Proceedings of the Institute of Acoustics

THE TRANSMISSION LOSS OF SINGLE AND DOUBLE SKIN CLADDING CONSTRUCTIONS

R.M.Windle

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

1. INTRODUCTION

This research is incorporated in a project which aims to provide a comprehensive prediction method for the radiation of noise from factories. The prediction model should be capable of predicting the radiated noise from a building before construction in order that noise control measures can be inherently incorporated. The transmission of noise from a building's interior is of especial interest as it sets the minimum error "at source" for the overall prediction scheme before outdoor sound propagation algorithms are applied.

Modern industrial structures invariably include some amount of profiled metal cladding. Such materials are cheap and simple to construct. However, they may consequently have poor sound reduction characteristics. This paper presents sound reduction measurements on idealised single-skin profiled cladding. Basic theories are developed to describe their performance, which is related to noise transmission through more common double-leaf walls.

2. SOUND REDUCTION OF SINGLE-SKIN CLADDING

2.1 Measurement Method

The results presented are the Sound Reduction Index (SRI) of walls measured in a transmission suite according to ISO-140-1978 [1]. Measurements were performed at least twice for each construction to ensure good repeatability.

2.2 Tests on Idealised Profiles

Idealised profiled single-skin steel claddings were designed and fabricated in order to represent the full range of commercially available materials and to ensure control of the separate parameters; which may be described as the pitch (p), gauge (h), depth (d), the effect of profile asymmetry and that of additional stiffeners (figure 1). Construction of idealised panels afforded the opportunity to look at each parameter in isolation. Test 1 uses five panels of the same pitch (p=250mm) and depth (d=35mm) with varying gauge; Test 2 evaluates the effect of changing the pitch (where h=0.65mm and d=35mm); Test 3 investigates the effect of varying the depth (with h=0.65mm and p=250mm). Tests 4 studies the action of asymmetrical profiling,

SOUND REDUCTION OF CLADDING

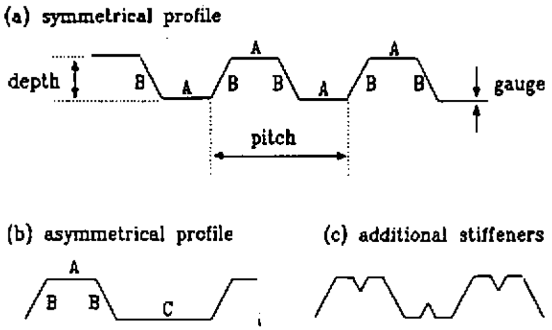

Figure 1 : Profiled cladding parameters.

where length C (figure 1b) is varied from 20mm to 245mm and lengths A and B are held at 95mm and 45mm respectively, with h=0.65mm. Finally, the panels of thickness h=0.65mm and 0.9mm used in test 1 are compared to profiles of exactly the same dimensions except for the addition of stiffeners as shown in figure 1c.

The SRI of panels with the same profile, but of varying thickness (Test 1) is shown in figure 2. It is seen that none of the observed curves are particularly smooth and that large discrepancies occur between the gauges. Most notable are the dips which occur in the transmission loss at mid-frequencies (i.e. between 630Hz and 2KHz) of magnitude up to 6dB above the value expected from interpolation of the remainder of each SRI characteristic. Table 1 gives the 1/3 octave bands in which the two dips occur in each curve, one very approximately at double the frequency of the first. As the thickness of the panel increases the position of the dip also increases in frequency. As one would expect, the values for SRI broadly increase for thicker samples, although this breaks down at the dips.

Figure 3 displays similar characteristics for panels with various profile pitch (Test 2). In this case the dip frequencies tend to decrease as the pitch increases. It is noted that the dips are greater than 10dB in magnitude in certain cases, e.g. at 1.6KHz for p=150mm, and that this magnitude broadly decreases for a larger pitch. When one increases the profile depth (Test 3, figure 4) the dip frequency is also seen to decrease and the sound transmission can be observed to depreciate considerably.

