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THE DIRECTIVITY OF ORTHOTROPIC FACTORY CLADDING PANELS

M.A. Rowell and D.J. Oldham

Dept of Building Science, University of Sheffield, Sheffield S10 2TN

INTRODUCTION

When a new factory is being designed for construction on a site close to dwellings, schools or hospitals it is frequently necessary to attempt to predict the level of noise noise arising from operation of the factory at these noise sensitive locations. The text book equation used for this purpose is:

$$L_e = L_i - R + 10 \log S - 20 \log r - 14 \text{ dB} \qquad (1)$$

where L_e is the external noise level,
L_i is the internal noise level,
R is the sound reduction index of the wall,
S is the area of wall radiating sound and
r is the distance from source to receiver.

This equation is based upon the assumption of classical reverberant field excitation of the building envelope and hemispherical radiation of sound. In this paper we attempt to highlight some of the reasons why this simple equation is inadequate for the prediction of sound radiation from typical industrial buildings. These reasons include directivity effects associated with radiation from panels, non-reverberant excitation and ground and meteorological effects.

Directivity Effects

Oldham and Shen [1] have shown that a homogeneous panel excited by a classically reverberant sound field exhibits strong directional effects above the critical frequency (see Figure 1). They explained this effect in terms of the existance of a strongly resonating 1:m mode in the measured frequency band (see Figure 2). The effect of these strongly resonating mode shapes is to enhance the sound radiation in a direction given by $\phi_m = \sin^{-1} (f_c/f)^{1/2}$.

Shen and Oldham devised an empirical model for predicting the directivity of homogeneous panels. This model, however, cannot be applied to typical industrial buildings for a number of reasons. The first is the assumption of a classically exciting reverberant field which, does not apply in the typical factory situation and the second reason is that the cladding systems typically employed in industrial buildings are not homogeneous but are structurally orthotropic.

Sound Radiation from Cladding Panels

Most cladding is profiled with the result that the bending stiffness in a direction in line with the direction of profiling is different from that at right angles to the direction of profiling. Cladding panels are thus structurally orthotropic.

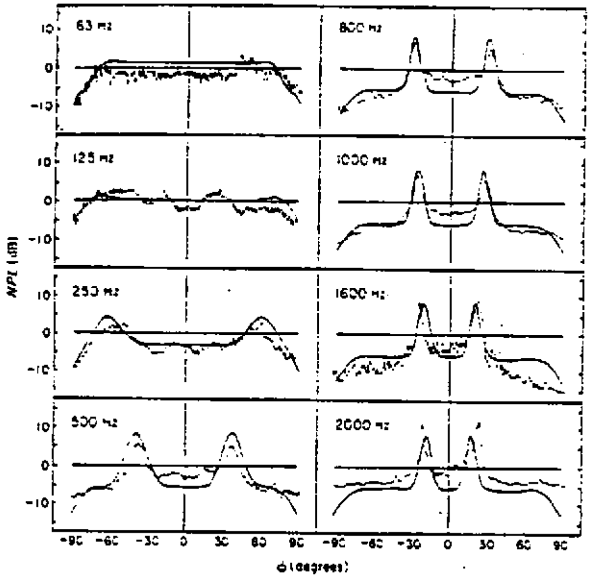


Figure 1 Radiation Patterns for 100mm Concrete Wall 6 x 4(m)

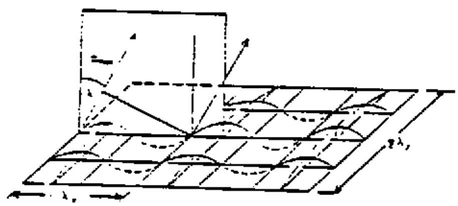


Figure 2 Sound Radiation in the ϕ_{max} direction due to the (5.1) mode

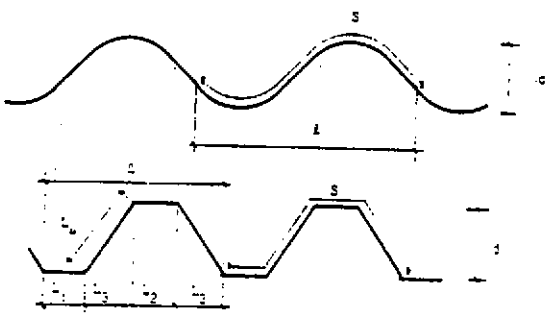


Figure 3 Profile Dimensions

Heckl [2] has suggested that such orthotropic materials have two critical frequencies given by:

