mind that the noise can be produced both outside and inside the building: for instance, how many people have experienced, even in a very expensive hotel, the noise of the bath, telephone or TV, coming from another room!

As clearly and exhaustively presented by Cops[5] at Inter-noise 94, there are many possible methods to predict or check the acoustic behaviour of a partition or façade wall, but the sound insulation of even a very good element can be deeply penalized by the way it will be connected to other boundary elements.

Furthermore, but this is not only a matter of acoustics, we can realize good elements (walls, windows, ventilation elements an so on) with different kinds of materials so affecting more or less the capability of the building to keep out hot, cold, V.O.C., Radon, bacteria and so on: even if at the beginning each designer was able to think only to one aspect of the whole problem, now it is clear that the acoustician should know and manage the other aspects of the problem or must talk with other professionals, and vice versa.

2. SOUND INSULATION

From the energetic point of view, when some force generated by an acoustic field is applied to a surface separating two different media, a fraction of the energy is redirected back while the remaining part can cross the surface and propagates into the second medium: in real structures of finite thickness, we have always a sequence of three media, air-solid-air, where the solid presents bigger impedance than air to the propagation of the sound energy. So, while crossing the solid, a certain amount of mechanical energy is dissipated like thermal energy or heat, with an entropy increase: when dealing with the propagation of an acoustic wave, the quantity of energy is very small and temperature and entropy usually increases are insignificant. This means that usual thermodynamic approach of analysis are not well practicable for the structure-borne sound. Furthermore, if one try to explain the absorption of acoustical energy within a medium when the energy is already converted into heat, any information about frequency is loose and we get the only information that heat is able to tell: some amount of good mechanical energy has gained the lowest level of usefulness!

The evaluation of the amount of energy reflected in the first medium and of that dissipated in the second one is in general of difficult experimental measurement, without loosing any spectral information. Then, the problem of evaluating the acoustic insulation of a partition to an exiting airborne sound can usually be faced in the classical way, that is comparing, in a frequency domain, the energy transmitted in the third medium to the incident one: this can be made theoretically in terms of force per unit of surface (or pressure) and local velocity of acoustic waves or, experimentally, with sound pressure levels and intensity levels, as it is usual in acoustics.

Maybe anybody is aware of this, but for the only one acoustician who doesn't know this misleading terminology, we remember that both academically and in practice it is usual to distinguish between **airborne sound insulation** and **impact sound insulation**, where the first one refers to structures excited by acoustic waves travelling in air, while the other concerns an exciting force generated by a solid impacting the structure: but in any case the transmission of the acoustic wave takes place along a solid structure and the physical rules are the same, even if the response of the structure differs both in the frequency range and for the amount of energy involved.

So, it would be possible to study the sound insulation of a structure with the same mathematical approach: this approach will be of particular interest for horizontal partitions, making possible to correlate the airborne sound insulation of a floor to its impact sound insulation.

If we face the problem under this point of view, we need first of all to pay homage to Manfred Heckl, whose scientific life vas devoted to "Vibroacoustics" or "Structural Acoustics", the branch of knowledge dealing with ***the forms, characteristics and effects of interaction between vibrational disturbances in solid structural elements and acoustic disturbances in fluids***

contiguous with structures, conventionally ***referred to such processes which occur within the audio frequency range*** (Fahy[6]).
If we read the fundamental survey paper by Heckl[7], we find this correlation in the very simple equation:

$$L_N + TL = 43 + 30\log(f) \qquad [\text{dB}] \tag{1}$$

where L_N is the impact noise level, TL is the transmission loss and f the frequency in Hz.
We always think that the nature is very complicated to understand but, anyway, it is necessary to find simple relationships to model mathematically its behaviour: Newton, Ohm, Einstein and, in our little field, Sabine formulas are only some milestones on the way of the knowledge, and even in the computer era, where complicated equations are solved in a very short time, they are not obsolete when we need a quick response to the most common problems of our life.
However, if we don't like to get hold of the wrong end of the stick, the input to these simple formulas is sometime very complicated, as it is for instance the case of (1) where either LN or TL must be known very well, that means having carefully avoided any influence of a particularly enhanced airborne transmission (as it is the case in presence of resilient layers on the floor) and/or of flanking transmission. The use of simple formulae like (1), the mass law for sound insulation, and other semi-empirical formulations, can lead to mistakes or erroneous understanding of the real performances of a partition, as shown in the following figure 1: acoustic parameters, TL or R, and L_n, are measured in situ where flanking transmissions coming from lateral structures or heating system piping and other workmanships, affect the effective insulation of a floor.