Various measurements on asymmetrical profiles are compared to the symmetrical panel (h=0.65mm, used in Test 1) in figure 5. Only the flat well length (length C in figure 1b) is varied such that each panel contains similar elements. It can be seen that the sound reduction is not affected by a very significant amount except at the mid-frequency dips, which notably occur at exactly the same point. At these points the magnitude of the dips vary considerably. Finally, figures 6 and 7 clearly demonstrate that the addition of profile stiffeners can have a highly detrimental effect on the SRI at higher frequencies (>500Hz). Two SRI measurements were carried out on every profile above and the SRI were not seen to vary by more than ±1dB except at very low frequencies (~50Hz) - examples are shown in figures 6 and 7.

SOUND REDUCTION OF CLADDING

It is clear from the results that a comparatively small change in the profile parameters can produce a substantial alteration in the sound reduction characteristics. One notes that the mid-frequency dips become wholly unacceptable for smaller values of profile pitch and larger values of depth. Further it is possible to alter the relative magnitude of these dips by employing various degrees of asymmetry.

Table 1 : Position of observed mid-frequency dips.

test	panel dimensions (mm)			1/3 octave band of dips (Hz)	
	h	p	d		
	0.45			630	1250
	0.55			800-1000	1600
1	0.65*	250	35	1000	2000
	0.72			1000-1250	2000-2500
	0.90			1600	3150
		150		1600	3150
		200		1250-1600	2500-3150
2	0.65	250*	35	1000	2000
		300		800	1250-1600
		350		500-630	1000
			25	1250	2000
3	0.65	250	35*	1000	2000
			45	800	2000
			55	630	2000
		175			
4	0.65	250*	35	1000	2000
		325			
		400			

* Reference panel - same in each test.

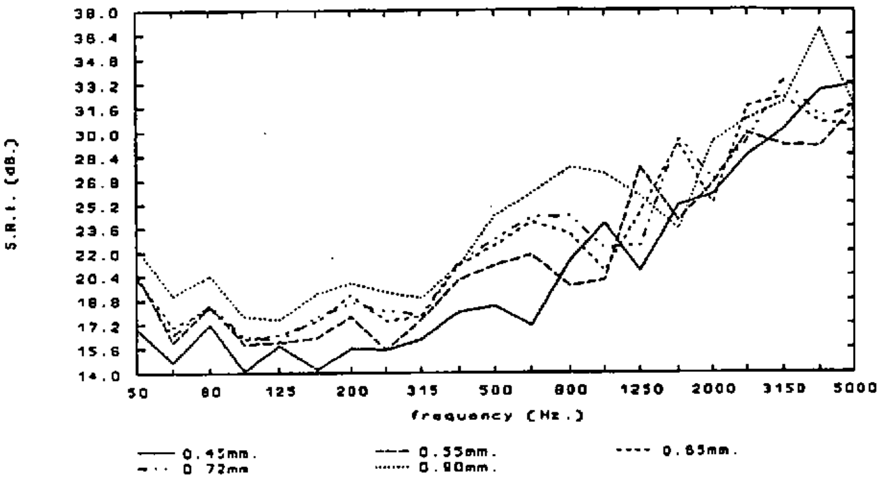

Figure 2 : Test 1, effect of varying gauge. Profile pitch and depth are constant (p=250mm, d=35mm).

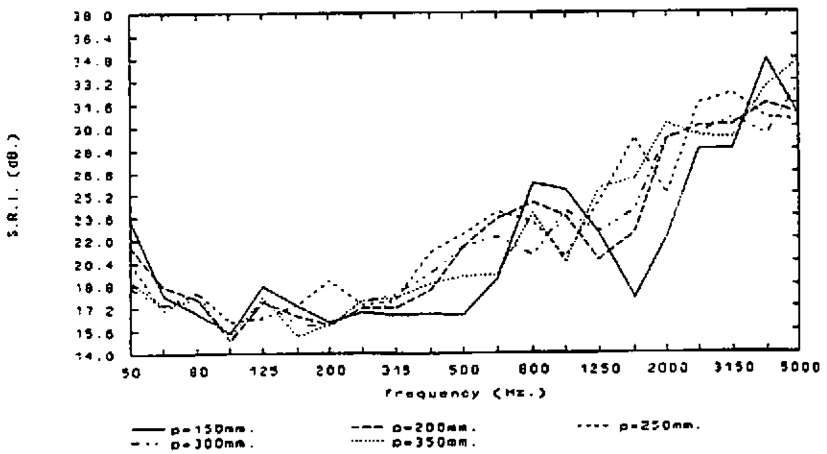

Figure 3 : Test 2, effect of varying profile pitch. Gauge and profile depth are constant (h=0.65mm, d=35mm).

