Proceedings of the Institute of Acoustics

PREDICTION OF THE SOUND REDUCTION OF COMMERCIAL DOUBLE-SKIN PROFILED METAL CLADDING SYSTEMS

Y.W. Lam

Department of Applied Acoustics, University of Salford, Salford M5 4WT

1. INTRODUCTION

Previous research [1,2] has studied the sound transmission through single-skin cladding systems in detail. It was found that the sound reduction index (SRI) of these systems is generally characterized by large "dips" at mid-frequencies, and that these "dips" are linked to distinct vibration modes whose shapes repeat over each profile corrugation period. Based on these findings, appropriate methods, both analytical and empirical, have been developed to reliably predict the sound reduction index of single-skin systems. However single-skin materials are generally used only for industrial and agricultural storage sheds or peripheral workshops where specifications are less strict. In the great majority of cases industrial buildings are constructed from more complex cladding systems normally containing two layers of profiled metal sheet with some form of cavity filling and structural fixings. Unfortunately the mid-frequency "dips" which degrade the SRI of single-skin cladding can also occur in double-skin cladding (see Figure 1). Current theories [3] on double-layer SRI prediction are mainly for isotropic structures and cannot adequately account for the orthotropic nature and the existence of the mid-frequency "dips" of profiled cladding. Therefore one need to extend the previous study to cover the prediction of the SRI of double-skin cladding constructions.

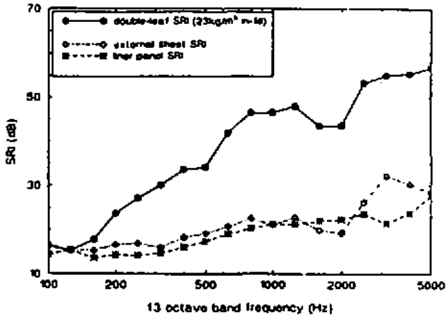

Figure 1 : The sound reduction of a double-skin cladding system and its constituent skins.

II. PREDICTION OF DOUBLE-SKIN CLADDING SRI

Without sound bridges between the two constituent sheets, and with sufficient absorption in the cavity to prevent air cavity resonances, the following engineering approximation provides a good prediction of the ideal sound reduction of a double sheet construction [3], where $\mathbf{R}_1$ and $\mathbf{R}_2$ are the individual skins' sound reduction (with subscripts 1 and 2 corresponding to the liner and external sheets respectively), **d** the cavity span and $\mu = \mu_1 + \mu_2$ the total surface mass of the skins,

$$
\begin{aligned}
R_{NB} &= 20\log_{10}\mu f - 47 \quad dB, && f < f_o \\
R_{NB} &= R_1 + R_2 + 20\log_{10} fd - 29 \quad dB, && f_o < f < f_L \\
R_{NB} &= R_1 + R_2 + 6 \quad dB, && f > f_L
\end{aligned}
\qquad (1)
$$

The mass-air-mass resonance f_o and limiting frequency f_L are given by

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1.8\rho_o c^2}{d}\,\frac{(\mu_1+\mu_2)}{\mu_1\mu_2}}\,, \quad and \quad f_L = \frac{c}{2\pi d} \qquad (2)$$

The empirical correction of 1.8 in equation (2) was suggested by Refs. [4,5]. Equation (1) can be applied to both isotropic and orthotropic sheets. However, the assumption of no sound bridging is rather unrealistic for cladding systems. Figure 2 shows the five most common type of cladding system constructions and Figure 3 shows the typical fixing method of standard double-skin cladding systems. The cladding is usually affixed by screws to the structural building frame or purlins. In the most common constructions Z-spacer rails are fastened through the liner panel to the purlin and the external sheet is then affixed to the rail. The rail spacing is universally within 10% of 2m, as is the separation of purlins. The Z-spacer fixing to the external sheet is usually every 1 or 2 profile periods (about 300mm). In this case the link between the liner and the external sheet can be considered as point-to-point. However spacer rails are sometimes replaced by other means of structural support (e.g. systems C,D,E). The span (distance between liner panel and external sheet) is typically in the range 60-100mm, although alternative systems can provide larger cavities. "In-fills" or "cavity insulation" are mostly formed from glass or mineral wool.