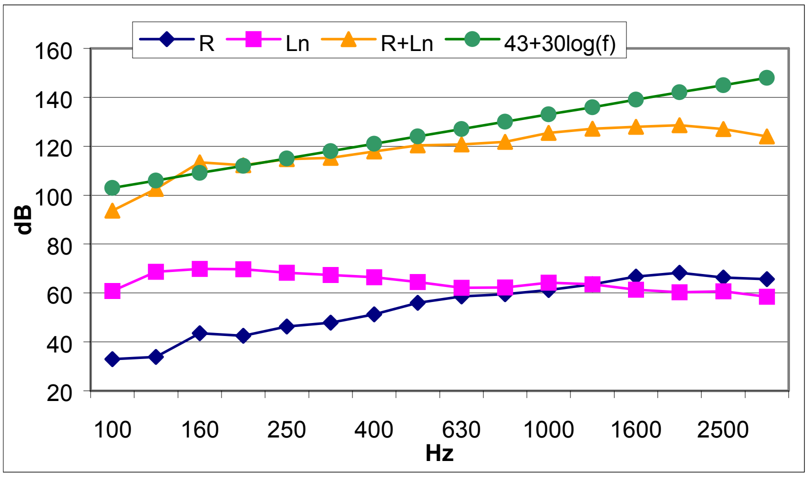

Figure 1. *In situ sound reduction index and impact sound insulation for a concrete slab floor .*

3. FLANKING TRANSMISSION

When the sound field generated by a source in a room excites a partition wall between two rooms (see figure 2), some fraction (τ_d) of the acoustic incident energy crosses the boundary wall and is transmitted to the receiving room: in common buildings some other fraction of the energy can reach the receiving room through other different ways and the sum of all fractions ($\tau_f + \tau_s + \tau_e$) affects the received sound level so reducing the sound insulation between the two rooms: generally speaking we can say that this reduction is due to the flanking transmission, even if the structure born sound is, strictly speaking, only (τ_f).

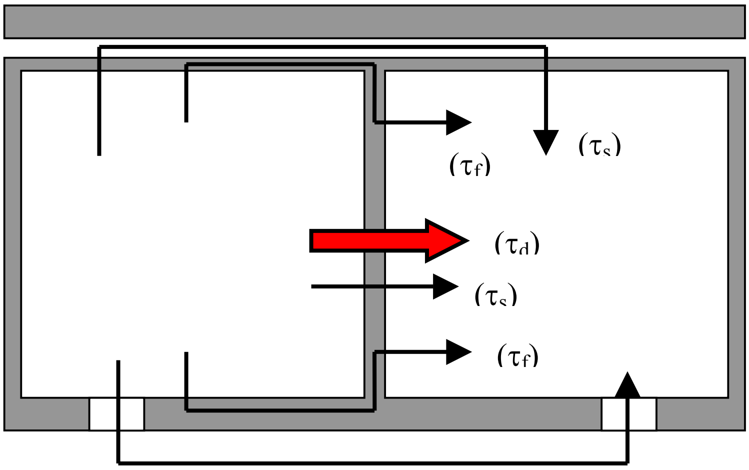

Figure 2. *Direct(τ_D) and flanking (τ_f, τ_s, τ_e) transmission coefficient .*

Any term τ_i, representing a transmission factor related to the incident energy on the source room, is in general a very small quantity, so it is usually preferred to work with logarithmic expressions. Concerning the energy transmitted only by the partition, we are usually defining the Sound Reduction Index R, frequency depending, with the following relationship:

$$R = 10\log\left(\frac{1}{\tau_D}\right) \qquad [\text{dB}] \qquad (2)$$

When R is measured in a test facility with flanking transmission suppressed, as requested in the relevant EN-ISO 140-1 Standard [8] only the direct transmission through the partition is evaluated, this depending on the physical characteristics of the partition and of kind of connection to the source room (usually not relevant).
In a real building the same performance of the partition, influenced by flanking transmissions, the Apparent Sound Reduction Index R’ is defined with the following relationship:

$$R' = 10\log\left(\frac{1}{\sum \tau_i}\right) \qquad [\text{dB}] \qquad (3)$$

As an example, figure 3 shows a comparison between the apparent sound reduction index R' for a 7 m^2 double masonry wall and the laboratory values of R of a similar wall, where differences are very important especially at low frequencies. Usually designers refer to laboratory data sheet of a product but the effective insulation in a building construction depends on the size of the wall and particularly on the flanking transmission. The reduction of R due to structural flanking transmission is strongly related to the ratio of the surface masse of partition to those of lateral walls, and of kind of junction.

