41

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INFLUENCE OF BOUNDARY ENERGY LOSSES ON SOUND TRANSMISSION THROUGH WALLS

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ABSTRACT

Vibration energy losses at the boundary of a planar wall greatly influence the wall's sound reduction index.

The extent of these losses depends on the structural characteristics of the boundaries, and on the coupling between them and the wall.

The importance of these vibration boundary conditions was first pointed out in a theoretical study and afterwards confirmed by experiments, carried out in a standard laboratory insulation testing facility.

Results show that the present International Standards do not adequately allow for this problem, and therefore make it possible for the same specimen to give very different results in different boundary situations. They also show that the measurement of the structural (or vibration) reverberation time gives an estimate of the boundary losses, enabling the experimenter to correct the sound reduction measurements, and compensate for the particular characteristics of the test site.

In alternative, it has been shown that acoustic intensity mappings or vibration velocity mappings can be used for this goal.

THEORY

The sound reduction index **R** of a wall is usually defined as:

$$\mathbf{R} = 10 \cdot \lg \left(\frac{P_{inc}}{P_t} \right) \qquad \text{(dB)} \qquad (1)$$

where P_{inc} is the total acoustic power incident on the wall, and P_t is the acoustic power passing through.

Laboratory measurements of the sound reduction index in conformity with ISO 140/3 give values which do not correspond to any of the four possible definitions of this property in relation to the four theoretical boundary conditions, that are:

1) undefined plate affected by the sound field over its entire area;
2) finite plate with anechoic termination on the boundary (roughly equivalent to an undefined plate with only a finite portion affected by the sound field);
3) plate of finite dimensions with its boundary restrained with a fix joint;
4) plate of finite dimensions hinged on its boundary.

(please note that the free-edge condition is not applicable to the definition of R!).

In normal laboratory testing facilities that are in conformity with ISO 140/3 the measured value of **R**, however, results from a boundary condition that lies between the no. 3) and 4) (whilst it would be desirable to obtain the **R** value for the first condition), providing us with a fifth, *real-word* condition:

5) plate of finite dimensions surrounded by constraints with finite rotational and translational

impedances.

In this case, one has to take into account the existence of a certain power quota which is transmitted by the test wall towards the boundary structures (a well-shielded source room should not transmit any power from the boundaries to the wall under test).

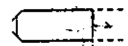
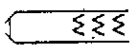
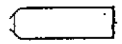
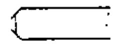
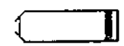
The transmission of this power towards the boundary can influence the measured **R** value quite significantly, as pointed out by Gerretsen [1], who found variations of 3 ÷ 5 dB between one laboratory and another.

To reduce this problem a possible solution would be to standardize the boundary structures of the various laboratories. Alternatively, we suggest procedures for correcting the measured values, evaluating the boundary effects always present. The correction should be included in the test report.

The boundary effect could be calculated analytically or ascertained experimentally by determining the structural reverberation time of the test panel and of the boundary structure. [2],[3].

In this formulation, the boundary effect is quantified by a linear absorption coefficient α_{lin}, which represents the ratio of the vibrational energy "*absorbed*" by the boundary to the vibrational energy incident on the boundary. This coefficient is, in effect, a coefficient of apparent vibrational absorption, in strict analogy to the (surface) acoustic absorption coefficient α_s: in fact the vibrational energy removed from the vibrating panel by the boundary is only in part dissipated in heat; part of it is transmitted elsewhere and, in the case of sound reduction index measurements, it can, to a certain extent, contribute to the sound field in the receiving room.

The value of the linear absorption coefficient for each of the possible constraint conditions is given in the following table, in which the structural boundary condition is compared with the corresponding termination of a standing wave tube:

Condition no.	Structural boundary condition	Parameter	Acoustical boundary condition	Parameters
1		α_{lin} not def.		α_s, CRF not def.
2		α_{lin} = 1		α_s=1 CRF=0
3		α_{lin} = 0		α_s=0 CRF=1
4		α_{lin} = 0		α_s=0 CRF=-1
5		0 < α_{lin} < 1		0<α_s<1 CRF=a+jb

The first condition requires further explanations: there is, in fact, an energy flow along the plate. However, looking at any boundary line on its plane we find that the outgoing energy flow is exactly compensated by an equal flow in the opposite direction. Therefore, from the energy view point, it is as if each finite portion of the undefined plate were surrounded by a boundary which didn't absorb any energy at all.