SOUND REDUCTION OF CLADDING

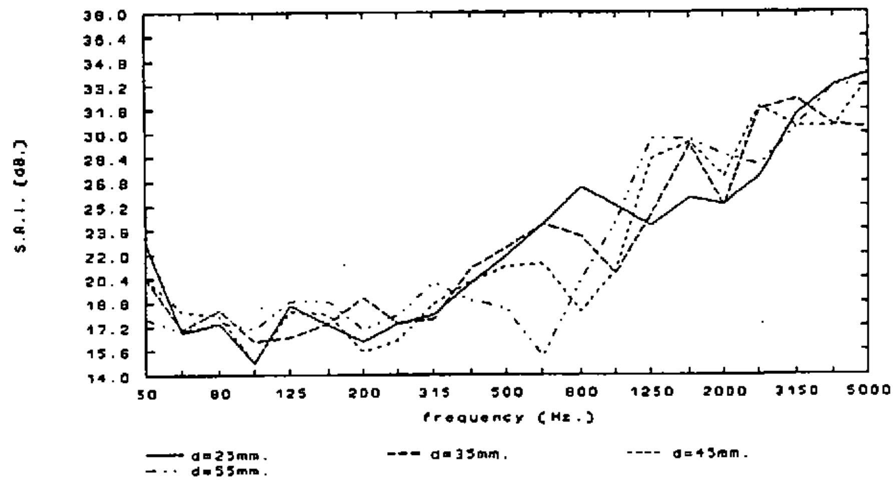

Figure 4 : Test 3, effect of varying profile depth. Gauge and profile pitch are constant (h=0.65mm, p=250mm).

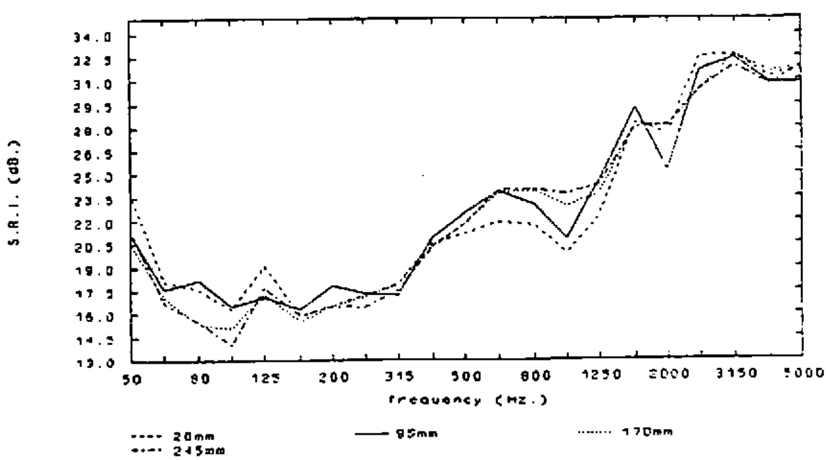

Figure 5 : Test 4, effect of asymmetry. Panels have same well side and ridge lengths, with varied well length (given).