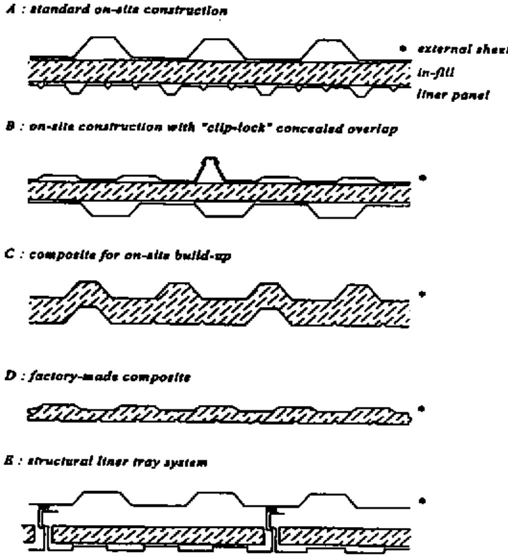

Figure 2 : Diagrammatical representation of five common commercial double-skin cladding constructions.

With the presence of sound bridges, the calculation of sound reduction becomes complicated. For isotropic plates, Sharp's method [3] can be used. For cladding systems, existing methods need to be extended to cover the orthotropic nature of the systems.

Effect of Sound Bridges in Orthotropic Systems

Let W_i, W_{NB}, and W_B be respectively the incident sound power, the radiated sound power without bridging, and the sound power radiated by the action of the sound bridges alone. Then the sound reduction R may be written, in terms of the no-bridging reduction R_{NB}, as

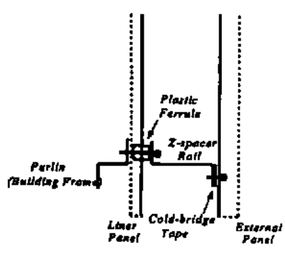

Figure 3 : Representation of the built-up of a typical double-skin cladding system.

$$R = R_{NB} - L_B \quad , \quad \text{where } L_B = 10\log_{10}\left|1 + \frac{W_B}{W_{NB}}\right| \tag{3}$$

W_{NB} is radiated from the forced response of the external sheet (plate subscript 2). Away from the critical frequencies of the plate, $W_{NB} = \rho_o c S u_2^2$, where S is the area of the plate and u_2 is the root-mean-square velocity of the plate. W_B is radiated by the action of the sound bridges on the external sheet. The sound power caused by a single sound bridge, W_{B1}, is given by the sound power radiated by an orthotropic plate under a point force excitation (point support) [6], $W_{B1} = \rho_o c \sigma_{rad} u_B^2$, where u_B is the velocity at the bridge and σ_{rad} is given by

$$\sigma_{rad} = \frac{8}{\pi^3}\lambda_{c1}\lambda_{c2} \qquad f < f_{c1}$$

$$\sigma_{rad} = \frac{2}{\pi^4}\frac{\lambda\lambda_{c2}}{\eta}\left[\ln\left(\frac{4f}{f_{c1}}\right)\right]^2 \qquad f_{c1} < f < f_{c2} \tag{4}$$

$$\sigma_{rad} = \frac{2}{\pi^2}\frac{\lambda_{c1}\lambda}{\eta} \qquad f_{c2} < f$$

where f_{c1} and f_{c2} are the plate's lower and upper critical frequencies, λ_{c1} and λ_{c2} are their corresponding wavelengths, and η is the loss factor of the plate. If there are m such sound bridges, then $W_B = mW_{B1}$ (incoherent), and

$$\frac{W_B}{W_{NB}} = \frac{m\rho_o c\sigma}{S\rho_o c}\frac{u_B^2}{u_2^2} = \left(\frac{\sigma}{S_{B1}}\right)\left[\left(\frac{u_B}{u_1}\right)\left(\frac{u_1}{u_2}\right)\right]^2 \tag{5}$$

where S_{B1}=S/m is the sheet area per sound bridge. The ratio between u_B and u_1 is obtained from a consideration of the impedance at the two ends of the bridge,

$$\frac{u_B}{u_1} = \left|\frac{Z_{B1}}{Z_{B1} + Z_{B2}}\right| \tag{6}$$

where Z_{B1} and Z_{B2} are respectively the orthotropic point impedance of the liner and external sheets [6],

$$Z_{Bi} = \frac{4}{\pi}c^2\frac{\mu_i}{\sqrt{f_{c1_i} f_{c2_i}}} \quad , \quad \text{where } i = 1,2 \tag{7}$$

