SOUND ABSORBING LAYERS: A SIMPLE PREDICTION MODEL FOR CALCULATING ABSORPTION AND THE EFFECT ON SOUND TRANSMISSION

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1. INTRODUCTION

The acoustical performance of a sound absorbing layer or facing added to a wall or ceiling can be of interest not only in terms of sound absorption but also because the transmission loss is increased.

The work presented here started at The Norwegian Institute of Technology (NTH) and results from renewed interest in glass covered spaces, in particular glass covered "streets". The requirement for heat insulation in the facades of the buildings in such "streets" is then reduced, but because of possible noise build up some additional acoustical treatment is normally required. A model for computing the sound absorption as well as the sound insulation of a combination of lightweight panels and porous insulation materials was then in demand.

Owing to the complex nature of the problem any single model is not able to cover all practical cases with the desired accuracy. It is believed, however, that the model presented here gives estimates suitable for design purposes in a wide range of cases.

The model evaluates the absorption and the transmission characteristics of multiple layers including limp panels, limp perforated panels, mineral wool type absorbents and air spaces. It is based on four-pole theory using partly theoretical, partly empirical data for the impedance of the various layers.

The purpose of this paper is twofold. Firstly, to show some results from a series of measurement of transmission loss performed at NTH [1] and compare these with the prediction. The transmission loss data were obtained from conventional diffuse field measurements. These measurements were unfortunately not combined with absorption measurements as is the case with similar measurements now performed at Salford, Department of Applied Acoustics. The latter is a part of an SERC-project with a more general scope on sound propagation and transmission from buildings as outlined in reference [2].

In this connection a free field method has been developed to obtain more detailed information on the absorption characteristics of a facing, e.g. the variation with angle of incidence. The second part of the paper therefore presents results obtained with this free field method on constructions similar to those presented in the first part.

2. THEORETICAL MODEL

As stated above the aim was initially to develop a simple and practical method to assess the added transmission loss introduced by an absorbent layer mounted on a lightweight wall. In particular, the effect on a single number index as R_W was of interest. Sound transmission through plane multilayer constructions has been studied for many years, recently concerning the general problem of plane acoustic "lagging" structures [3] and also addressing the particular problem above [4].

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The procedure used here is in principle the same as in [3] but put into the form of four-pole calculation. A recent paper by Hamada and Tachibana [5] uses this technique for the calculation of the transmission loss of multilayer structures. Here, we also calculate the input impedance of the structure and thereby the absorption coefficient. Furthermore, we have added expressions for the perforated type panel.

Basically, the model sets up a transfer matrix for each layer which is assumed to be of infinite extent. Furthermore, if we may neglect the effect of any coupling elements, such as studs or purlins between the layers, the transfer matrix for the total system is obtained simply by multiplying the matrices for the individual layers.

The effect of coupling elements on the sound transmission can be handled within the model assuming one part of the system being coupled, another part being uncoupled and then sum the contribution of each part. The accuracy of such a procedure is however low because the relative areas of these parts have to be estimated.

Figure 1 defines the basic variables used. The matrix A with the components a_{11}, a_{12}, a_{21} and a_{22} represents the four-pole matrix for the total system arrived at by multiplying the matrixes for the individual layers. The sound pressure p_i is the incident pressure, giving pressure and particle velocity components p_1, u_1 and p_2, u_2 at the input and output side of the construction. Z_0 and Z_ℓ represent the corresponding wave impedances.

