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A SIMPLE EMPIRICAL METHOD FOR PREDICTING THE SOUND REDUCTION OF SINGLE-SKIN CLADDING

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1. INTRODUCTION

Profiled metal cladding is an increasingly prevalent feature of modern industrial buildings. Such materials have a good structural and thermal performance in relation to cost. However, their acoustic characteristics are often poor [1]. The sound reduction of single-skin cladding can be estimated using established "global" theories, such as that developed by Heckl [2,3]. However, previous work by the authors [4-8] has shown that large "dips" (of up to 10dB in magnitude) occur at mid-band frequencies. The occurrence of these depressions varies systematically as the parameters of the cladding "profile" (fig.1) are changed by relatively small amounts; e.g. fig.2. Furthermore, when the profiles are incorporated into more common double-leaf structures, the dip in transmission loss remains [1,4,5]. This poses a significant environmental noise problem.

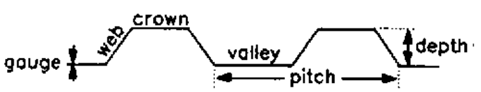


Figure 1 : Definition of cladding profile parameters.

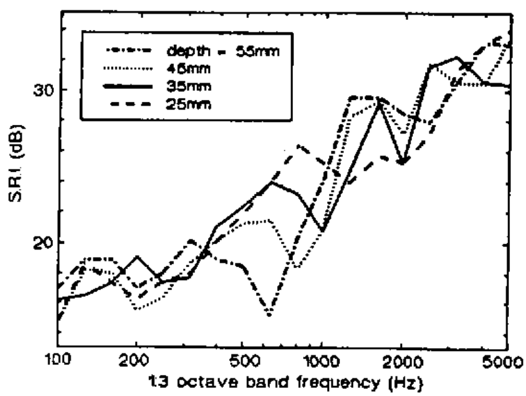


Figure 2: Variation in the Sound Reduction Index (SRI) of symmetrically profiled cladding as depth is varied. Other parameters are constant (0.65mm steel, pitch = 250mm).

It has been shown that the "dips" are related to specific vibrational modes (fig.3) which may be accurately predicted by use of Finite Element Analysis (FEA) [5-8]. The wavelength is small in relation to those on an unprofiled (isotropic) plate such that the radiation efficiency is enhanced. However, the process of "selection" by which certain modes result in "dips" and others do not is the acoustic excitation, which can be evaluated using a combination of FEA with modal analysis or the Boundary Element Method (BEM) [8]. In any case, it is clear that global approaches fail because they are unable to account for these "localised" effects.

Use of approaches such as FEA and BEM is not likely to encourage common usage of predictive techniques, especially where they may be most useful in manufacturing industry. Even if these techniques were programmed to allow for uncomplicated input, they would still be *extremely* slow. Accordingly, it is the purpose of this paper to discuss the feasibility of employing very simplistic, empirical models which are quick and user-friendly. It is demonstrated that very elementary theory can be employed to produce surprisingly accurate results.

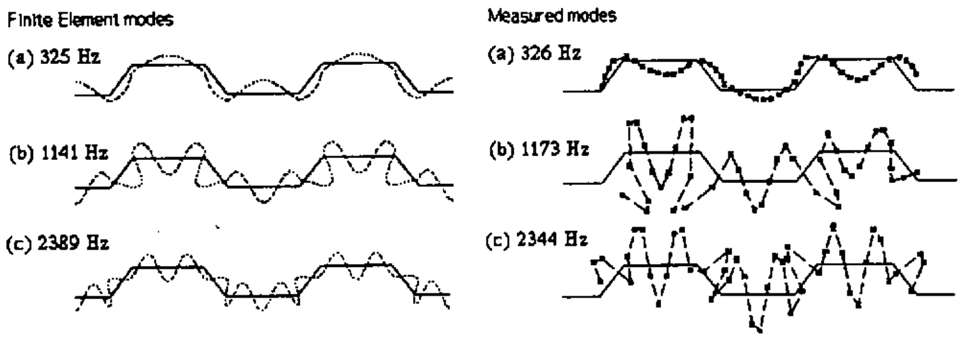


Figure 3 : Modeshapes on symmetrically profiled cladding (not to scale).