The constraint condition no. 3 is the one that most resembles cond. no. 1, if we consider how the plate vibrates. Therefore, from this analysis we can conclude that to correctly measure the sound reduction index of a wall in a laboratory, it is necessary to fix the wall onto a boundary with infinite translational and rotational impedances (that is, with infinite mass and stiffness).

Since in reality measurements are carried out in condition 5, we have to analyze in detail the reasons for which the measured **R** value is different from the "true" **R** value.

In each of the cases 1), 3) or 4), the total incident power P_{inc} is divided into three parts: P_r is reflected back into the transmitting room, P_a is dissipated as heat within the wall, and P_t is transmitted into the receiving room.

In condition 5 the total incident power is divided into four parts: the three above mentioned and a fourth, P_{bound}, which is transmitted to the boundary structures. P_{bound} divides into three parts too: P_{br} is sent back by various pathways to the transmitting room, P_{ba} is dissipated as heat and P_{bt} is transmitted into the receiving room.

The sound reduction index measurement which results, R_{meas}, can be expressed as follows:

$$R_{meas} = 10 \cdot \lg \left(\frac{P_{inc}}{P_t + P_{bt}} \right) \quad (dB) \qquad (2)$$

Looking at this formula, it seems that R_{meas} should always have a lower value than the theoretically defined **R**. However, it should be also noted that the division of the incident power into 4 parts can have the effect of reducing the power transmitted P_t; this effect tends to increase the value of R_{meas}: if the boundaries are very absorbent (condition 2 is the limit case), there is a relevant increase of the measured sound reduction index.

The power quota transmitted by the boundaries, P_{bt}, can be greatly reduced by using appropriate construction methods of the laboratory, such as completely separating the structures of the two rooms and covering them with resilient skins, which reduce the acoustic radiation.

Let we consider P_{bt} negligible; then, if we can determine the value of α_{lin} of the boundaries, which depend on both the wall under test and on the particular test site; it is possible to correct the measured value of **R** using the following formula, which is valid only for frequencies above the critical frequency:

$$R_{corr} = R_{meas} - 10 \cdot \lg \left(\eta_i + \frac{\rho \cdot c \cdot \sigma}{\pi \cdot f \cdot m} + \frac{c_b \cdot \sum_i l_i \cdot \alpha_{lin_i}}{\pi^2 \cdot S \cdot \sqrt{f \cdot f_c}} \right) + 10 \cdot \lg \left(\eta_i + \frac{\rho \cdot c \cdot \sigma}{\pi \cdot f \cdot m} \right) \quad (dB) \qquad (3)$$

where η_i is the internal loss factor of the wall, $\rho \cdot c$ is the impedance of the air, σ is the radiation ratio, f is the frequency considered, m is the superficial mass of the wall, c_b is the propagation speed of the bending wave l_i is the lenght of the boundary i, S is the area of the test wall, and f_c is the critical frequency.

The internal loss factor η_i for common homogeneous buildings materials is roughly 0.01 . Above the critical frequency f_c, the radiation ratio σ can be assumed to be 1.

For example, assuming a linear absorption coefficient α_{lin} = 0.05, a brick wall having m = 100 kg/m^2, l=12.6 m, f_c = 357 Hz, a longitudinal wave velocity c_L= 1800 m/s, at f=1000 Hz a bending wave velocity c_b=569 m/s is found. With these data, the difference R_{meas} - R_{corr} results 1.92 dB.