The ratio between u_1 and u_2 can be obtained from a consideration of the diffuse field acoustic transmission in the absence of the sound bridges. With Z_2 being the diffuse field impedance of the external sheet, and Z_c that of the air cavity, then $\frac{u_1}{u_2} \approx \left|\frac{Z_2}{Z_c}\right|$.

In the case of an orthotropic plate the impedance Z_2 does not follow the mass law once the frequency is close to or higher than the lower critical frequency f_{c1}. For profiled metal cladding sheets, f_{c1} is usually around 200 - 300 Hz. Furthermore the impedance will also be affected by the "local" profile resonances which are responsible for the sound reduction "dips". Hence the mass law cannot be used here. Instead, one note that the equation for the sound reduction of a flat but orthotropic plate can be generally written as

$$R(\theta,\phi) = 10\log_{10}\left|1 + \frac{Z(\theta,\phi)}{2\rho_o c}\cos\theta\right|^2 \tag{8}$$

where θ and ϕ are the elevation (from z-axis) and azimuth angles of the incident plane wave. Assuming that this equation may also be used to approximate the relationship between the diffuse field sound reduction R_2 and the diffuse field impedance Z_2, so that

$$Z_2 = 2\rho_o c\left(10^{\frac{R_2}{20}} - 1\right) \tag{9}$$

Hence

$$\frac{u_1}{u_2} = 2\left(10^{\frac{R_2}{20}} - 1\right)\beta$$

$$\text{where } \beta = \frac{\omega d}{c} \quad \text{for} \quad f < f_L, \quad \text{and} \quad \beta = 1 \quad \text{for} \quad f > f_L \tag{10}$$

High density in-fills at high frequencies can also provide additional sound reduction through the insulation. This sound reduction, TL_{ins}, can be estimated using standard transfer matrix method for fibrous materials with rigid frames [7]. The total sound reduction through the double-sheet cladding system is therefore,

$$R = R_{NB} - 10\log_{10}\left|1 + \frac{\sigma_{rad}}{S_{B1}}\left|\frac{Z_{B1}}{Z_{B1} + Z_{B2}}\right|^2\left[2\left(10^{\frac{R_2}{20}} - 1\right)\beta\right]^2\right| + TL_{ins} \tag{11}$$

Composites

For composite panels the core is usually "rigid" enough to form a direct mechanical link. The sound reduction resembles that of a double-sheet system with a high stiffness cavity [8]. Equation (1) can still be used to estimate R_{NB}, but with the mass-cavity-mass resonant frequency f_o and limiting frequency f_L calculated by

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1.8E_{core}}{d}\frac{(\mu_1+\mu_2)}{\mu_1\mu_2}} \tag{12}$$

$$f_L = \frac{c_{core}}{2\pi d} \tag{13}$$

where E_{core} and c_{core} are the Young's modulus and speed of sound of the core's material.

With equation (12) the frequency f_o usually occurs at mid-frequencies (1k to 2k Hz). A "dip" in the sound reduction will occur at this frequency. The "dip" magnitude depends on the loss factor. As yet we have no reliable theoretical means of predicting this magnitude. An empirical correction of 10dB seems adequate but further work may be required to refine this prediction of the "dip" magnitude.

Summary of theory

The theory described above predicts the SRI of a double-skin construction based on the SRI of the constituent orthotropic skins. The constituent SRI can either be measured or predicted. When combined with the single-skin prediction procedure described in an earlier paper [2], this theory provides a completely predictive procedure for determining the SRI of double-skin profiled metal cladding systems.