2. PREDICTION OF MODEFREQUENCIES

It has been demonstrated that one can reduce the level of complexity of the FE analysis to an idealised two-dimensional model which imitates an "infinite" cross-section of the cladding [5-7]. This produces an exceptionally good approximation of the actual mode frequencies and shapes (fig.3). It is also clear from examining measurements that only certain modeshapes consistently correspond to a "dip" in the sound reduction of particular profiles [5,6]. However, it becomes apparent that intuitively similar modes will occur on most different profiles : e.g. in fig.4 the modeshape is not exactly the same but it does retain the characteristic of three "cells" on the crown and one "cell" on the web. The frequency at which these modes are measured is always that of a dip in sound reduction. This suggests that one can predict the frequency at which SRI "dips" occur by determining each of the modeshapes concerned.

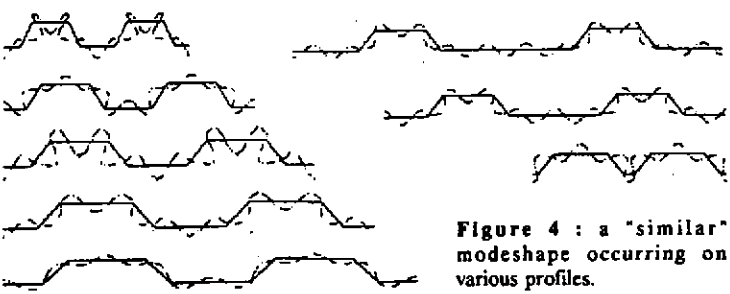


Figure 4 : a "similar" modeshape occurring on various profiles.

The use of simple beam elements in the two-dimensional FE analysis might lead one to contemplate the possibility of using elementary bar theory to predict given modeshapes. The well-known solution for natural mode frequencies of a simple beam pivoted at both ends can be written as :

$$f_n = \frac{n^2 \pi t}{2L^2}\sqrt{\frac{E}{12\rho}} \tag{1}$$

where n is an integer representing the mode number, t is the material thickness, ρ density and E Young's modulus. One can now regard the profile crown, web and valley as independent simple beams of length L, such that n represents the number of "cells". Thus, eqn.(1) implies that the modefrequency is proportional to the metal gauge. This can easily be validated considering the data above.

By applying eqn.(1) to each flat section of profile, one calculates a different frequency for each length. Some relationship must then be assumed between the results to form an overall natural frequency for the composite model. Simply averaging the frequencies associated with the crown, webs and valley can actually predict the 2D FEA result to within 1% in cases where the profile bends correspond to vibrational nodes [5]. However, this is not normally the case. It is apparent from fig.4 that the bends in the steel sheet (i.e. the point at which the simple beam is assumed to be pivoted) more often correspond to significant displacements. Nevertheless, this approach suggests a more versatile empirical method by simply allowing the modenumber n to take any real value ($n \in \mathbf{R}$). This might even be interpreted physically as in fig.5.

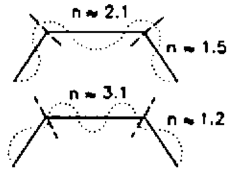


Figure 5 : Interpretation of "real modenumber", n.

By modelling a full range of trapezoidal profile shapes with 2D FEA, the frequencies of any characteristic modeshape can be entered into eqn.(1) which is then solved to yield n. Assuming the ratio of profile lengths is the same as the ratio of the number of "cells" on each section (i.e. $n_c/L_c = n_w/L_w = n_v/L_v$ where the subscripts c,w,v represent the crown, web and valley respectively) all modenumbers may be determined. Accordingly, one can produce a curve for each characteristic modeshape; e.g. fig.6. This provides the basis for the proposed empirical method which may be summarised in four steps :