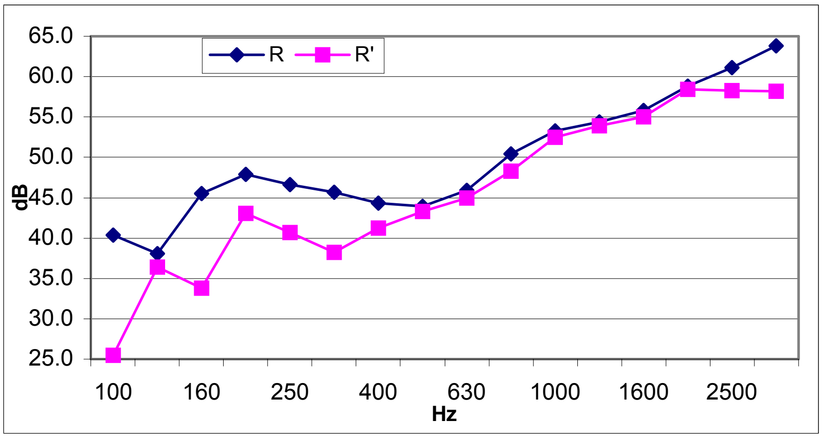

Figure 3. *Comparison of R and R' for a double masonry wall* .

4. PREVISIONAL MODELS

Theoretical evaluation of acoustic performances of building and of building components has been for many years one of the main fields of research on acoustics. Structure-borne sound theory has been well developed [9, 10] for simple homogeneous thin plate and it is the usual background for solving any sound insulation problem: mass, spring, damper are the simplest models to describe the frequency behaviour of a plate, in particular for the explanation of the "mass law" and of coincidence and resonance effects.

Deterministic models based on a physical description of the system have not successful in the past due to the complexity of the building construction, to the non homogeneity of materials and mainly to the so wide frequency field of investigation connected to the audio frequencies. Anyway, some investigations in last years have been carried out using FEM, BEM or hybrid methods for the analysis of particular junctions and at low frequencies. But energetic models seems to be less time consuming and give better results especially in the audio frequency domain.

At the end of sixties the new approach called Statistical Energy Analysis (S.E.A.) was developed by Lyon [11]. This approach was successfully used for energy transmission through complex structures where assumptions of the method (uniform distribution of the modal energy density in each subsystem into which the system can be divided) are well satisfied, like aircraft and naval structures. Due to his validity especially at medium and high frequencies, S.E.A. was also used for building acoustics analysis. Experiences were first developed by Crocker [12] until Gerretsen [13] and Craik [14]. Nevertheless, S.E.A. models are still too complex because they require lot of parameters related to coupling loss factors between connected structures.

Even if S.E.A. or modified energetic models will be suitable methods for the analysis of structure-borne and air-borne noise transmission through the whole building, a more simplified model was required for the evaluation of sound insulation problems between adjoining rooms. This new model was developed by CEN/TC 126 and now approved as an international standard in the EN 12354 [15]: the idea was to develop a simplified method based on S.E.A. assumption, using performance data of single building products measured in laboratory. As shown in figure 2, the sound transmission from the source room to the receiving room, is outlined as an overlapping of acoustic and vibration energies propagating in different ways: the direct path through the partition and flanking paths through lateral structures. The apparent sound reduction index R' can then evaluated from the knowledge of the sound reduction index of the direct path (R_d) and of lateral paths (R_{ij}).

$$R' = -10\lg\left(10^{-R_d/10} + \sum 10^{-R_{ij}/10}\right) \qquad \text{[dB]} \tag{4}$$

$$R_{ij} = \frac{R_i + R_j}{2} + \Delta R_{ij} + K_{ij} + 10\lg\frac{S}{l_0 l_{ij}} \qquad \text{[dB]} \tag{5}$$

where:

R_i, R_j are the sound reduction index of structures involved in the lateral transmission,
ΔR_{ij} is the sound reduction index improvement by additional layers for separating elements,
K_{ij} is the vibration reduction index for each transmission path ij over a junction
S is the area of the partition,
l_0, l_{ij} are respectively the reference length and the coupling length between elements i and j depending on the structural reverberation time of elements.

All these parameters must be evaluated in a standard laboratory and corrected to structural reverberation time of the in situ installed product to take into account the real building configuration.

