Influence of static-load on airflow resistivity determination

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Dynamic stiffness of resilient materials used as underlayer in floating floors gives a useful knowledge on the acoustical behaviour of a floor in impact sound insulation. In previous works the influence of static load and compressive behaviour in resilient material, on the evaluation of dynamic stiffness, has been investigated. The effects observed led to believe that the particular behaviour of the materials under load could influence other parameters related to the elastic properties of the materials themselves. The airflow resistance, depending on density of the material, increases if the material is subjected to a static load. In order to quantify this dependence a new measurement technique of the airflow resistance in terms of static load applied on the resilient materials with open cells is proposed. In this work the first experimental results on the measurement of the airflow resistivity of resilient materials, as a function of applied load, is reported.

1 Influence of airflow resistivity in dynamic stiffness determination

The knowledge of the airflow resistivity r [Pa·s/m^2], according to Standard ISO 9053 [1], of a resilient material (fibrous or porous), used as insulator in a floating floor, can be used to properly evaluate the dynamic stiffness per unit area of the material, s', i.e. the real elasticity or stiffness, that depends on the rigidity of air contained in it. In fact, the dynamic stiffness of a resilient material, s', is a combination of the material structural stiffness s'_t, and the stiffness of air contained in open pores, s'_a, namely:

$$s' = s'_t + s'_a \quad [\mathrm{MN/m^3}], \tag{1}$$

where the stiffness of the air is given by:

$$s'_a = \frac{p_0}{\varepsilon \cdot d} \quad [\mathrm{MN/m^3}], \tag{2}$$

where p_0 is the atmospheric pressure, ε is the porosity of the material and d thickness of the specimen measured under a static load of 2 kPa.

The dynamic stiffness of a resilient material is evaluated by the determination of the resonance frequency of a mass-spring system. The result is s'_t, also called apparent dynamic stiffness:

$$s'_t = (2\pi f_0)^2 \cdot m' \quad [\mathrm{MN/m^3}], \tag{3}$$

where f_0 [Hz] is the resonance frequency of the system, m' [kg/m^2] is the mass per unit area used during the test.

In order to evaluate whether in dynamic stiffness measurement the contribution of gas contained in the material s'_a has to be taken into account or not, it is necessary to measure the airflow resistivity r. In Standard ISO 9052-1 [2] three categories of materials, depending on different values of r, are indicated:

(A) Materials with high airflow resistivity:

$r \geq 100$ kPa·s/m^2;

(B) Materials with medium airflow resistivity:

10 kPa·s/m$^2 \leq r < 100$ kPa·s/m^2;

(C) Materials with low airflow resistivity:

$r < 10$ kPa·s/m^2.

In materials with high airflow resistivity, typically $r \geq 100$ kPa·s/m^2, air remains trapped in pores as in a material with closed cells ($r \approx \infty$). The dynamic stress which the material is subjected to is not strong enough to pump out the trapped air, which acts like a spring. Data experimentally measured of the apparent dynamic stiffness, according to the Standard ISO 9052-1, is therefore of the structure and of air in it, i.e. $s'_t = s'$.

In resilient material having an airflow resistivity between 10 kPa·s/m^2 and 100 kPa·s/m^2, the air is pumped in and out the pores during the dynamic stress. In this case, by determining the frequency resonance f_0, the contribution due to air stiffness is neglected. Experimentally, the measurement of dynamic stiffness of resilient materials is made on small samples, typically (200 × 200) mm, while in large samples the air remains trapped inside the material adding his contribution to stiffness. The Standard ISO 9052-1 - § 8.2, in order to get a correct measurement of dynamic stiffness per unit area of resilient material, indicates that it is necessary to add the stiffness of air, as shown in Eq.(2). Considering an average porosity $\varepsilon \approx 0.9$ and the static atmospheric pressure p_0 = 0.1 MPa, the stiffness of air can be taken into account as a function of the thickness d [mm] of the material only, using the following simplified relation:

$$s'_a = \frac{111.1}{d} \quad [\mathrm{MN/m^3}]. \tag{4}$$

A significantly expanded range of porosity, in materials used in building applications, could be $0.8 \leq \varepsilon \leq 0.99$: under these conditions the error due to approximation of the dynamic stiffness s'_a evaluation using an average value of 0,9 is within 10%.

The dynamic stiffness of air s'_a contained in the material, may lead to a significant correction in the apparent dynamic stiffness, s'_t, measured experimentally. In Table 1 the values of s'_a, calculated using Eq.(2), for different thickness and porosity values are shown.