(i) calculate crown/web length ratio L_c/L_w,
(ii) read crown modenumber n_c from curve for each modeshape,
(iii) calculate modenumbers n_w and n_v from assumption that $n_c/L_c = n_w/L_w = n_v/L_v$,
(iv) eqn.(1) implies that the average modefrequency may be calculated from :

$$f_n = \frac{\pi t}{6}\sqrt{\frac{E}{12\rho}}\left(\frac{n_c^2}{L_c^2} + \frac{n_w^2}{L_w^2} + \frac{n_v^2}{L_v^2}\right) = \frac{\pi t}{2}\sqrt{\frac{E}{12\rho}}\left(\frac{n_c^2}{L_c^2}\right) \tag{2}$$

One should note that the modefrequency is now dependant on the crown length and modenumber only, which is a result of the assumption that $n_c/L_c = n_w/L_w = n_v/L_v$. This suggests that the method should be strictly limited to the range of L_c/L_w tested.

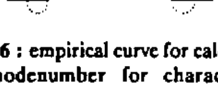
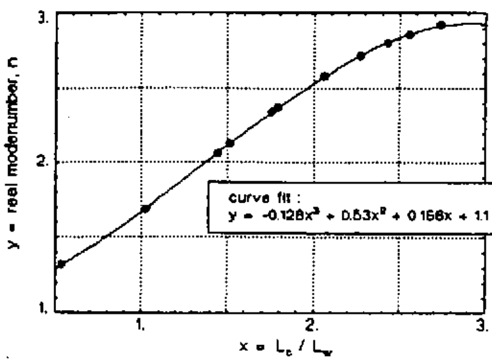
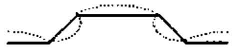


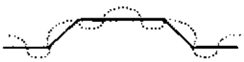
Figure 6 : empirical curve for calculating real modenumber for characteristic "mode B" (above). Valid only over L_c/L_w range shown.



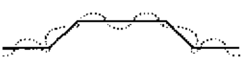
Use of fig.6 and eqn.(2) will produce an extremely good approximation to the modefrequency of mode B calculated by 2D FEA. However, because this approach is two-dimensional, the actual (measured) modefrequency is generally overestimated. Therefore, the empirical equation for n_c is corrected by comparison to measurements (of SRI or vibration on parts of the cladding surface). Five modeshapes are found which will always be associated with dips in sound reduction. The final (corrected) equations derived from the graphs (e.g. fig.6) are given below. Equations for modes A-C are valid over $0.5 \leq L_c/L_w \leq 3.0$, modes D and E over $1.5 \leq L_c/L_w \leq 2.5$:



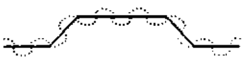
mode A $\quad n_c = -0.289x^4 + 0.278x^3 - 1.044x^2 + 1.945x - 0.178 \qquad (3)$



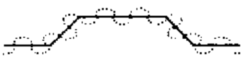
mode B $\quad n_c = -0.121x^3 + 0.503x^2 + 0.157x + 1.044 \qquad (4)$



mode C $\quad n_c = -0.319x^4 + 2.572x^3 - 7.459x^2 + 9.773x - 1.798 \qquad (5)$



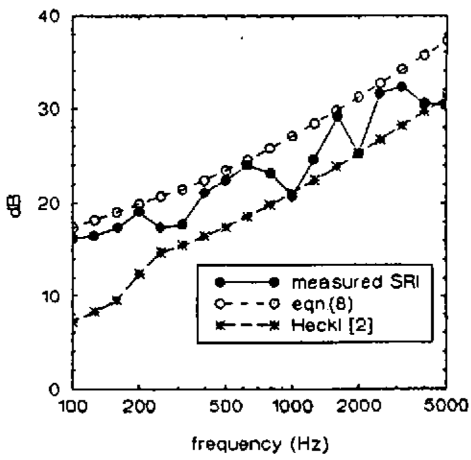
mode D $\quad n_c = 3.08x^3 - 19.1x^2 + 40.3x - 24.3 \qquad (6)$