The input impedance Z_1 is given by

$$Z_1 = \frac{p_1}{u_1} = \frac{a_{11}Z_\ell + a_{12}}{a_{21}Z_\ell + a_{22}} \qquad \ldots(1)$$

and the absorption coefficient $a(f,\theta_0)$ as

$$\alpha(f;\theta_0) = 1 - \left|\frac{Z_1 - Z_0}{Z_1 + Z_0}\right|^2 \qquad \ldots(2)$$

The argument f and θ_0 in the function represents the frequency and the incident angle of the assumed plane wave. A diffuse sound absorption coefficient is obtained by evaluating the integral

$$\int_0^{\pi/2} \alpha(f,\theta_0)\sin 2\,\theta_0 d\theta_0$$

Furthermore, assuming $Z_0 = Z_\ell$ the sound transmission coefficient is expressed by

$$\tau(f,\theta_0) = \left|\frac{p_2}{p_1}\right|^2 = \left|\frac{2}{a_{11} + a_{12}/Z_0 + a_{21}Z_0 + a_{22}}\right|^2 \qquad \ldots(3)$$

Again, the diffuse sound transmission coefficient is arrived at by integrating over all angles of incidence.

The matrices used for the different layers are briefly outlined below:

a) Panels

The matrix is given by

$$A_{panel} = \begin{Bmatrix} 1 & Z_B \\ 0 & 1 \end{Bmatrix} \qquad \ldots(4)$$

with Z_B expressed by the classical equation of Cremer [6]

$$Z_B = \frac{B(1+j\eta)}{j\,2\pi\,f}\left\{k_0{}^4\sin^4\theta_0 - k_B{}^4\right\} \qquad \ldots(5)$$

Here B and η are the bending stiffness and the loss factor of the panel. k_0 and k_B are the wave number in air and the flexural wavenumber in the panel, respectively.

For a perforated panel, perforated with a regular pattern of either holes or slits, the actual transfer matrix is calculated using a parallel combination of two matrixes of the form (4), one containing the impedance of the panel and the other containing the impedance of the holes or slits. The detailed expressions are not given here.

b) Porous absorber

The matrix for a porous absorber of thickness d is written as

$$A_{porous} = \begin{Bmatrix} \cosh Q & Z_x \sinh Q \\ \sinh Q/Z_x & \cosh Q \end{Bmatrix} \qquad \ldots(6)$$

with

$$Q = \Gamma d \cos\theta_1 \qquad \ldots(7a)$$

$$Z_x = \frac{Z_a}{\cos\theta_1} \qquad \ldots(7b)$$

$$\cos\theta_1 = \left\{1 - \left[\frac{j\,k_0\sin\theta_0}{\Gamma}\right]^2\right\}^{\frac{1}{2}} \qquad \ldots(7c)$$

Γ = a+jb and Z_a are the complex propagation constant, with attenuation constant a and phase constant b, and the specific acoustic impedance for the porous material, respectively, both evaluated using expressions given by Mechel [7]. These are slightly corrected versions of the ones developed by Delaney and Bazley [8].

c) Air space

The matrix for an airfilled space, e.g. between two panels, can be derived from equation (6). Assuming no energy dissipation the propagation constant Γ is set equal to jk_0. However, in practice some energy dissipation must be introduced through a small but non-zero attenuation constant a.

3. MEASUREMENT METHODS

3.1 Transmission loss

All transmission loss measurements were performed using the conventional diffuse field method in a transmission suite with a $110m^3$ sending room and a $268m^3$ receiving room. The test area of the different specimens, however, was smaller than the usual 8 – $10m^2$, being only $2.8m^2$.

3.2 Input impedance and absorption coefficient

As noted in the introduction we are interested in studying the behaviour of acoustical absorbents in a more detailed way than only obtaining the conventional diffuse field absorption coefficient. To this end we have developed a free field method using a two microphone technique. At present, the basic assumptions are that the absorbing surface is locally reacting and being exposed to the sound from a point source. This is essentially the same approach as used by Carles et al [9]. The formula given below is also based on the approximation that the height of the microphones above the surface is much smaller than the source height, typically less than 10%. No account is presently taken for the F-factor in the so called van-der-Pol equation used, but this will be investigated.