III. RESULTS

Figure 4 shows a comparison between predictions using the above theory with the SRI data measured on a commercial double-skin system with different in-fill density. The "Complete Prediction" is compared with that using measured single-skin SRI data ("Predicted from measured SRI"). Both predictions show very good accuracy throughout the frequency range of 200 to 5000 Hz. The "partial" prediction has only slightly better accuracy than the "Complete Prediction" which serves to show the good accuracy of the single-skin SRI prediction. It is of interest to note that the SRI of the cladding system with the lower in-fill density shown in the figure has a rather large "dip" at 2000 Hz which is also evident in the SRI of one of the constituent skins. This "dip" has also been successfully predicted. Note that the magnitude of the "dip" at 2000 Hz was reduced by the higher density insulation.

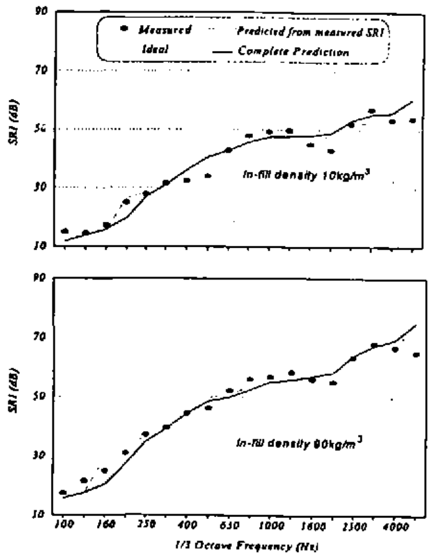

Figure 4 : SRI prediction on a double-skin profiled metal cladding system with different in-fill density.

The effect of using a structural liner tray (type E in Fig.2) rather than the standard purlin support is shown in Figure 5. Only the Complete Prediction is shown together with measurement in this figure. Again the prediction shows excellent agreement with the measured data up to 2500 Hz. At higher frequencies the prediction shows significant deviation from the measurement. It is believed that the profile depth of the liner tray is too deep for the assumptions made by the single-skin SRI prediction to be valid at these high frequencies.

Figure 6 shows a comparison of the prediction on a factory fabricated modular composite panels (type D in Fig.2). The core material in both panels is rigid PUR/PIR in-fill. Typical material data for the core are used: Young's modulus = $5.0\times10^6 N/m^2$, density ≈ 45 kg/m^3. A strong sound reduction "dip" can be seen at the predicted mass-cavity-mass resonant frequency. Again agreement between prediction and measurement is quite good in the frequency range of 200 to 2500 Hz. Outside this frequency range the measured SRI is generally higher than predicted, possibly because of the structural strength of the encapsulated modular structure being not accounted for by the theory.

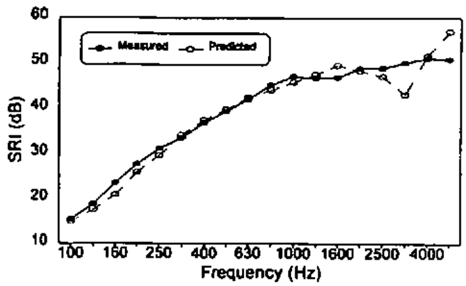

Figure 5 : Double-skin profiled steel cladding system with structural liner. 0.6mm thick external sheet

Overall the SRI of a total of 24 double-skin cladding systems (16 standard built-up units with various insulation density and thickness (Figure.1, type A), 4 units with "clip-lock" standing seam profiled sheets (Figure.1 B), 1 site assembled composite panel (Figure.1, type C), 2 modular composite panels (Figure.1, type D), and 1 unit with structural liner tray (Figure.1, type E)) were predicted and compared with measured data. The overall root-mean-square error over the 100 to 3150 1/3 octave frequency range was found to be 2.9 dB, while the root-mean-square error on the standard weighted index Rw [9] was found to be 2.1 dB. The root-mean-square error may be considered as an approximate estimate of the standard deviation of the predicted from the measured values. These errors may be compared with the discrepancy found by an international round robin test on the measured SRI of a double metal sheet sample involving 13 laboratories [10]. The discrepancy was found to be more than 10 dB in the 1/3 octave bands from 100 to 3150 Hz, and by about 6 dB in the Rw (see Figures 8.26 and 8.27 of Ref.[10]). The reproducibility was estimated to be 4.2 dB in Rw and almost 10 dB on individual mid-frequency 1/3 octave values (Figure 8.32 of Ref.[10]). It seems that the theory provides a reliable method of predicting the SRI of common double-skin cladding systems.