mode E $\quad n_c = -1.35x^4 + 11.9x^3 - 39.3x^2 + 57.9x - 27.1 \qquad (7)$

3. PREDICTION OF SOUND REDUCTION

Now that one is able to predict the frequency at which "dips" occur in sound reduction, some means of describing the "dip magnitude" is required. However, this dictates that an initial estimate of SRI should be made. By comparison to a large set of measurements [4] it becomes apparent that it is possible to employ one of Heckl's formulae [2] with 5dB added to provide a curve from which the "dips" can be deducted. This should be calculated in 1:3 octave bands (fig.7). Below the lower critical frequency of the panel f_{c1} the SRI should be calculated by assuming a constant 2.5dB/octave decay :



$$SRI = \frac{\rho_o c}{\pi \omega \mu} \frac{f_{cl}}{f} \left(\ln \frac{4f}{f_{cl}} \right)^2 + 5\ dB \qquad f \geq f_{cl}$$
$$SRI \sim -2.5\ dB/octave \qquad f < f_{cl} \qquad (8)$$

where μ is the surface mass (kgm^{-2}) of the panel; f_{c1} is calculated using the bending stiffness across the profiled cross-section; c.f. [2,3 or 5].

Figure 7 : initial prediction of SRI prior to subtracting "dips" at predicted modes A-E.

Eqn.(8) works well for all of the measured single-skin panels. It is now required to deduct "dips" from this response. Several methods have been described by which the relative strength of different vibrational modes can be evaluated. One could use the Boundary Element Method on FE data. This would clearly be extremely tedious and require expert usage. A simpler method is to undertake modal analysis; but this would still be based on FE data. Consequently, it is proposed to use a regressive error reduction on the existing SRI characteristics [4] and associate this with identifiable physical properties of the profile cross-section (e.g. stiffness, length ratio, etc). As such, one can plot the curves shown in fig.7 for all different profiles, noting the magnitude and bandwidth of each "dip". This yields five equations for the "dip magnitude" Δ of modes A-E which can be expressed purely as functions of the metal gauge t (*in millimetres*) and the length ratio ζ :

$$\textit{mode A}: \quad \begin{aligned} \Delta_A &= 3.45\zeta - 0.9\ dB \\ \Delta_{A\pm1} &= 2\Delta_A/3 \\ \Delta_{A\pm2} &= \Delta_A/3 \\ \Delta_{A\pm3} &= \Delta_A/6 \end{aligned} \tag{9}$$

$$\textit{mode B}: \quad \begin{aligned} \Delta_B &= 29.4\zeta + 3.74t - 30.5\ dB \\ \Delta_{B\pm1} &= \Delta_B/2 \\ \Delta_{B\pm2} &= \Delta_B/4 \end{aligned} \tag{10}$$

$$\textit{mode C}: \quad \begin{aligned} \Delta_C &= 2.81\zeta - 6.15t + 4.73\ dB \\ \Delta_{C-1} &= \Delta_C/4 \\ \Delta_{C-2} &= \Delta_C/2 \end{aligned} \tag{11}$$

$$\textit{mode D}: \quad \begin{aligned} \Delta_D &= 21.3\zeta + 7.13t - 27.4\ \ dB \\ \Delta_{D-1} &= \Delta_D/2 \\ \Delta_{D-2} &= \Delta_D/2 \end{aligned} \tag{12}$$

$$\textit{mode E}: \quad \begin{aligned} \Delta_E &= -0.864\zeta + 5.09\ \ dB \\ \Delta_{E-1} &= \Delta_E/2 \\ \Delta_{E-2} &= \Delta_E/2 \end{aligned} \tag{13}$$

$$\textit{where} \quad \zeta = \frac{(L_c + 2L_w + L_v)}{\textit{profile pitch}}$$

Δ will be a positive number which should be subtracted from eqn.(8) at the 1:3 octave band which includes the frequency calculated from eqns.(3)-(7) and (2). Values of Δ should also be deducted in bands consecutive to this, as shown in fig.8 : Δ_{B+1} represents the 1:3 octave band above the "dip", Δ_{B+2} the band above this again, etc. It is clear that the bandwidth of dips becomes narrower for higher order modes. Where "dips" overlap the Δ factors should simply be summed.