In materials with low airflow resistivity (r < 10 kPa·s/m^2) compression of air in the material during the dynamic stress, is rather irrelevant. The dynamic stiffness of the material is due only to the structural stiffness. In this particular case the apparent dynamic stiffness is considered as equal to the actual dynamic stiffness of the material, if the following condition is verified:

$$s'_t = s' \text{ only if } s'_a \ll s'_t$$

If s'_a is not negligible compared to the measured value of s'_t, the dynamic stiffness s' of the material can not be determined.

According to the theory of Cremer [3], which the predictive models listed in Standard EN 12354-2 [4] are based on, with the dynamic stiffness of insulation layer it is possible to evaluate the reduction of transmitted impact noise in a floating floor according to the following relation:

$$\Delta L = 30 Log \frac{f}{f_{res}} \text{ dB,} \quad (5)$$

where the resonance frequency of floating floor, f_{res}, is given by the following relation:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{s' \cdot 10^6}{m''}} \approx 160\sqrt{\frac{s'}{m''}} \text{ Hz,} \quad (6)$$

where s' is the dynamic stiffness of resilient layer [MN/m^3] e m'' is the mass per unit area of the floating mass [kg/m^2].

It is evident that neglecting an accurate determination of the airflow resistivity can lead to significant errors of evaluation of the acoustical performance of the examined material.

Thickness [mm]	Dynamic stiffness of air s'_a[MN/m^3]		
	$\varepsilon = 0.99$	$\varepsilon = 0.9$	$\varepsilon = 0.8$
10.0	10.1	11.1	12.5
9.0	11.2	12.3	13.9
8.0	12.6	13.9	15.6
7.0	14.4	15.9	17.9
6.0	16.8	18.5	20.8
5.0	20.2	22.2	25.0
4.0	25.3	27.8	31.3
3.0	33.7	37.0	41.7
2.0	50.5	55.6	62.5
1.0	101.0	111.1	125.0

Table 1. Values of dynamic stiffness of air according to different thickness for three different values of porosity ε with atmospheric pressure $p_0 = 0.1$ MPa.

As it is shown in Table 1, the dynamic stiffness of air leads to a correction of a certain relevance to the actual dynamic stiffness of a resilient porous material.

2 The airflow resistance measurement

The first relevant studies on the behaviour of a gas flow through porous media by J. L. Fowler, K. L. Hertel [5] and R. R. Sullivan [6] date back to the years 40 of the last century, besides the first experimental studies on the determination and measurement methods of resistance to air flow through porous materials are mainly due to L. L. Beranek [7] and R. L. Brown and R. H. Bolt [8]. The airflow resistance of a material, R, is defined as the ratio between the actual difference in pressure between the two sides of a test material, Δp [Pa], and the air flow rate q_v [m^3/s], through the material:

$$R = \frac{\Delta p}{q_v} \text{ [Pa·s/m}^3\text{],} \quad (7)$$

For low values of airflow velocity through the material (typically < 4 mm/s), the value of airflow resistance is constant: over this linear range the airflow resistance increases quickly with velocity. For the experimental determination of airflow resistance of a material is therefore necessary to generate particularly low velocity airflow through the specimen.

The methodologies for the determination of airflow resistance are well known: the Standard ISO 9053 shows two methods of measurement. In particular, the experimental principle is based on measuring the difference in pressure upstream and downstream of a test material (porous or fibrous) traversed by an continuous airflow at low velocity, or the pressure variation in time upstream with an alternate flow.

2.1 Some considerations on the airflow resistance

The airflow resistance, and therefore its related quantities specific airflow resistance R_S [Pa·s/m] and airflow resistivity r [Pa·s/m^2], depends on the intrinsic properties of the material. In particular, with increasing density, the airflow resistance can increase significantly.
In fibrous materials with high porosity, as an example, an empirical relation [9] between the airflow resistance R and surface density (or mass per unit area) S [kg/m^2], the thickness T [m] and the range of fibres φ [m], is known:

$$R = K\frac{S^{(1+x)}}{T^x} \cdot \frac{1}{\varphi^2} \quad (8)$$

where K is a constant feature of the material and x is a value depending on the arrangement of fibers.

It has been shown that the airflow resistance varies in proportion to the thickness. In particular:

(A) The airflow resistance varies linearly with thickness at constant density. This assertion can be easily verified by measuring the airflow resistance R_n of n samples superimposed of the same typology of material:

$$R_1 = \frac{1}{n}R_n \text{ [Pa·s/m}^3\text{],} \quad (9)$$

(B) The airflow resistance is inversely proportional to a power thickness at constant density surface (e.g. by varying the thickness compressing the sample):

$$R = \frac{c}{T^x} \text{ [Pa·s/m}^3\text{],} \quad (10)$$

where c is a constant depending upon the distribution of fibre size, shape and orientation, and x depends on the distribution of fibres in the material.