A precise assessment of the α_{lin} value can, however, be obtained only for boundary structures with simple geometric shapes. Accelerometric measurements of the vibration speed of the two elements (the test wall and the boundary structure) and of the structural reverberation time T_j of the boundary are used to obtain the data required for the following formula:

$$\alpha_{lin(i \to j)} = \frac{v_j^2}{v_i^2} \cdot \frac{m_j}{m_i \cdot c_{bi}} \cdot \frac{2.2 \cdot \pi^2 \cdot S_j}{l \cdot T_j} \qquad (4)$$

where v is the vibration speed, m is the surface mass, c_b is the bending wave speed, S is the area, l is the border lenght, and T the structural reverberation time; the subscript i refers to the test wall, and the subscript j to the boundary strueture.

EXPERIMENTS

Experiments evaluating the boundary effect on common types of walls have been carried out at the acoustic insulation laboratory of the University of Parma. This laboratory consist of two rooms, and conforms to the regulation ISO 140/1 and /3.

This laboratory is however particular in that it uses a boundary structure of limited mass and rigidity: a solid brick wall, 25 cm thick, with a surface mass of 477 kg/m^2, with resilient skins obtained using plasterboard and an air space filled with mineral wool. The receiving room has the same structure and there are not solid connections between the two rooms, which rest entirely on two indipendent floating fundations.

It is therefore presumable that in this laboratory there will be a considerable energy flow from the test wall to the boundary structures. This flow will obviously be greater when the test wall has inertial characteristics and rigidity comparable to those of the costraints.

The testing was carried out with 2 samples: the first consisted of a hollow brick wall with granular filling, with a total thickness of 28.5 cm and a surface mass of 260 kg/m^2. The second consisted of a laterocement floor with a total thickness of 25 cm and a mass of 361 kg/m^2.

Tests were carried out on each wall using three different procedures:
- traditional measurement of R in conformity with ISO 140/3;
- intensimetric measurement of R, employing an intensity probe at the receiving side;
- accelerometric measurement of the vibration speed levels on the wall surface facing towards the receiving room.

Mappings of the measured entity (acoustic intensity and velocity) were provided by the second and third measurement technique. These mappings were obtained from a grid of 7x6 measurement points set out regularly on the wall.

Figures 1 and 2 show two of these maps for sample B, at the frequency 2000 Hz: particularly in fig 1 we can see that most of the intensity flux flows out across the perimeter of the wall.

The determination of R with the last two techniques is based on the evaluation of the total acoustic power radiated from the test wall to the receiving room, P_t. The evaluation of this quantity is straightforward from the intensity levels L_i measured at the N (42) grid points, as:

$$P_t = 10\cdot lg\left(\frac{1}{N}\cdot\sum_{i=1}^{N}10^{L_i/10}\right) + 10\cdot lg(S) \qquad (\text{dB re } 10^{-12}\text{ W}) \qquad (5)$$

Also from the velocity data the total radiated acoustic power can be computed, as:

$$P_t = 10\cdot lg\left(\frac{\sigma\cdot\rho\cdot c\cdot S\cdot\bar{v}^2}{10^{-12}}\right) \qquad (\text{dB re } 10^{-12}\text{ W}) \qquad (6)$$

where the radiation ratio σ can be assumed equal to 1 above the critical frequency, and $\bar{v}$ is the surface averaged mean square value of the velocity.

The value of R is then obtained as difference between P_{inc} and P_t, the incident power P_{inc} being evaluated from the spatial averaged sound pressure level in the source room L_{ps}:

$$P_{inc} = L_{ps} + 10\cdot lg\left(\frac{S}{4}\right) \qquad (\text{dB re } 10^{-12}\text{ W}) \qquad (7)$$

The diagrams of the sound reduction index R versus frequency for the samples A and B are shown in figures 3 and 4. The three curves drawn on each diagram relate to the three measurement techniques used: we can see that in sample A all three provided almost the same results, while in sample B the accelerometric measurement gave rise to consistent deviation (but in this case it was very difficult to get the accelerometer to stick to the surface of the sample).

To eliminate the boundary effect from the measurements taken we did not follow the theory quoted, which would have required detailed accelerometric surveys of the boundary structure of the transmitting room; instead we simply used the 5x4 points from the central zone of the intensity and velocity mappings to recalculate R.