In this way not only the sound reduction index is a characteristic parameter of the partition, but also the vibration reduction index K_{ij} are characteristic of the joint and of connected structures and therefore they must be evaluated by a standard procedure.

Waiting for a standard procedure for the evaluation of K_{ij}, the EN 12354 give simplified formula related to surface masses of structural elements involved in the flanking transmission. The application to the typical configuration of Italian buildings, where concrete joist and brick floors have a surface mass of about 350 kg/m^2 and the lateral internal partitions have a surface mass of about 150 kg/m^2 (the ratio between the surface masses of the flanking structures is 1 to 2,3), gives results as reported in table 1 for a rigid cross junction [16]. A global contribution to flanking transmission is evaluated, due to all flanking paths between source and receiving rooms, whith values increase as the mean surface mass of flanking walls decreases respect to those of the partition.

Table 1: *Global contribution to flanking transmission for rigid cross junctions and ratio 1:2,3 between surface masses of flanking structures.*

Surface mass of the partition (kg/m²)	Mean surface mass of flanking structures (kg/m²): 100	150	200	250	300	350	400	450	500
100	2.5	1.5	1.0	0.5	0.5	0.0	0.0	0.0	0.0
150	4.0	2.5	1.5	1.0	1.0	0.5	0.5	0.5	0.5
200	5.0	3.5	2.5	2.0	1.5	1.0	1.0	0.5	0.5
250	6.0	4.5	3.0	2.5	2.0	1.5	1.0	1.0	1.0
300	7.0	5.0	4.0	3.0	2.5	2.0	1.5	1.5	1.0
350	7.5	6.0	4.5	3.5	3.0	2.5	2.0	1.5	1.5
400	8.0	6.5	5.0	4.0	3.5	3.0	2.5	2.0	2.0
450	8.5	7.0	5.5	4.5	4.0	3.5	3.0	2.5	2.0
500	9.0	7.5	6.0	5.0	4.5	3.5	3.0	3.0	2.5

5. EXPERIMENTAL EVALUATION OF ACOUSTIC PERFORMANCES OF BUILDING PRODUCTS

Many investigations have been carried out on sound insulation both in standard laboratory and in situ inside buildings, with different measurements techniques.

Classical technique for laboratory sound reduction index measurements, according to EN ISO 140–3 standard, is based on the measurement of sound pressure levels both in source and receiving room, supposing a diffuse sound field in the source room:

$$R = L_{p1} - L_{p2} + 10\lg\frac{S}{A} \qquad [\text{dB}] \qquad (6)$$

where L_{p1} and L_{p2} are the time and space averaged sound pressure levels in the source and receiving room. Recent round robin tests [17, 18] show a poor repeatability of data for different laboratory with flanking transmission suppressed, depending on background noise that influences measurement at low frequencies, on room dimensions and on typical junction of the test partition. So a revision of the standard is needed including new measurement techniques like MLS or intensity method.

Concerning the laboratory measurement of the vibration reduction index K_{ij}, a new standard project is in progress by CEN [19]. At this stage two different methods are proposed for the evaluation of K_{ij}: a direct method, based on the measurement of the average vibration level difference $D_{v,ij}$ on two structures connected at the joint and of structural reverberation time of both elements, by the formula (7), and an indirect method based on the measurement of the normalised sound pressure level difference $D_{n,f}$ between two rooms when only the flanking path ij is affected by noise transmission. Also different measurement techniques are proposed, sound or impact excitation, stationary or impulsive methods, all requiring more investigation for the reliability and repeatability of results. We must keep in mind that K_{ij} values can affect the apparent sound reduction index for only few dB: in many cases the difference between R'_w and R_w can usually vary from 1 to 3 dB, i.e. very near the margins of uncertainty of the method, as shown in figure 4.

$$K_{ij} = \overline{D_{v,ij}} + 10\lg\frac{l_{ij}}{\sqrt{a_i a_j}} \qquad [\text{dB}] \tag{7}$$

$$K_{ij} = D_{n,f} - \left(\frac{R_i - R_j}{2}\right) + 10\lg\frac{l_{ij}}{\sqrt{a_i a_j}} + 10\lg\left(\frac{\sqrt{S_i S_j}}{A_0}\right) \qquad [\text{dB}] \tag{8}$$