The input impedance is measured using the following equation

$$Z_1 = \frac{\rho c}{\cos\theta} \cdot \frac{H_{12}\sinh(A) - \sinh(B)}{\cosh(B) - H_{12}\cosh(A)} \quad \ldots(8)$$

where H_{12} is the transfer function between the sound pressure at the two microphones. A and B is given by

$$A = \frac{x}{h}\cos^2\theta + j\,k\,x\cos\theta$$

$$B = \frac{(x-s)}{h}\cdot\cos^2\theta + j\,k\,(x-s)\cos\theta \quad \ldots(9)$$

s is the distance between the microphones in the probe being placed normal to the surface. The perpendicular distances between the surface of the specimen and the two microphones are x and x−s, respectively. h is the corresponding height of the source above the surface and θ is the incident angle. In the special case of θ=0 and with a limiting value $x/h \rightarrow 0$ equation (8) reverts to the equation first derived by Chung and Blaser [10] for the measurement of impedance in a tube.

The absorption coefficient is again calculated using equation (2).

4. RESULTS

4.1 Transmission loss

A series of measurements were conducted on various combinations of light weight panels, either steel or chipboard, and mineral wool. The latter could be covered with a perforated panel made from steel or gypsum, the perforation being in the form of a regular pattern of holes or slits. The percentage of perforation was varied in the range of 2 - 33%.

Some measured results together with the calculated values using the model described above are shown in figures 2 and 3. The lowermost two curves in figure 2 give the reduction index $R=10\log(1/\tau)$ for a single 12mm chipboard panel, the next two curves show the effect of adding 70mm mineral wool with a specific flow resistance of 8400 Ns/m^4. Finally, we have added a 1mm steel panel with 2% perforation.

The fit between measured and calculated results is quite good especially in the middle frequency range. Concerning the result when adding a perforated panel the effect here is quite large due to the very small perforation. Increasing the amount of perforation to 30% the effect on the reduction index is almost negligible.

Figure 3 shows some results using the same configuration as above but without the mineral wool. The two lowermost curves give measured and calculated results for a combination of 12mm chipboard, 70mm airspace and a 2% perforated steel panel. Exchanging the perforated panel with a non-perforated 1mm steel panel gives the two upper curves. As expected the fit between measured and calculated results for the latter double wall construction is not good except in the middle frequency range.

On the basis of the whole series of measurements a design chart has been worked out for estimating the increase in the weighted reduction index R_w of a lightweight panel due to an added absorbing layer [1].

4.2 Impedance and absorption coefficient

The measurement method presupposes a free field and all the measurements reported here were conducted in an anechoic room at the University of Salford. Furthermore, the method does not allow for any scattering effect due to the necessary finite area of the test specimen. Based on pilot experiments a rule of thumb was found that the linear dimension of the sample should preferably be larger than twice the wavelength. The area used was 3m square, setting a reasonable lower limiting frequency to about 200Hz.

The test specimen consisted of a total of 25 squares of the material, each measuring 600mm x 600mm. The microphone probe positions were always in front of the centre sample. The minimum distance between the loudspeaker source fed by random noise and the microphone probe was about 2 metres.

In the results shown below only the measured and the calculated absorption coefficient are given. Figure 4 shows the absorption coefficient for 50mm mineral wool with a specific flow resistance of 35,000Ns/m^4 (mean of 5 samples), measured at two different angles of incidence, 0 and 58 degrees. The mineral wool was supported by a steel frame.

The measured data, the solid curves, are in this experiment obtained using two overlapping frequency ranges, 200 - 1100Hz and 500 - 3000Hz, corresponding to a microphone separation of 125 and 50mm, respectively. Each curve is a mean value for three measuring positions.

Figure 5 shows the results when the mineral wool is placed in wooden boxes with a backing of 18mm chipboard. Two results are given, the mineral wool freely exposed and then covered with a perforated 6mm hardboard plate, 5% perforation. The angle of incidence is 60 degrees. The agreement between measured and calculated results seems very good except for the Helmholtz type absorber at the highest frequencies. The result here is believed to be affected by scattering from the edges of the boxes. Even more important could be the influence of an extended reaction, a modal behaviour of the hardboard plate which is not accounted for in the measurement model.

5. CONCLUSIONS

A model based on four-pole network theory seems to predict the absorption characteristics and the transmission loss of some simple multilayered structures with a reasonable accuracy for design purposes. A free field method used for measuring the input impedance and the absorption coefficient gives results which compare well with the prediction even for a distributed type resonance absorber.