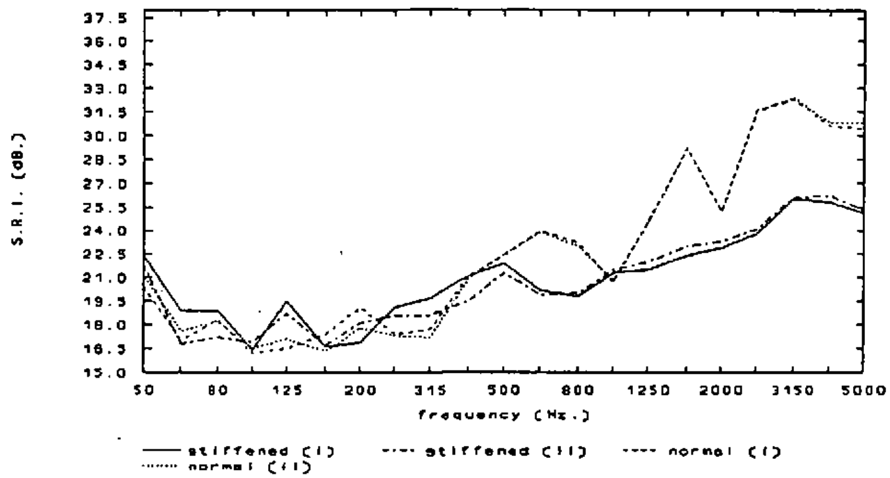

Figure 6 : Test 5, effect of profile stiffeners added to symmetrical panel (h=0.65mm, p=250mm, d=35mm).

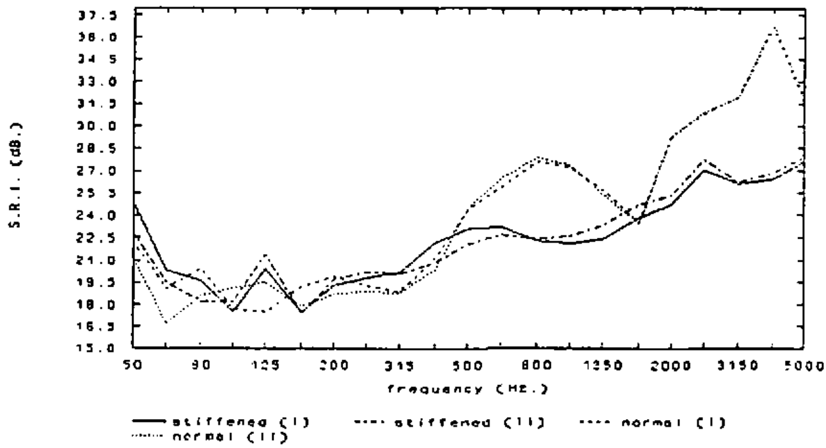

Figure 7 : Test 5, effect of profile stiffeners added to symmetrical panel (h=0.9mm p=250mm, d=35mm).

2.3 Discussion

The largest sources of uncertainty in the prediction of sound transmission through profiled single-skin claddings is undoubtedly the presence of the mid-frequency "dips" and the reliability of measurements at low frequencies. The dips observed cannot be explained away by resonances in the finite panels measured in a transmission suite as they have been exactly correlated with in situ measurements [2]. Below ~100Hz the transmission suite measurements are unreliable due to room modes and transmission of noise back from the receiver to the source room. Without undertaking tests using some other method an analysis of low frequency transmission is not possible.

Above this lower limiting frequency, certain approximations may already be employed for giving reasonable predictions of the SRI, notably that of Heckl [3], as has been demonstrated [2]. However, no author has yet attempted predictions of sound transmission through profiled cladding incorporating these dips, although Cederfeldt [4] has undertaken similar measurements. Several conjectures have been forwarded as to their cause : one idea is that there is some interaction between the two critical frequencies of the panel associated with the different bending stiffnesses in the vertical and horizontal dimensions. However, simple formulation of the critical frequencies, e.g. [5], indicates that the dip frequencies would vary in a much different fashion by altering profile dimensions in the manner described above.

It is more likely that the increased transmission may be due to individual resonances in certain parts of the cladding. For example, the well bottom may have a resonance at one frequency and the well side may have a resonance at some other point resulting in two distinct dips as observed. Alternatively, it is possible that one dip is a harmonic of the other because the second dip frequency seems to be roughly double that of the first. A further suggestion is that the wells in the profile allow resonances to occur in air, which may drive or be driven by the individual panel resonances.