The results of this operation can be seen in figures 5 and 6, where they can be compared with the corresponding R curve for the whole wall measured with the intensity probe.

CONCLUSIONS

The theory here reported does make it possible to correct the results of laboratory measurements of R to allow for the effects of boundary absorptions, but it requires extra measurements of vibration velocity and of structural reverberation time, and an estimate of the internal loss factor η_i of the wall under test.

It has been shown that intensimetric surveys covering the entire testing area provide an R value which closely coincides with the traditional one, obtained in conformity with ISO 140/3; the intensity mappings obtained have shown that the central area of the wall is not affected by boundary effects. Therefore if we use only the intensimetric survey of this central area it is possible to assess the sound reduction index R of an *undefined* wall.

As a third possibility, accelerometric measurements were used; they were done at the receiving room side of the test wall, to calculate the radiated sound power and thus R. These results were very similar to the previous ones for one specimen, and for another gave rise to greater divergences. Also using accelerometric surveys it was possible to limit the analysis to the central area of the wall, and the R values obtained this way were very similar to those obtained using the same method applied to intensimetric data.

In conclusion we can state that boundary effects can be corrected in three ways: the first relies on the determination of the linear absorption coefficients of boundaries, and has been investigated theoretically. The other two are based on the determination of the sound power radiated from a central zone of the wall, that is assumed to be unaffected by boundary effects: both acoustic intensity mappings or accelerometer-derived velocity mappings can be used for this.

The two mapping techniques have shown themselves to be quite simple to use, taking into consideration that they remove many of the requisites for the receiving room.

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[3] E. Gerretsen - "Calculation of Airborne and Impact Sound Insulation Between Dwellings" - Applied Acoustics 19 (1986), pg. 245.

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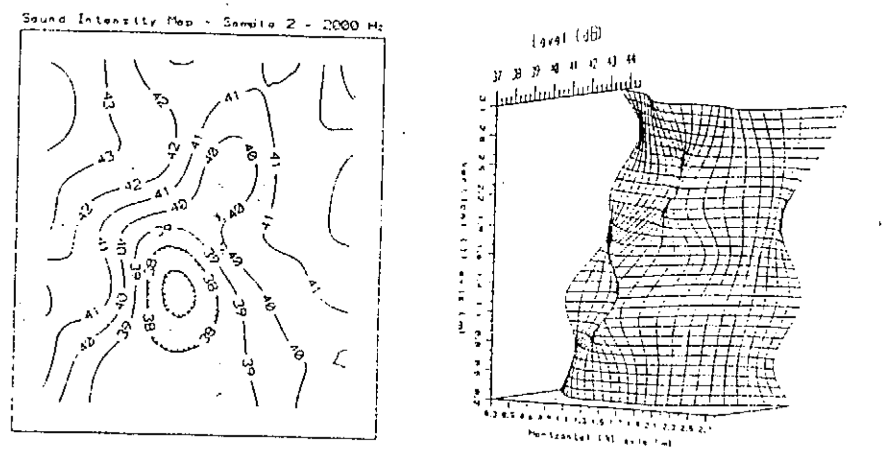


Fig.1 - Sound Intensity Maps - Sample 2 - Octave band of 2 kHz.