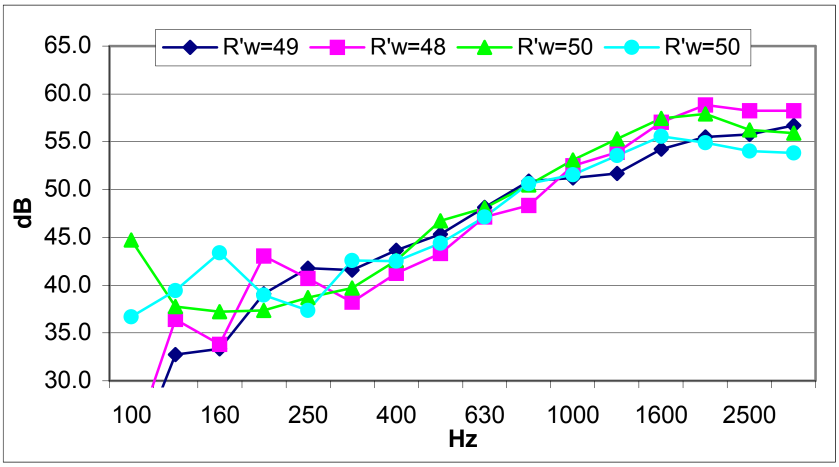

Figure 4. *Double masonry wall: comparison of R' values for 4 different installations*

6. THE DIRECTIVE 89/106

In the sixties a new approach to the problem of comfort in dwellings has been carried on by the Emilia Romagna regional government, based on the needs of inhabitants better than on the performances of the construction elements [20]: completely changing the point of view, as it concerns the acoustic behaviour of external walls, internal partitions and floors, this approach asked that within the living and sleeping rooms of the flat there must be well specified maximum values of sound pressure level, independently from the environmental level of noise.
This meant that the acoustician was involved in calculations to evaluate in each situation the necessary sound insulation spectrum: only after that it was possible to choose the best fitting wall, partition or floor.
Some time after, the U.E. Directive 89/106 stated that, among the others, external walls, internal partitions and floors must assure protection also from noise, and that this protection should be expressed by a single number: TC/5 stated that CEN had to be charged to prepare adequate standards, allowing to perform measurements both in laboratory and in the field, then to derive from the spectrum of the sound reduction an index to be used in legal statements.

Some time after, Italy decided to state at national level the amount of protection from noise to be realized independently from the external noise level.
The evolution of the original criterion seems to be very dangerous for many reasons, that can be summarized in:

- a misleading easy calculation of the inside sound pressure level, based on the idea that one can get this value simply subtracting the value of the index from the outside sound pressure level, moreover expressed in dB(A), independently from the shape of spectra of both external noise and sound insulation;
- many building designers, not acousticians, try to be judged as experts simply telling that this calculation must be performed at 500 Hz;
- even some acoustician choose its walls missing to give a look to the polluting spectrum, so neglecting to take into account the possible presence of frequency bands of particular interest (for instance in the presence of pure tones and/or low frequencies).

In front of this situation, any acoustician in charge of teaching building acoustics must take care to put in clear evidence the difference existing between different parameters that seem to signify the same thing: this is the case for instance of STL or simply TL (sound transmission loss), IL (insertion loss, correctly defined only for barriers and other devices inserted along a well specified sound path), R (sound reduction as intrinsic parameter of a wall or some device to be inserted in a facade), R' (apparent sound reduction index, taking into account also the effect of flanking transmission paths), D (sound pressure level difference, measured for instance between to rooms or outside and inside a room faced to the street), and the corresponding rating indexes.
Only if we win our fight against the deceptive simplicity of sound insulation indexes, the big amount of work made by researchers like Cremer, London, Cops, Heckl, Fahy and many, many others, will be of wide usefulness for those that are involved in design of building well shielded against noise.

6. CONCLUSION

From the above exposition of the state of art in the field of sound insulation, it is evident that much work must still be done: we need to improve the theoretical means of research, so reducing the uncertainty of our provisional techniques: if we get this result, then even some dB gained with a better knowledge of the coefficients K_{ij} can be useful, so encouraging more sophisticated researches in this particular field.
Common people not involved in acoustics can think that only few dB are of little interest, but we know that 3 dB are equal to a 50% gain in terms of acoustic energy, so it is very important to have the possibility of measuring sound insulation with and without of different kinds of flanking transmission: this is the reason why we have decided to build a new experimental facility where it is possible to realize any kind of link between the adjoining walls and the specimen under test, that can be either vertical or horizontal.

Figure 5. *The elastic suspensions of the whole system*

Figure 6. *The two rooms physically disconnected*

Now check tests are running, but in a very near future we think we will able to present some interesting result, as we have already planned the first measurement program dealing with impact sound insulation on a masonry and reinforced concrete made ceiling.

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