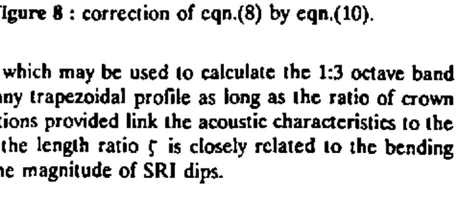


Figure 8 : correction of eqn.(8) by eqn.(10).

Accordingly, a full empirical method has been described which may be used to calculate the 1:3 octave band Sound Reduction Index over the range 100-5000Hz for any trapezoidal profile as long as the ratio of crown length to web length is within the range given. The equations provided link the acoustic characteristics to the physical properties of the profiled sheet. For example, the length ratio ζ is closely related to the bending stiffness [4,5] and seems to be roughly in proportion to the magnitude of SRI dips.

4. USE OF EMPIRICAL METHOD

The empirical method described can be very easily programmed on a Personal Computer. Over the range of cladding profiles on which the method was based, agreement with measurement is extremely good (figs.9,10). The SRI response to changes in profile parameters can be clearly seen (compare fig.11 to fig.2). However, the acid test is to make comparison with commercially-available profiles which were not a part of the initial sample on which regressive error reduction was performed. In these cases (figs.12,13) the agreement is less perfect but can be seen to be a vast improvement on existing methods.

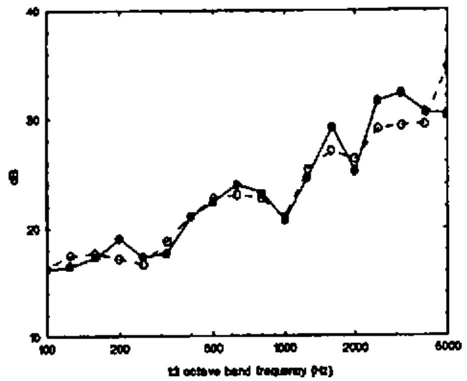


Figure 9 : empirical prediction (dotted) compared to SRI measurement (solid) for symmetrical profile ($t=0.65$mm, $L_c=L_v=95$mm, L depth = 35mm).

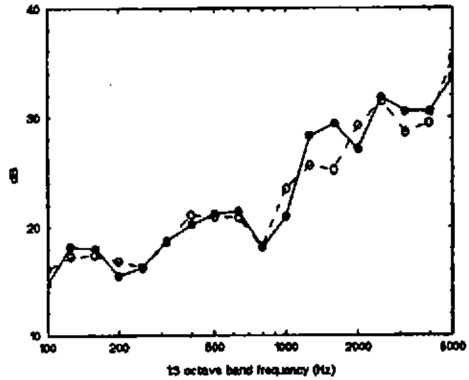


Figure 10 : empirical prediction (dotted) compared to SRI measurement (solid) for "deep" symmetrical profile ($t=0.65$mm, $L_c=L_v=95$mm, L depth = 45mm).

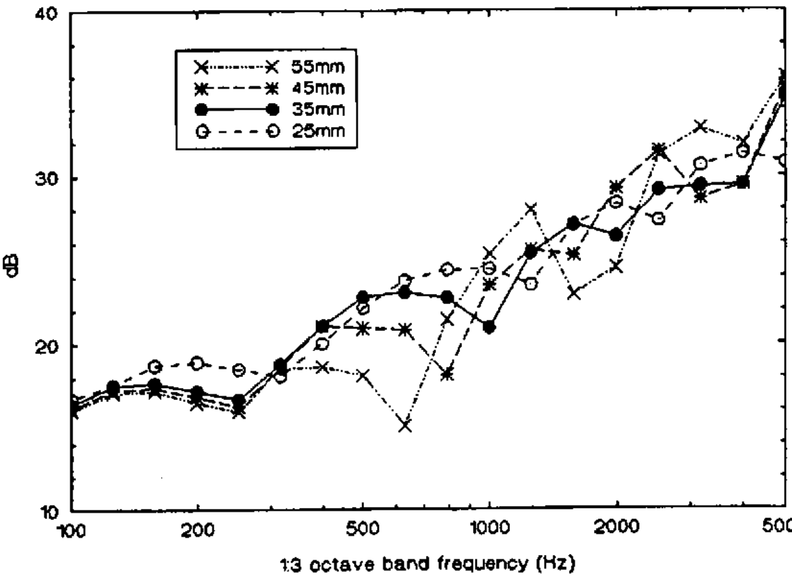


Figure 11 : empirical prediction of measurements shown in fig.2; parameter = profile depth; $L_c=L_v=95$mm, $t=0.65$mm steel.

