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PREDICTION OF THE SOUND REDUCTION OF METAL CLADDING USING A TWO-DIMENSIONAL BOUNDARY INTEGRAL APPROACH

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1. INTRODUCTION

Metal cladding is a common feature of the modern built environment, especially in the case of industrial constructions. Previous work by the authors has clearly demonstrated that large depressions in the sound reduction characteristics of these materials occur at mid-band frequencies [1]. This has significant repercussions in the prediction of environmental noise [2]. It is increasingly expected of contractors to ensure that building envelopes conform to specified sound reduction specifications.

The "dips" in sound reduction were found to be a consequence of acoustic excitation of the cladding. This resulted in certain modeshapes for which near-field "inter-cell cancellation" was reduced, thereby enhancing the radiation efficiency at particular frequencies [3,4]. If one were to measure the vibration spectrum for mechanically excited cladding, the same modes would not predominate. The modeshapes could be accurately predicted using a two-dimensional Finite Element model which also lead to an extremely effective empirical prediction. Figure 1 compares a selection of measured and predicted (FE) modes. This paper considers methods by which the radiation from these modes is analyzed. The transmission mechanism is split into the two concepts of "excitation" and "radiation". The results allow conclusions to be drawn on the mechanical-acoustic interaction on the "radiation" side.

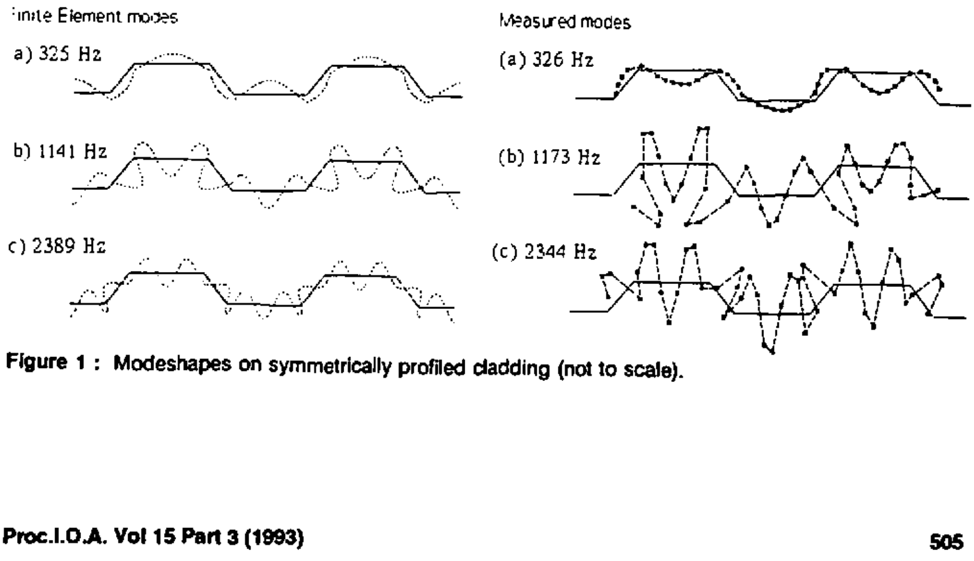

Figure 1 : Modeshapes on symmetrically profiled cladding (not to scale).

PREDICTION OF CLADDING CHARACTERISTICS USING BOUNDARY ELEMENT METHOD

2. TECHNIQUES FOR ANALYZING RADIATION

Several techniques of relating the far-field acoustic pressure to mechanical vibrations on the cladding have been applied. These may be loosely defined as follows :

1. **Volume Velocity Model :** a "small" representation of the cladding surface is taken, over which the volume velocity is summed such that positive and negative perturbations cancel [4]. Accordingly, one can attribute the residual radiation as the "source strength" of a single simple source (or cylinder in two dimensions). From this, the acoustic radiation is easily calculated.

2. **Point Source Array :** each half bending-wave may be represented by its own point source as represented in figure 2, where the source strengths Q_N will be alternately positive and negative to account for phase. This is a well-known approach commonly found in text books, e.g. [pp.512-514, 5]. If one requires a two-dimensional model (i.e. the surface velocity is taken to be constant in the infinite dimension) long, thin radiators may be applied in place of point sources; e.g. the "pulsating cylinder" or "vibrating wire" can be used [pp.356-359, 6] such that the points shown in fig.2 will be infinite in the dimension perpendicular to the page.

Figure 2 : application of the array method.

3. **Boundary Element Method (BEM) :** a numerical method based on the complex approach of boundary integral equations [7,8] which solves the radiation problem rigorously. Hence, as long as the surface velocity is modelled in sufficient detail, all acoustic interactions are fully dealt with.

The simple volume velocity model has been shown to pinpoint certain modes which consistently coincide with depressions in the sound reduction characteristics of cladding [3,4]. However, it should be clear that this approach is only valid at low frequencies (i.e. where the maximum separation between parts of the source with the potential to cancel is much less than the air wavelength). This limit is avoided by application of the point source array. In this case, radiation from adjacent "cells" will cancel as long as their separation is less than the air wavelength; much as one would expect in the actual situation. However, interactions between the incremental sections of the vibrating body are ignored; as are possible effects of the cladding shape (such as possible acoustic resonances in the profile cavities [1]). To incorporate all of these effects one must employ the BEM. Unfortunately, each of these steps obviously entails a corresponding increase in complexity, run time and computational power requirements.