A simple method of testing whether the second dip is purely a bi-product of the first is to obtain a measurement of sound reduction in a narrow-band frequency spectrum. This was achieved by measuring the sound level in both source and receiver room (L_S and L_R respectively) with a spectrum analyzer. The two spectra may then be subtracted to give an indication of the SRI in the form of a simple sound level difference (L_S-L_R) across the wall. Such measurements were repeated at least three times on every panel tested to ensure that the higher-resolution dip frequency was not overly effected by "random" small detail. It was shown that the two dips are distinct events as opposed to harmonic relations. An example is shown in figure 8, corresponding to the 1/3 octave spectrum for the d=45mm profile given in figure 4. It may be seen that predominant dips occur in the narrow-band analysis around the frequencies 775Hz and 1912Hz and between 2889 and 3775Hz (corresponding to dips in the 800Hz, 2KHz and 3.15-4KHz 1/3 octave bands in figure 4). If the dip around

775Hz is observed closely, it can be recognised that a harmonic seems to occur about 1550Hz as the dip "shape" is approximately repeated. However, the "harmonic" is only of the order of 2-3dB and does not appear in the 1/3 octave spectrum. Certainly, the second major dip (between 1775 and 2050Hz, or the 2KHz 1/3 octave band) is not attributable as a harmonic of the 775Hz dip and is, in fact, of greater magnitude (~10dB) in the narrow-band analysis.

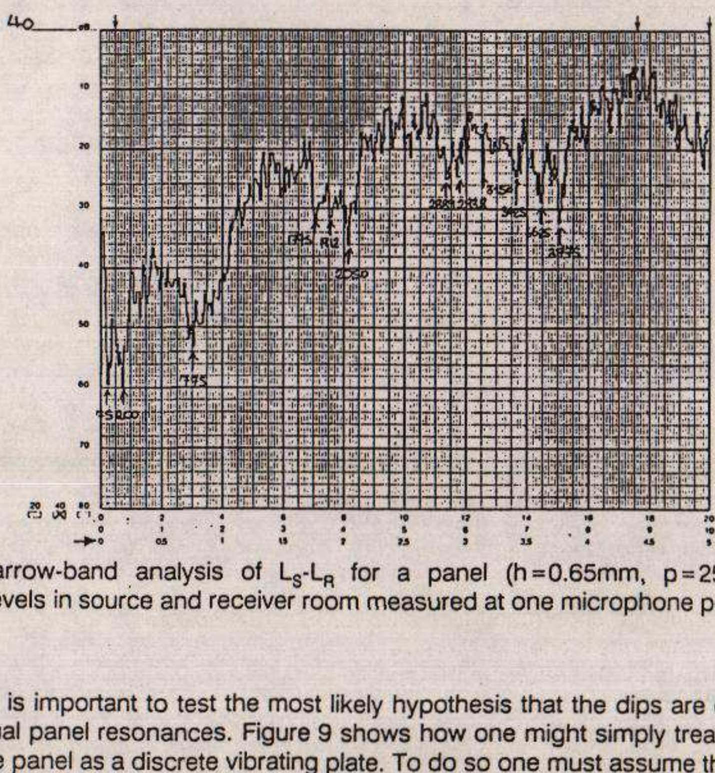

Figure 8 : Narrow-band analysis of L_S-L_R for a panel (h=0.65mm, p=250mm, d=45mm). Levels in source and receiver room measured at one microphone position only.

Henceforth, it is important to test the most likely hypothesis that the dips are due to some individual panel resonances. Figure 9 shows how one might simply treat each flat area of the panel as a discrete vibrating plate. To do so one must assume that the profile bends are stationary, i.e. that the plate is simply supported (no motion or bending moment at the edges). This will not be the case in the real situation where the individual plates are joined at the "bends" and transmit energy to one another. However, this allows an extremely simple formulation of how the dip frequencies may change as the profile parameters are altered. By solving Newton's second law for the simply held plate it can be shown that resonant modes occur at :