In materials with high porosity ($0.9 \le \varepsilon \le 1.0$) value of x can vary between 0.3 and 1 [9]. The graph of Figure 1 is an example of measurement of the resistance to flow measured on a series of 6 identical sheets of synthetic fibre material (35 kg/m^3 density, thickness 5.1 mm) superimposed.

In graphs of Figure 2 (a, b) two examples of variation in airflow resistance in function of density due to compression of the sample under load are shown. Samples are synthetic fibre material (Specimen a: density 35 kg/m^3, thickness 17.6 mm; Specimen b: density 35 kg/m^3, thickness 5.1 mm).

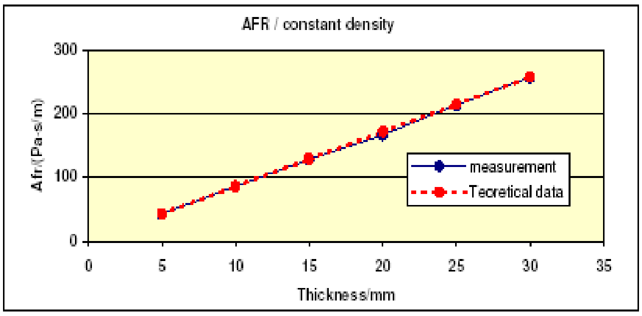

Fig.1 Experimental verification of linear variation of the resistance to flow depending on thickness at constant density.

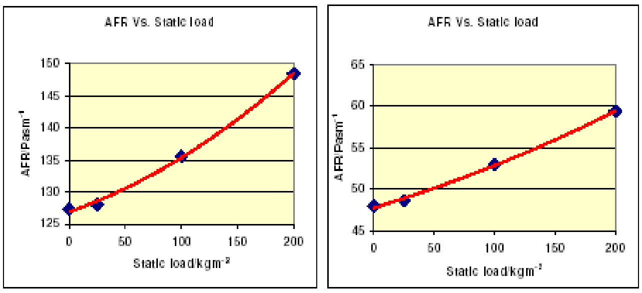

Fig.2 (a, b) Experimental verification of the airflow resistance variation depending on the thickness decrease (or density increase) in two materials subject to a compression under static load.

3 The experimental apparatus measuring

The measuring equipment it has been realized at the National Institute of Metrological Research of Turin (Figure 3 a), is characterized by:

- A measurement cell, diameter 100 mm;
- A perforated plate for the support of material;
- A piston (Teflon ®), diameter 50 mm, led by an eccentric connected to a stepper motor, which produces a flow of air, alternating at 2 Hz;
- A condenser microphone (1”, Brüel and Kjær Type 4144) for the measurement of alternating pressure component in the closed volume of the cell;
- A measuring amplifier (Brüel and Kjær Type 2636);
- A spectrum real-time analyser (Onosokki DS2000).

The apparatus has a load plate, with a surface perforation of 60% (Figure 3 b), where known masses can be added. In particular loads used for evaluations of the airflow resistance are the same adopted in other measurement used in building acoustics. Referring to the measurements of dynamic stiffness (EN 29052-1) and compressibility (EN 12431 [10]), the loads are 250 Pa, 1 kPa and 2 kPa.

Fig.3 (a, b) Apparatus for the measurement of the airflow resistance in porous and fibrous materials according to Standard EN 29053, made at INRIM of Turin.

4 Discussion on experimental results

Several trials have shown that some resilient material used as insulation in floating floors are very compressible: for example samples of synthetic fibre, subjected to a static load of 2 kPa, may suffer a decrease in thickness about 20% ÷ 25% [11]; this thickness decrease (or relative increase in density) induces a significant increase in flow resistivity. Evaluating analytically the increase in airflow resistance on the basis of density variation is particularly difficult.

For this reason, to correctly determine the airflow resistivity of a material used as a underlayer in a floating floor, it is necessary to make measurements using a static load of 2 kPa on the sample, i.e. the same conditions of the dynamic stiffness measurement.

To this end the airflow resistance, and then the resistivity, has been experimentally determined increasing the density by applying a known static load, in some yielding materials used as substrates in floating floors. In many cases, as shown in the graph of Figure (5), the variation of resistivity, as a function of applied load, is less than 10% of the initial value, in other cases the variation of resistivity is measured to be about to 30% of the initial value.