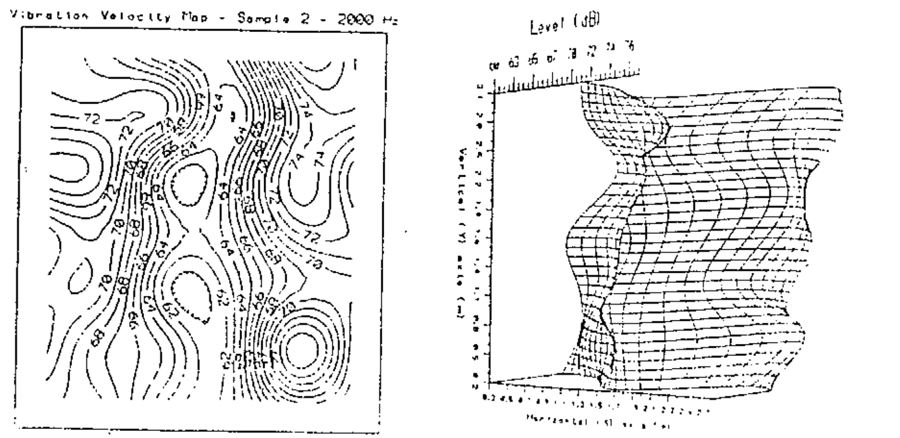
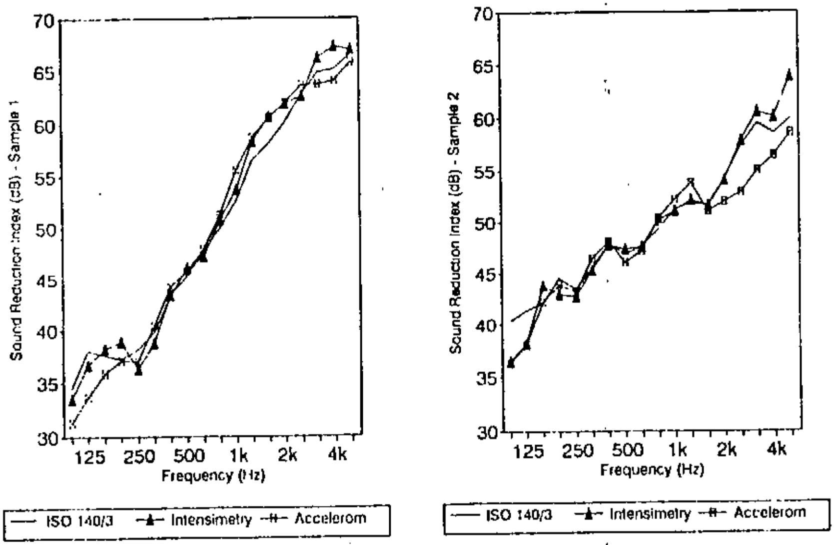
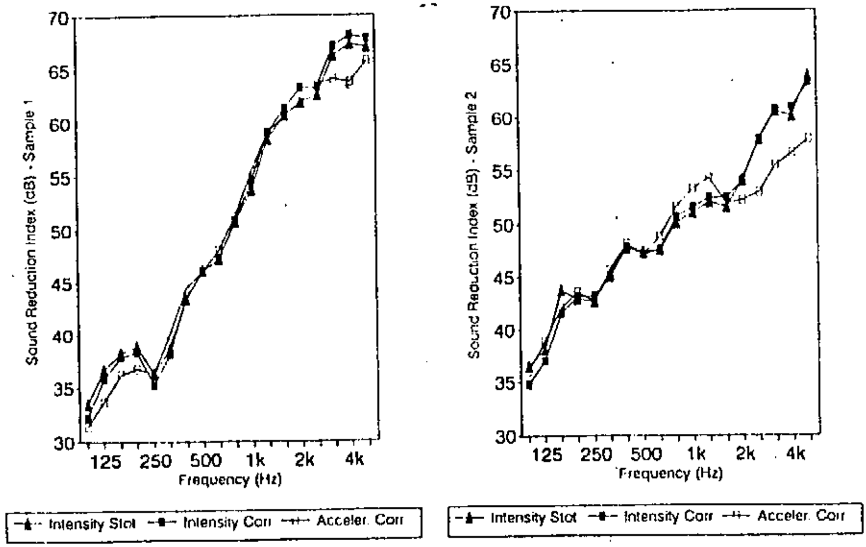


Fig.2 - Normal Surface Velocity Maps - Sample 2 - Octave band of 2 kHz.



Figg. 3 & 4 - Sound Reduction Index of sample 1 (left) & 2 (right) - no boundary effect correction.



Figg. 5 & 6 - Sound Reduction Index of sample 1 (left) & 2 (right) - with boundary effect correction.