$$f_{nm} = \frac{\pi}{2}\sqrt{\frac{EJ}{\mu(1-\sigma^2)}}\left[\frac{n^2}{a^2} + \frac{m^2}{b^2}\right]$$

where a and b are the panel dimensions with resonant mode numbers n,m respectively (such that figure 9 shows n=0,m=2), E is Young's modulus, J is the second moment of area ($J=h^3/12$), μ represents surface mass (kgm^{-2}) and σ is Poisson's ratio. Previous measurements [2,6] have shown that the dip frequency remains constant over different wall sizes. In other words, one is unsure of the vertical dimension, a, of the constituent single plate. However, the width is of the order b~10cm whereas a is usually more than 3m. It is then reasonable to say that :

$$\frac{n^2}{a^2} < \frac{m^2}{b^2} \quad - \quad f_{nm} \rightarrow f_m = \frac{\pi}{2}\sqrt{\frac{EJ}{\mu(1-\sigma^2)}}\frac{m^2}{b^2}$$

This equation is used to estimate modal frequencies for the constituent parts of the profile of the symmetrical panels, such that only two different dimensions need be considered : (i) the well tops and bottoms, (ii) the angled well sides. However, this brings into question the form of surface mass (or "surface density" in kgm^2) which should be used. Manufacturers typically quote a value which includes the profiles and overlap between panels. The above theory treats the panel as a finite, flat sheet such that if the profiling is accounted for in the surface mass ($\mu = \rho h$) then one is effectively predicting the transmission through a thicker panel of the same material. Therefore, in this analysis, the figures used for surface mass are those for $1m^2$ of **flat** steel of the same gauge. The results using this figure are given in Table 2 for modes up to m=3. Note that two of the dimension of the asymmetrical panels will give the same result as the h=0.65mm profile used in Test 1.

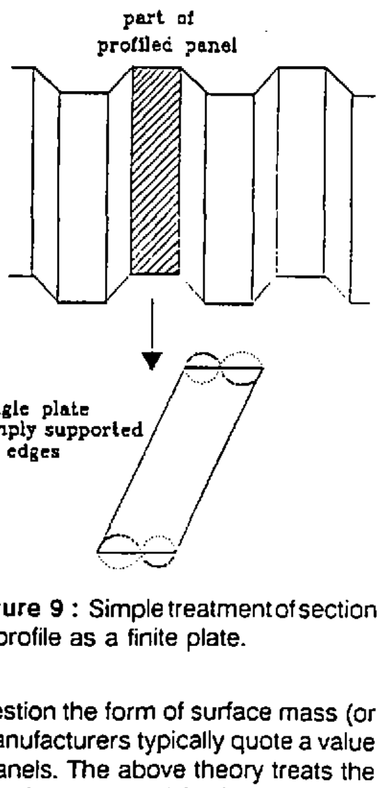

Figure 9 : Simple treatment of section of profile as a finite plate.

It is clear that this method does not produce correct dip frequencies, not surprising considering the large simplifications. However, it is observed that the movement of dip frequency in relation to changing profile parameters is predicted correctly and that the relative amplitude of the change is also broadly true. It is therefore probable that the two dips are related to the two flat lengths seen on each symmetrical panel. This can be further substantiated by considering what happens when the width of the well side and that of the top/bottom become similar. One would expect in this instance that the two dip frequencies will be close and that the resultant dip will increase in magnitude.

SOUND REDUCTION OF CLADDING

This will occur as the profile pitch becomes shorter and when the depth becomes larger. Inspection of figures 2-4 shows that this does occur; for example, in figure 4 the first dip magnitude increases in proportion to the profile depth and must therefore be a resonance in the well sides as the well bottom length does not change in width. In this instance the well top resonance is a constant frequency and may be said to occur in measurements (figure 4) at about 2KHz. Vibrational analyses have confirmed this. One should note that the predictions are not closest for mode m = 1. The dips will not necessarily occur at the lowest order resonances, but wherever the radiation efficiency is greater due to the profiles coupling to air or some well resonance.

Table 2 : Modal frequencies of a flat, long, steel plate.