ACKNOWLEDGEMENTS

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REFERENCES

[1] S Hole, "Sound transmission in facades facing glass covered areas". Siv.ing. - thesis, Norwegian Inst. of Technology, Trondheim 1987 (in Norwegian)

[2] K Attenborough, N Heap, D J Oldham and R J Orlowski, "The prediction of sound radiation from buildings", Acoustics 86, Proc. IOA, 8, 357–364, 1986.

[3] A C K Au and K B Byrne, "On the insertion loss produced by plane acoustic lagging structures", J.Acoust. Soc. Am. 84 1325–1333 (1987)

[4] A Trochidis, "Effect of sound-absorptive facings on the sound transmission through panels", J.Acoust. Soc. Am. 78 942--945 (1985).

[5] Y Hamada and H Tachibana, "Analysis of sound transmission loss of multiple structures by four-terminal network theory", Proc. Inter-Noise 85, 693–696 (1985)

[6] L Cremer and M Heckl, "Structure-Borne Sound", Springer, New York (1973)

[7] F P Mechel, "Ausweitung der Absorberformel von Delaney and Bazley zu tiefen Frequenzen", Acustica 35, 210–213 (1976)

[8] M E Delaney and E N Bazley, "Acoustical characteristics of fibrous absorbent materials", Appl. Acoust. 3, 105 (1970)

[9] C Carles, D Abraham and J C Pascal, "Measure in-situ de l'impedance acoustique des materiaux en fonction de l'angle d'incidence", 2nd International Congress on Acoustic Intensity, Senlis, 495–502 (1985)

[10] J Y Chung and D Blaser, "Transfer function method of measuring in-duct properties. 1. Theory", J.Acoust. Soc. Am. 68, 907–913 (1980)

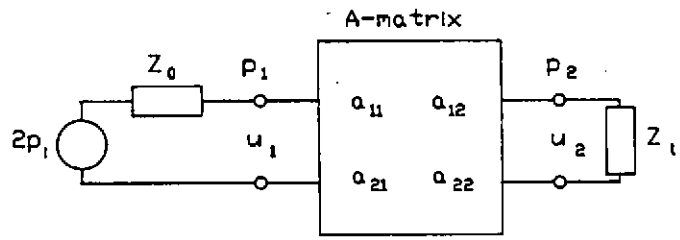

Fig 1. Basic variables used in model

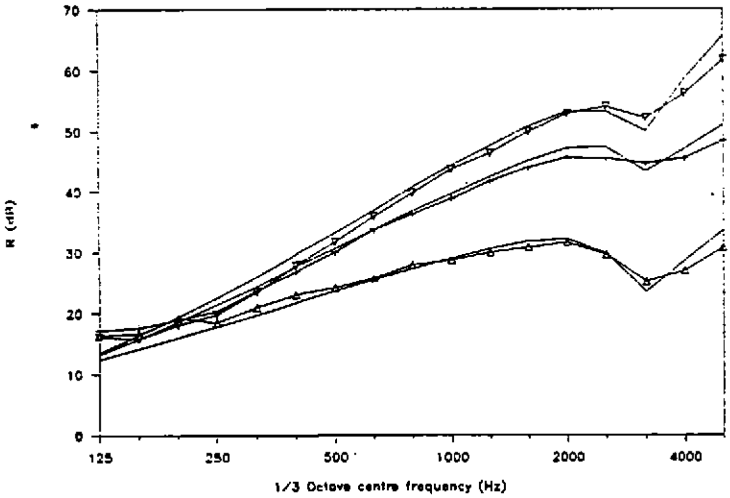

Fig 2. Reduction index.
△_____△ 12mm chipboard +_____+ 12mm chipboard, 70mm min wool
▽_____▽ 12mm chipboard, 70mm min wool, 1mm perf steel plate
_______ Calculated