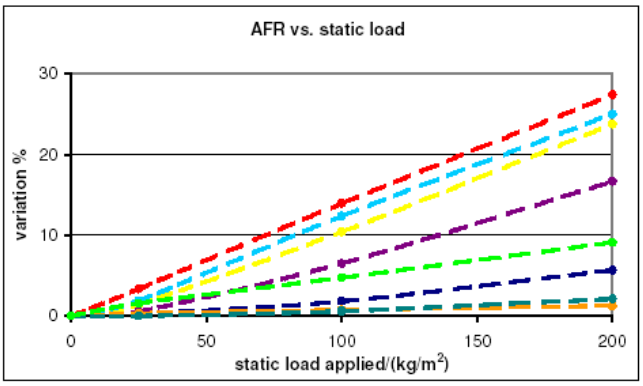

Fig.5 Percentage variation of airflow resistivity, as a function of the applied load, in various typologies of materials used as insulation in floating floors.

In the examples below trends of three materials with a critical behaviour are shown. The value of airflow resistivity, if measured under load or unloaded, places the material in a different category, as defined in the Standard EN 29052-1.

The airflow resistivity data are used to correctly determine the dynamic stiffness Eq.(1). Finally, dynamic stiffness is used to calculate the value of reducing impact noise with Eq.(5) and the results are compared with data obtained from measurements of insulation performed in the INRIM laboratory according to standard ISO 140-8 [12].

In the graph of Figure 6-a the trends of airflow resistivity as a function of applied load of two samples of fibrous material (density ~30÷40 kg/m^3, thickness resting ~5 mm) are shown.

In the graph of Figure 6-b the trend of flow resistivity as a function of load of a sample of waste of natural fabric (~130 kg/m^3 density, thickness resting ~10 mm) is shown.

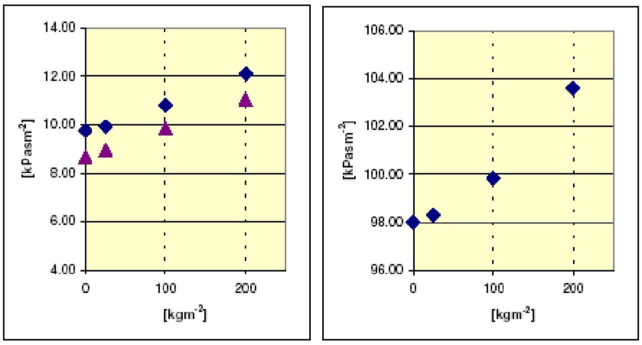

Fig.6 (a, b) The airflow resistivity as a function of applied load.

As shown in the graph of Figure 6-a the materials examined provide a value of the airflow resistivity r less than 10 kPa·s/m^2 if unloaded; the same materials, subjected to a static load of 2 kPa, give a value of the flow resistivity between 10 kPa·s/m^2 and 100 kPa·s/m^2. A similar behaviour is shown in the graph of Figure 6b: the material unloaded provides a airflow resistivity between 10 kPa·s/m^2 and 100 kPa·s/m^2, but if subjected to a static load of 2 kPa the same material provides a flow resistivity r higher than 100 kPa·s/m^2.

The reported cases are critical because lead to a reconsideration of the correction in dynamic stiffness evaluation.

In the first case, the material provides a value of dynamic stiffness s'_t = 27 MN/m^3. Since s'_a = 22 MN/m^3, according to Eq.(4), it would not be possible to determine s' because the restriction $s'_a << s'_t$ is not verified. But when the material is under compression, it provides a flow resistivity r > 10 kPa·s/m^2, and dynamic stiffness can be estimated, being s' = 49 MN/m^3.

In the latter case the dynamic stiffness measured is s'_t = 37 MN/m^3. The material, if not loaded, provides a value of r between 10 kPa·s/m^2 and 100 kPa·s/m^2, it would be necessary to add the contribution of air stiffness, in this case s'_a = 11 MN/m^3, then s' = 48 MN/m^3. However, since the material under load gives a flow resistivity r > 100 kPa·s/m^2 the apparent dynamic stiffness as measured already includes the dynamic stiffness of air.

Using the values of dynamic stiffness so determined, with Eq.(5) and Eq.(6), the following values of impact sound insulation are calculated:

Material (a): $\Delta L \cong 19$ dB;

Material (b): $\Delta L \cong 22$ dB instead of 20 dB.

These data are obtained using Eq.(5) with f = 500 Hz. The mass per unit area of the floating slab used in standard measurement in the laboratory of INRIM is ~ 90 kg/m^2, for Material (a) and ~ 110 kg/m^2, for Material (b)

Data of impact sound reduction measured according to standard ISO 140-8, on a normalized base floor of 10 m^2 are ΔL = 18.6 dB for Material (a) and ΔL = 22.5 dB for Material (b). The data are extracted at 500 Hz from the global spectrum of the reduction of impact sound pressure level. The agreement is very good.

References

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