To implement the BEM one must model the vibrating surface as a number of finite size surface elements. The size of each element should be no greater than one-quarter of the acoustic and dynamic wavelengths (as a rule-of-thumb) and also small enough to ensure adequate representation of the modeshape. The modeshapes with which one is concerned (e.g. fig.1) are of a relatively high-order such that a large number of elements is required for a relatively small section of the cladding. Hence the size of the model is limited. A three-dimensional BEM is consequently not a great deal of use on a desk-top PC because one would only be able to model a small area of cladding, resulting in significant levels of edge effect. Further, the vertical height will be arbitrary and non-infinite if one wishes to employ the 2D Finite Element results (fig.1) which were so successful in pinpointing the Sound Reduction Index (SRI) "dips". Hence, a two-dimensional BEM program was developed at Salford such that 2D vibration data could be utilized, allowing for speedier run-times and larger models (i.e. reduced uncertainty in edge effect). However, it should be noted that reducing the computations to two dimensions does not necessarily reduce the program's complexity. The 2D BEM procedure is based on that often used for analysis of barriers [7,8]. It was validated by comparison to simple formulae for an infinite strip [5,9] and by comparison to the 3D BEM (which is more readily related to actual situations).

To ensure that BEM results are not overly influenced by edge effects, the way in which one models the cladding may be adjusted. For example, the point on the cladding profile at which the model is terminated can be changed or baffles may be included (although this increases the number of elements required). Figure 3 shows how the calculated radiation efficiency of the vibrational modes of one cladding profile changes as the number of profile pitches (i.e. overall model size) and the element definition are altered. The modeshape data was obtained by 2D FE analysis [3,4]. It was concluded that greater than approximately 10 profile pitches (a total model length of 2 to 3 metres) produced an adequate representation of modal radiation without undue uncertainty due to edge effects. It should be noted that the model is limited by the available run-time memory of the computer. In the case of a 33MHz 486 PC with 8MB RAM, up to about 600 elements could be used. Such a model took almost 30 hours to run for 15 modeshapes. Clearly, the model should be kept as small as possible without introducing unwarranted errors. This is evidently easier at high frequencies (fig.3).

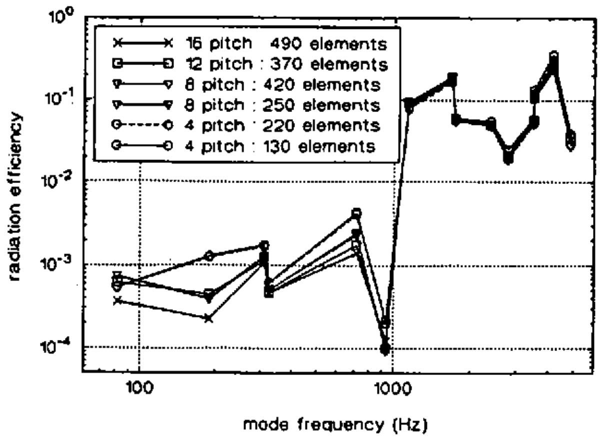

Figure 3 : 2D BEM results of radiation from one cladding profile as the profile pitch and element density are altered.

3. RADIATION FROM CLADDING MODES

The following discussion shall confine itself to the consideration of a single cladding profile with the sound reduction characteristics given in figure 4. It is clear that "dips" in the response occur about the 250, 1K, 2K and 5K Hz 1:3 octave bands. Measurement and prediction of modeshapes linked the two central depressions to modes (b) and (c) shown in fig.1 [3,4]. Similar modeshapes on other cladding profiles also correlated with SRI "dips" and this has formed the basis of an accurate, simple empirical method for predicting the dip frequency.

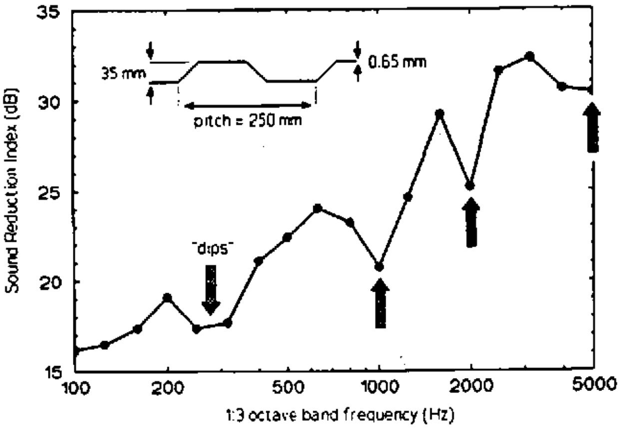

Figure 4 : sound reduction of profiled steel cladding.