$$f_{cx} = \frac{c^2}{2\pi}\left(\frac{\rho_s}{B_x}\right)^{1/2} \tag{2}$$

$$f_{cy} = \frac{c^2}{2\pi}\left(\frac{\rho_s}{B_y}\right)^{1/2} \tag{3}$$

where f_{cx} and f_{cy} are the critical frequencies and B_x and B_y are the bending stiffnesses in the x and y directions respectively and ρ_s is the effective superficial mass of the panel.

The bending stiffness is given by

$$B = EI \tag{4}$$

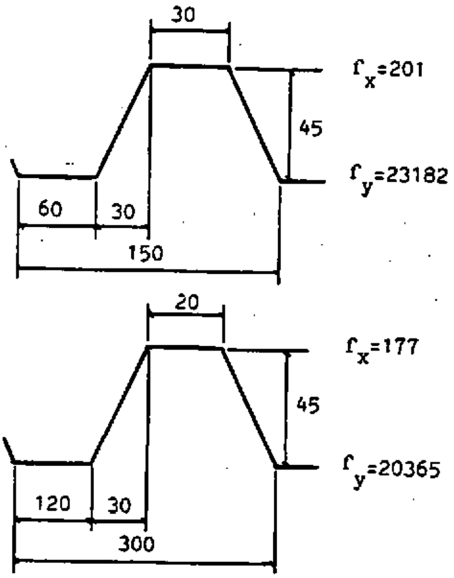
where E is the Young's modulus of the panel material and
I is the second moment of inertia/unit width which will be a function of direction.

For profiled panels the moments of inertia can be calculated using the equations contained in Table 1 where the panel dimensions are defined in Figure 3.

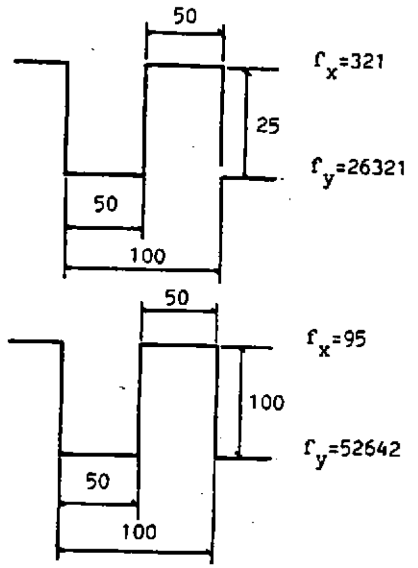
Table 1

Profile Type	I_x m^4/m	I_y m^4/m
Sinusoidal	$\frac{d^2h}{8}\left[1 - \frac{0.8}{1 + 2.5(d/2\ell)^2}\right]$	$\frac{h^3}{12(1-\nu^2)} \times \frac{\ell}{S}$
Trapezoidal	$\frac{hd^2}{\ell}\left(L_2 + \frac{2L_4}{3} - \frac{(L_2 + L_4)^2}{S}\right) + \frac{dh^2}{\ell}\left(L_2 + \frac{3L_4}{2}\right)$	$\frac{h^3}{12(1-\nu^2)} \times \frac{\ell}{S}$

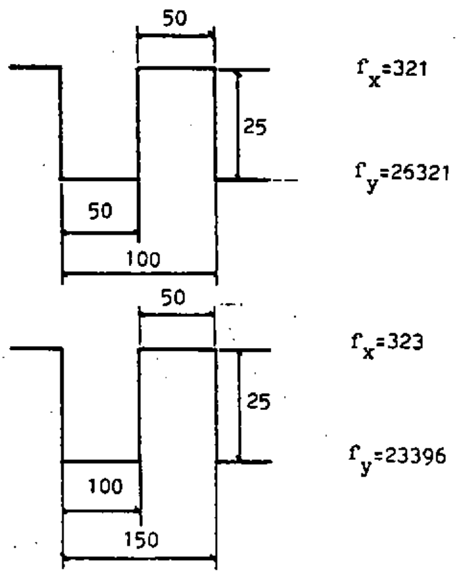
Figure 4 shows critical frequencies calculated by Cederfeldt [3] for a range of typical profiled panels. It can be seen that the effect of profiling is to reduce the critical frequency by approximately two orders of magnitude when compared with the unprofiled sheet material. The critical frequency is reduced from a typical value of around 20,000 Hz to a typical value of around 200 Hz.