Test	panel dimensions (mm)			modal frequency, f_n (Hz)					
				m=1		m=2		m=3	
	h	p	d	top	side	top	side	top	side
1	0.45	250	35	119	503	474	2013	1067	4530
	0.55			145	615	579	2461	1303	5536
	0.65			171	727	685	2908	1541	6543
	0.72			190	805	759	3221	1707	7247
	0.90			237	1007	948	4027	2134	9060
2	0.65	150	35	476	997	1902	3989	4280	8975
		200		268	858	1070	3431	2407	7720
		300		119	613	476	2452	1070	5518
		350		87	349	349	2067	786	4651
3	0.65	250	25	171	1012	685	4051	1541	9114
			45		727		2908		6543
			55		394		1575		3543

3.4 Vibrational Analysis

An accelerometer was placed at many positions over the cladding panels used in Test 4 (asymmetrical profiles). The panel was excited by pink noise in position in a transmission suite. A transfer function is obtained by normalising the accelerometer output (panel vibration) to the exciting force, measured with a standard pressure microphone in the source room. A significant vibrational peak was measured at ~1KHz on all well sides (45mm length, represented as length B in figure 1b). Similarly, a ~2KHz peak was always measured on the flat top (95mm length A, figure 1b). These corresponded exactly to dips in the SRI and narrow-band L_S-L_R. One can conclude that the SRI dips are therefore caused in some way by the individual resonances due to the cladding profile. However, there is no evidence as yet to suggest whether the strong radiation at these frequencies is due to radiation directly from the resonant vibration or from the resonance of the air column in a well driven by the mechanical resonance. It would seem unlikely that the extra radiation is directly caused by the vibration as the wavelength in air seems to be much larger than that of the panel bending waves. The 2KHz resonance would seem to have a mode number m~3 (it must be m>1 as it is a higher frequency than the 1KHz resonance on the shorter profile length), which begs the question why the fundamental mode is not excited. Possibly, this may be caused by a panel well resonance on either the driving or radiation side, which is certainly feasible by looking at the $\lambda/4$ or $\lambda/2$ resonances where relevant.

3. RELATION TO DOUBLE-LEAF WALLS

A possible criticism of the work on single-skin claddings is that they are not commonly used in factory construction, which are often built with double or triple leaf walls. However, it is suggested that a thorough understanding of single-leaf systems is required before double-skin applications can be properly analyzed. Additionally, one may show that a large SRI dip measured in single-skin cladding can translate into a similar dip if it is used in a double-leaf construction : figure 10 shows the measured transmission loss of a double-leaf wall and compares it to the SRI of its constituent single-skin profiles. From the single-skin panel data, predictions are attempted of the double-leaf wall (neglecting the in-fill apart from assuming it to be adequate enough to damp out cavity resonances). The double wall constitutes a 0.55mm gauge cladding (LR1000W) and 0.4mm profiled liner panel (1000LP). The gap between these is 80mm, which is fully filled with mineral wool. Simple calculations of the mass-air-mass and cavity resonances, etc. have shown that it is highly unlikely that such double-panel effects cause the SRI dip.

Two predictions are shown. The first is a simple addition of the two single-skin SRI and makes a barely adequate rough prediction of the performance. The second prediction is based on the mass law, e.g. [5] : below the mass-air-mass resonance, f_{mam}, the two panels vibrate as one element of mass $M = m_1 + m_2$; above f_{mam} the two panels act independently such that the prediction is based on their summed sound reduction. The SRI will then increase rapidly up to a limiting point at kd=1, where k is the wavenumber in air and d is the double-leaf cavity width. It can be seen that this prediction gives a very good idea of the double-leaf wall's sound reduction and demonstrates how a mid-frequency dip in any single-skin cladding will translate into a similar dip in the full wall's response. Such results have been confirmed on other double-skin constructions.