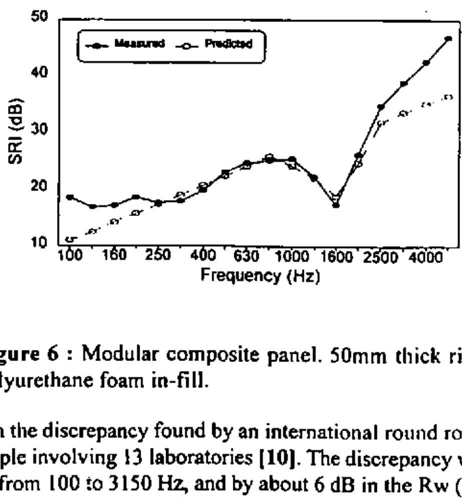

Figure 6 : Modular composite panel. 50mm thick rigid polyurethane foam in-fill.

IV. CONCLUSIONS

A theory has been developed which has been shown to provide accurate prediction of the SRI of common double-skin profiled metal cladding systems. The prediction was found to be most accurate on standard built-up systems (within ±3dB of the measured SRI values in the 200 to 3150 Hz 1/3 octave bands on all 16 standard built-up cladding systems), and least on systems with "clip-lock" standing seam profiles, mainly because the single-skin prediction theory does not cope very well with profiles with large depth but small crown length. The error margin (root-mean-square error of 2.1dB on Rw and 2.9dB on individual 1/3 octave frequency band SRI) should be acceptable for preliminary design purposes. The prediction methods has now been implemented under a contract with the Metal Cladding and Roofing Manufacturers Association into a user-friendly computer model which can be used for assessing double-skin metal cladding designs.

ACKNOWLEDGEMENTS

This research was supported by the Engineering and Physical Science Research Council under Grant No. GR/H77088. The authors also wish to thank British Steel Profiles Ltd. and the Metal Cladding and Roofing Manufacturers' Association for providing cladding materials for testing.

REFERENCES

1. Lam Y.W., R.M. Windle, "The noise transmission through profiled metal cladding, part I: single skin measurements", Journal of Building Acoustics Vol.2(1), p.341-356, 1995
2. Lam Y.W., R.M. Windle, "The noise transmission through profiled metal cladding, part ii: single skin SRI prediction", Journal of Building Acoustics Vol.2(1), p.357-376, 1995
3. B.H.Sharp; "Prediction Methods for the Sound Transmission of Building Elements"; Noise Control Eng. 11(2) (1978); pp.53-63.
4. D.A. Bies and C.H. Hansen, **ENGINEERING NOISE CONTROL**, 1st Ed., Unwin Hyman, London, p.193-194, 1988.
5. R.E. Jones, "How to accurately predict the sound insulation of partitions", J. Sound and Vib. 10, p.14, 1976.
6. M.Heckl; "Untersuchungen an Orthotropen Platten"; Acustica 10 (1960); pp.109-115.
7. K.U. Ingard, **NOTES ON SOUND ABSORPTION TECHNOLOGY"**, Noise Control Foundation, New York, Appendix A, p.A-1 to A-8, 1994.
8. F. Fahy, **SOUND AND STRUCTURAL VIBRATION**, Academic Press, London, p.195-197, 1985.
9. BS 5821: Part 1, "Rating the sound insulation in buildings and of building elements", British Standards Institution, 1984.
10. P. Kruppa and H.S. Olesen, "Intercomparison of laboratory sound insulation measurements on window panes", BCR Report EUR 11576EN, Commission of the European Communities, 1988.