a) Effect of Periodicity



b) Effect of Profile Depth



c) Effect of Assymmetry

Figure 4 Examples of Critical Frequencies for Typical Profiled Panels

(All dimensions in mm)

Shen and Oldham reported directivity effects at above critical frequency hence directivity is unlikely to be significant for unprofiled cladding given the high value of f_c. However, for profiled cladding this is not the case.

In addition to profiling, typical cladding systems usually incorporate thermal insulation plus a lining tray. The thermal insulation may be bonded to the profiled panel or may be "loose lay" in the tray. In some modern systems the profiled panel, the thermal insulation and the inner tray may all be bonded.

In the first case the cladding panel plus thermal insulation constitutes a two ply laminate. The effect may be to further alter the stiffness of the cladding panel. The approximate bending stiffness per unit width of a two layer plate is given by:

$$B = \frac{E_1 t_1}{12}\left[t_1^2 + \left(y - \frac{t_1}{2}\right)^2\right] + \frac{E_2 t_2}{12}\left[t_1^2 + \left(y - \frac{2t_1 + t_2}{2}\right)^2\right.$$

and the superficial mass is given by:

$$\rho_s = \rho_1 t_1 + \rho_2 t_2$$

where ρ_i is the density of layer i,
t_i is the thickness of layer i and
E_i is the Youngs modules of layer i.

If the lining tray, thermal insulation and profiled panel are all bonded then the system is a three-ply laminate. A three layer panel usually exhibits shear deformation in the middle layer and the theoretical treatment of a three ply laminate is thus very complex.

Given the complexity of cladding systems it is not feasible to investigate directivity by means of acoustic scale model experiments which was the technique employed by Shen and Oldham for homogeneous panels. However, the existance of the two critical frequencies predicted by Heckl has been verified by means of measurements on small profiled plastic panels of the type sold for roofing domestic conservatories. Figure 5 shows measured far field sound pressure levels in the XZ and YZ planes for such a panel having a pitch of 38mm. The difference in directivity between the two sets of measurements is very obvious. The radiation pattern in the XZ plane displays the peaks similar to those observed by Shen and Oldham. These peaks are absent in the YZ plane. The material of the panel is unknown but it was believed to be PVC.

The calculated critical frequency in the XZ plane is approximately 9,000 Hz and in the YZ it is approximately 50,000 Hz. Directivity effects are therefore being observed even below the critical frequency. It is possible that this is due to the profile itself which re-enforces the effect of radiation from a strongly resonating 1:m mode shape or that clamping the panel increases its effective bending stiffness.