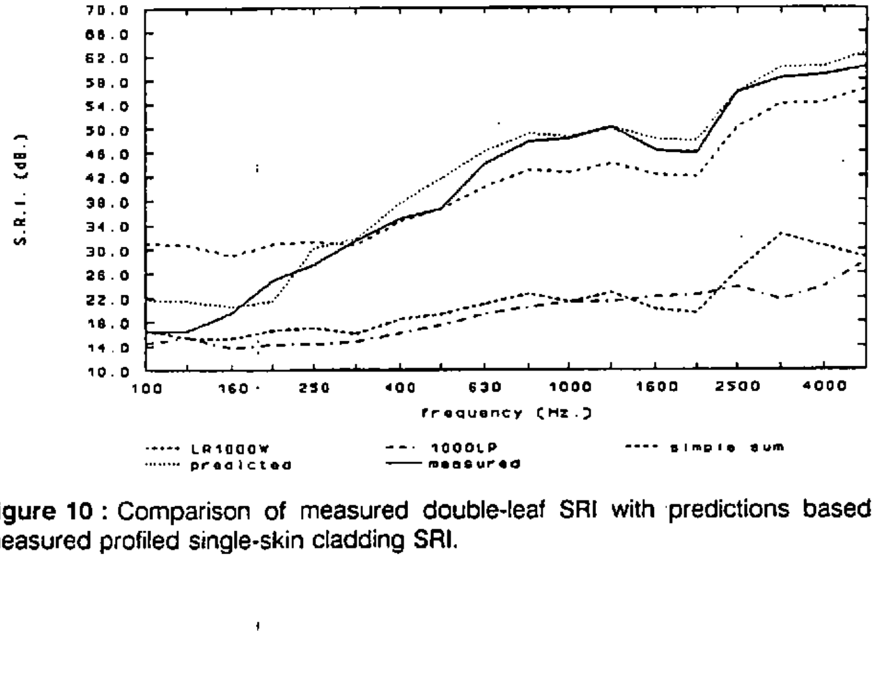

Figure 10 : Comparison of measured double-leaf SRI with predictions based on measured profiled single-skin cladding SRI.

4. CONCLUSION

It has been demonstrated that the Sound Reduction Index of profiled steel cladding can vary greatly when relatively small dimensional changes are made. Dips of 10dB or more can occur in the mid-frequency range (630Hz-2KHz), which tend to degenerate as profile pitch becomes smaller and the depth increases. The magnitude of the dip can be varied by employing varying degrees of asymmetry. Inclusion of extra profile folds to stiffen a panel can have a serious detrimental effect on the transmission charateristic. The dips observed correlate with vibrational resonances associated with particular sections of the cladding, but probably do not cause SRI dips directly. It is likely than some form of well resonance also effects the transmission. Finally, it is seen that such dips should be avoided in single-skin profiles as dips translate into a deterioration of the response of double-leaf walls also.

SOUND REDUCTION OF CLADDING

5. REFERENCES

[1] ISO140-1978 (BS2750), "Methods of Measurement of Sound Insulation in Buildings and of Building Elements"; I.S.O.(1978).

[2] R.M.WINDLE, R.J.ORLOWSKI & N.J.H.ALEXANDER, "A Comparison of the Sound Transmission of Profiled Metal Claddings when Measured in the Laboratory and In Situ"; Proc.IOA 12(5) (1990); pp.29-39.

[3] M.HECKL, "Untersuchungen an Orthotropen Platten"; Acustica 10(1960); pp.109-115.

[4] L.CEDERFELDT, "Sound Insulation of Corrugated Plates - A Summary of Laboratory Measurements"; Division of Building Technology Report No.55 (1974); Lund Institute of Technology, Lund, Sweden.

[5] D.A.BIES & C.H.HANSEN, "Engineering Noise Control"; 1st edition (1988); Unwin Hyman, London.

[6] R.M.WINDLE, "The Prediction of Noise Radiation from Industrial Buildings Constructed from Lightweight Cladding"; Proc.IOA 12(1) (1990); pp.271-279.

6. ACKNOWLEDGEMENTS

This work is funded by and published with the permission of the Department of the Environment. The author is also most grateful for the help and support of the British Steel Corporation; in particular the Product Development Centre, Shotton for fabrication of the claddings. Thanks are due also for the guidance of Dr.Y.Lam of the University of Salford.