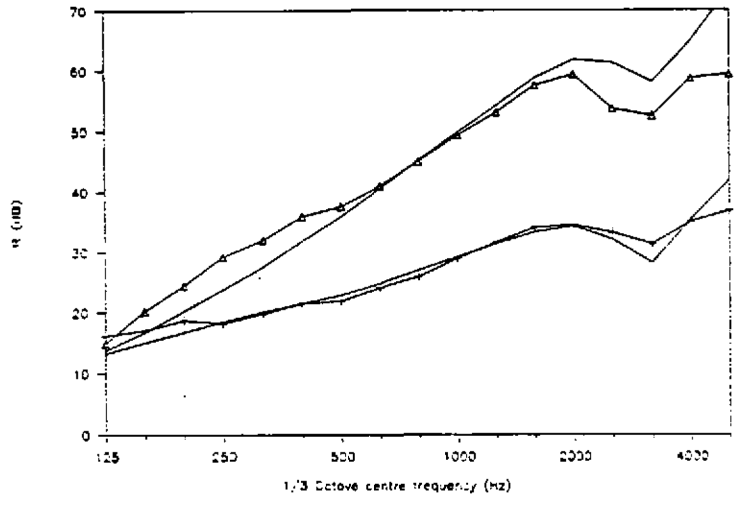

Fig 3. Reduction index.
+_____+ 12mm chipboard, 70mm airspace, 1mm perf steel plate
△_____△ 12mm chipboard, 70mm airspace, 1mm steel plate
_______ Calculated

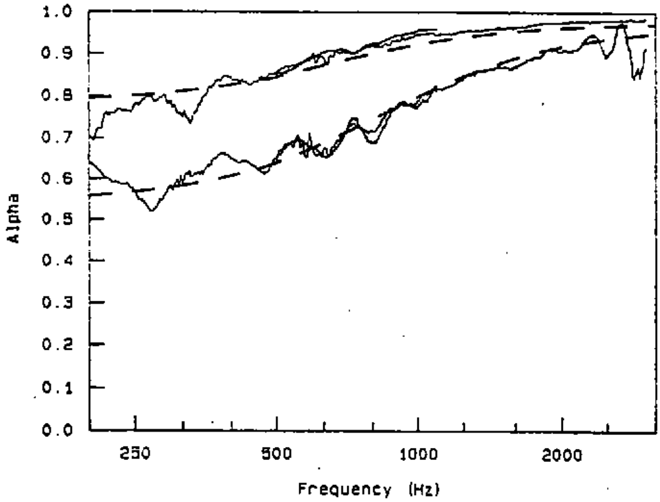

Fig .4. Absorption coefficient, 50mm mineral wool with no backing.
a) Normal incidence b) 58 degrees incidence ----- Calculated

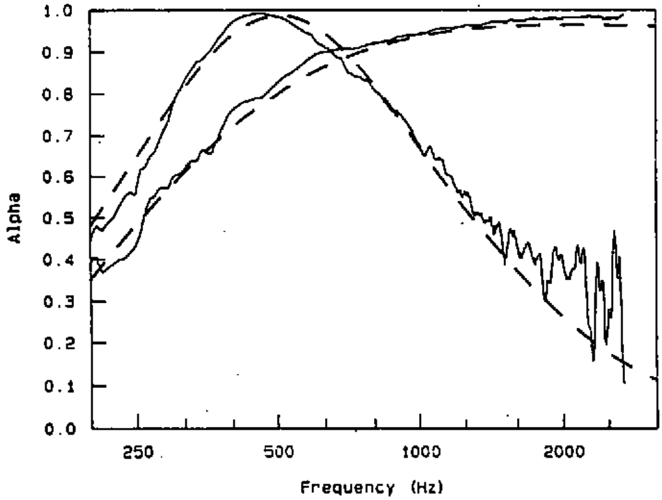

Fig 5. Absorption coefficient at 60 degree angle of incidence.
a) 50mm mineral wool on 18mm chipboard
b) 5% perforated hardboard plate, 50mm min wool, 18mm chipboard
----- Calculated