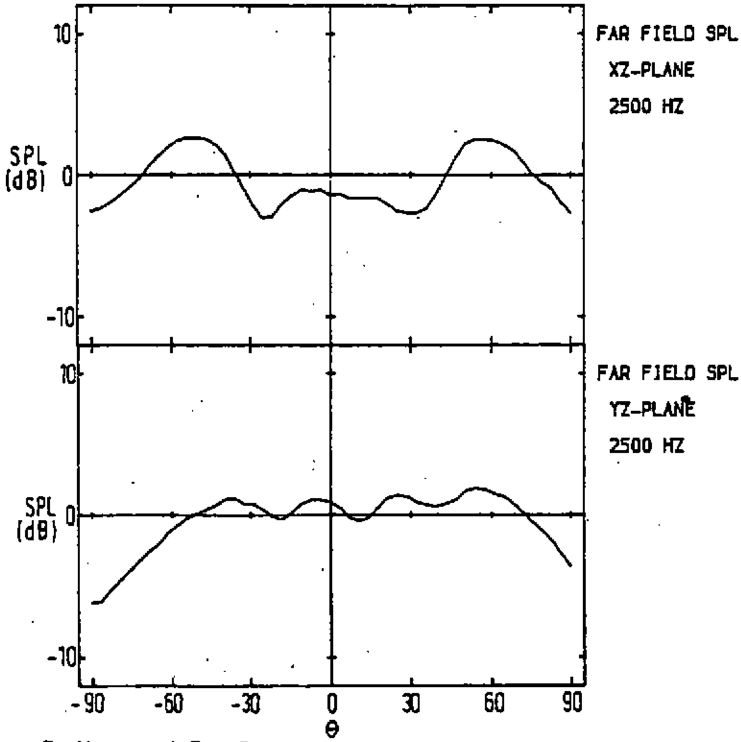


Figure 5 Measured Far Field SPL in 2 Different Planes for Profiled Plastic Panel

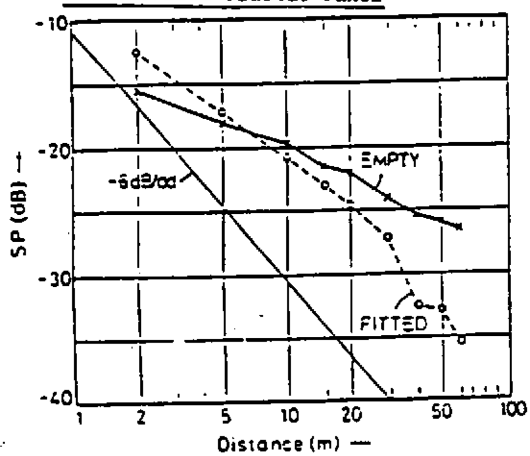


Figure 6 Sound Field in Factory Building. "After Hodgson (Ref. 6)

Non-Reverberant Excitation

The sound reduction index of a partition is usually measured in a transmission suite. This consists of two reverberant chambers separated by the test panel with adequate precautions taken to ensure that flanking transmission is negligible. The important feature of this arrangement is that the exciting sound field in the source chamber is classically reverberant. The observed sound transmission characteristics under these conditions has been explained by two mechanisms. The first relates to excitation above the critical frequency of the panel material. Above the critical frequency the sound transmission is determined by the action of resonating modes. In effect there exists an equilibrium situation involving exchange of energy between the resonating modes of the source room and the resonating modes of the panel.

For frequencies below the critical frequency the radiation efficiency of the resonating modes of the panel is very low with the result that the sound reduction index predicted assuming this to be the only mechanism in operation is greater than that actually observed. Crocker and Price [4] suggested that the sound transmission below the critical frequency was determined by forced vibration of the panel. Mulholland and Lyon [5] subsequently explained this in terms of spatial matching of resonant modes in the source chamber with mode shapes of the test panel.

This explanation of the mechanism by which sound is transmitted through a partition in a standard transmission suite casts doubt on the validity of using values of sound reduction index measured in this way in Equation 1. It has been reported by many workers that the classical reverberant field is not found in rooms having the disproportionate shape typical of factories. Figure 6 shows some measurements obtained by Hodgson [6] which illustrates this point. The lack of a classically reverberant field composed of resonating room modes means that the theories of Crocker, Price, Mulholland and Lyon do not apply. It is possible that the sound field inside a factory can be explained in terms of a system of propagating modes and that this model can be incorporated into the existing theories with only minor modifications such that conventional test chamber measurement data can be used. However, until this approach is validated extreme caution should be employed when attempting to use conventionally acquired data to predict sound radiation from factory buildings.

The directivity effects reported by Shen and Oldham were also observed with panels excited by a reverberant field. It is thus possible that the directivity of cladding panels observed for excitation by a factory noise field will differ from that measured in the laboratory situation where the panel is excited by the sound field in a reverberant chamber.

Ground Effect

A considerable amount of work has been carried out on factors affecting the propagation of sound where the propagation path is close to the ground. Most of this work has been concerned with point sources but attention is now being given to extended sources. The ground effect (excess attenuation relative to free field propagation) results from interference between direct sound reaching the receiver and sound reflected in the ground plane. The effect is usually most significant for low frequency sound.

In the context of sound radiation from factories it is interesting to note that the effect of profiling (reduction of the critical frequency to a very low value) may be such, in certain situations, to result in the intensity of reflected sound being greater than the direct sound. This will have an important bearing on the ground effect.

CONCLUSION

Some factors which affect the radiation of sound from typical modern industrial buildings have been examined. It has been shown that the effect of profiling metal panels is to increase the bending stiffness in the direction of the profiles with the result that a profiled panel exhibits two critical frequencies. This has been confirmed by experimental measurements.

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