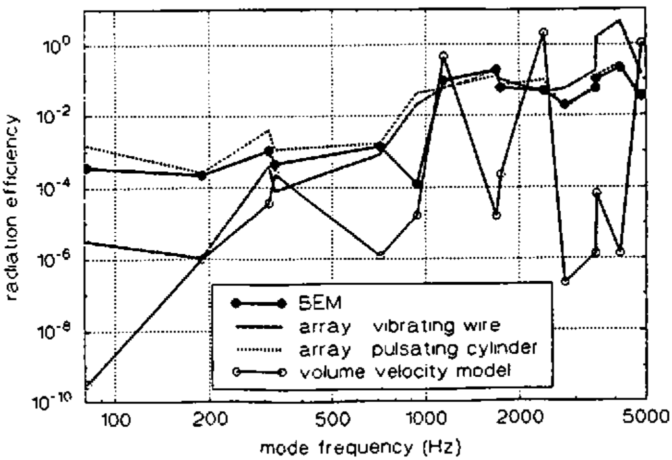

Figure 5 : comparison of methods for describing the mechanical-acoustic interaction in the radiation from profiled steel cladding (as shown in fig.4).

Figure 5 compares the three methods described; each implemented in a two-dimensional manner. The radiation efficiency is effectively independent of the mode strength such that the results purely describe the radiation (as opposed to excitation and transmission). The simple volume velocity method plainly correlates very well with the observed dips in sound reduction. However, it cannot be valid at the frequencies shown! The 2D BEM and source array method using infinite cylindrical sources are seen to produce very similar results. Use of the vibrating wire in the array model also provides a comparable outcome displaying the same trends. This would suggest that the effect of loading between the incremental sources is minimal. One can certainly conclude that the radiation is not affected by resonances in the profile wells (as has been inferred from an initial analysis of the situation by the authors [1]). However, neither model pinpoints individual modes which could cause such significant depressions in the sound reduction characteristics.

It is undoubtedly possible that the particular modes which cause the SRI dips do not have a much greater radiation efficiency than nearby modes, but that they are more readily excited. The measured vibration shapes (such as in fig.1) were obtained by exiting a panel with plane waves (using a maximum length sequence signal to achieve a phase reference; c.f. [3,4]). In this case it may be possible to describe the excitation mechanism using the simple volume velocity model as it will not be restricted by the same arguments as above if (i) the input force is constant over the vibrating body, and (ii) one can neglect the effect of back-scattered energy and the further loading this causes on the body. This assumption would seem reasonable considering the conclusion already made that the interactive loading seems to have a negligible effect on the radiation side.

Accordingly, one could use the BEM or source-array models to predict the comparative radiation from modes with their vibration magnitudes taken from measurements. This was achieved by calculating the non-normalised acoustic power radiated by each vibration mode of the cladding with the modal magnitude weighted by the vibrations observed in the measured spectra. Figure 6 was produced in this way using the BEM. The result does correlate far better with the sound reduction characteristics and the specific modes identified previously are again those pinpointed.

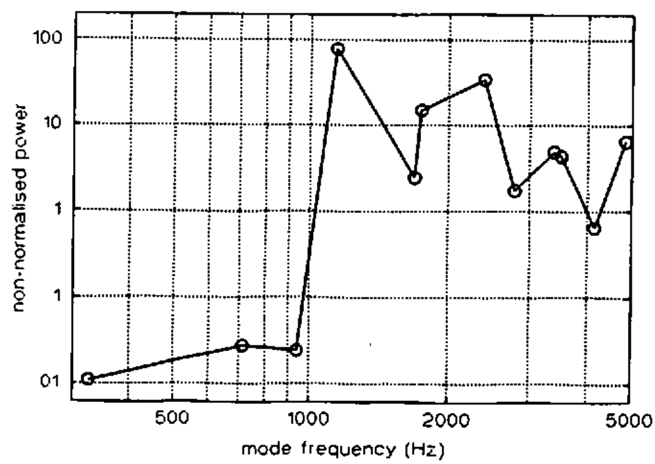

Figure 6 : radiation from profiled cladding (as shown in fig.4) using the 2D BEM on actual non-normalised velocity magnitude data.

PREDICTION OF CLADDING CHARACTERISTICS USING BOUNDARY ELEMENT METHOD

4. CONCLUSION

Use of the two-dimensional Boundary Element Method has shown that the familiar dips in the sound reduction characteristics of profiled metal cladding cannot be solely attributed to the heightened radiation efficiency of certain modes on the "radiation side" of the transmission mechanism. These modes *do* have a value of radiation efficiency which allows the dip in transmission loss to appear, but the value is not conspicuously high in relation to neighbouring modes. Comparison of the BEM to simple formulations using arrays of cylindrical sources shows that the interactions between incremental areas of the vibrating body (source) are not significant in determining radiation such that the straightforward array solution may be adequate. Furthermore, one can conclude with certainty that acoustic resonances in the profile wells do not have any effect on the radiation mechanism.

One can speculate that the depressions in sound reduction are a result of the efficient *acoustic excitation* of certain modes, which results in a greater radiated power when combined with the calculated value of radiation efficiency. The simplistic volume velocity model may be adequate for describing this excitation, which will be the subject of further detailed research.

5. REFERENCES

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6. ACKNOWLEDGEMENTS

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