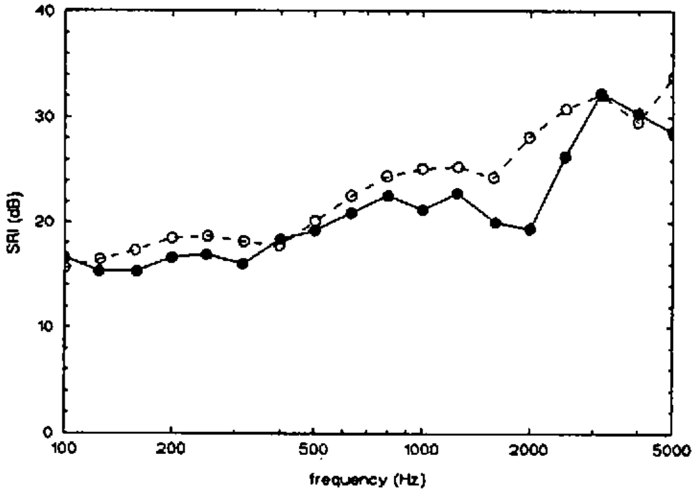


Figure 12 : comparison of predicted curve with commercial cladding (t=0.55mm, pitch=200mm, depth=35mm, L_c=38mm) not used in empirical sample.

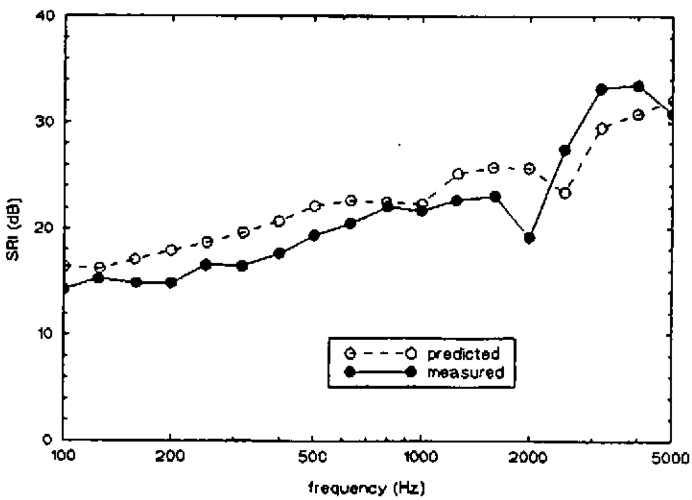


Figure 13 : comparison of predicted curve with commercial cladding (t=0.55mm, pitch=180mm, depth=32mm, L_c=35mm) not used in empirical sample.

The comparisons exhibited (figs.12,13) show that the suggested approach is able to pinpoint depressions in the sound reduction performance of any trapezoidally profiled cladding. Major "dips" are highlighted within the nearest 1:3 octave band. Thus, it can be said that empirical methods can be usefully employed in the prediction of sound reduction of metal cladding. Further work at the University of Salford will refine this method and ensure a wider availability to non-acousticians, particularly in the construction industry. It should also be possible to produce much more accurate models by increasing the degree of analytical approximation to existing complex methods.

5. CONCLUSION

A detailed knowledge of the physical characteristics of metal cladding has been applied to produce a simple empirical prediction method for sound reduction. "Dips" in the SRI are caused by certain characteristic modeshapes, for which the frequency can be accurately predicted by development of simple bar theory. The occurrence of these dips can be used to correct existing theory to attain a realistic prediction of the 1:3 octave band sound reduction of any trapezoidal profile.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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