A COMPUTATIONAL METHOD FOR ANALYSIS AND DESIGN OF ACOUSTIC ABSORBERS AND LOW FREQUENCY TRANSMISSION LOSS

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1 INTRODUCTION

Architecture is in a constant state of evolution, with architects striving for increasingly novel designs using materials and geometric forms in new ways. In the light of such advances, the acoustic consultant must often think of similarly novel ways in which the acoustic intent can be accommodated in a design whose impact is primarily visual. Manufacturer's data is often unreliable or inappropriately tested and it is important that the acoustician is able to place confidence in a design in the absence of a third party.

An example of a typical problem is the architectural form that is curved in shape and incorporates large amounts of glass and concrete – this is not ideal for the control of reverberance. Whilst the modular construction of many office buildings gives flexibility to the user, it can be at the expense of providing sufficient levels of sound insulation. It is often necessary therefore for the acoustician to design bespoke solutions, tailored to the particular problem. This is especially the case where there are financial constraints on a project.

Using established acoustic theory, a computational model has been developed that readily allows prediction of the absorptive properties and low frequency transmission loss of multi-layer structures employing commonly used materials. This paper discusses the mechanisms that are modelled and gives examples of the situations where the model has been of significant benefit.

Discussion and results will centre on a multi-layer absorber system used in the design of a studio control room and an example of where a window construction was checked for its low frequency sound insulation performance. Comparison with experimental data will be given where possible.

2 THEORETICAL MODELS

2.1 Porous Materials

Raleigh[1] was the first to consider the mechanisms through which porous materials dissipate sound energy. His one-dimensional model of parallel tubes illustrated the relationship between the porosity of an open cell material and the amount of sound absorbed. In the extended, three-dimensional model (attributed to Zwikker[2]), other variables such as the microscopic form of the pores and their connectivity (structure factor) led to a more accurate description.

Delany and Bazley[3] were the first to identify the importance of flow resistance and its characterisation of many of the acoustic properties of a porous material. In particular, they showed that there is a power law relation between the flow resistance and the surface normal acoustic impedance and propagation constant. Others have built on their work, considering the difference between foam and fibrous materials, over a range of flow resistances[4]. The above research allows for prediction of the properties (surface impedance and propagation constant) necessary for calculating the absorption coefficient and transmission loss through a material whose flow resistance in known.

2.2 Perforated Panels

As predictable as porous materials are, their acoustic performance is limited at low frequencies both in terms of absorption and transmission loss. In addition, its appearance often makes it unpopular with the architect striving for the clean, uninterrupted form so suited to materials like glass and fair-faced concrete. In many cases therefore a panel with slits or perforations is useful, either in combination with a porous material or instead of, in the case of panels with very small holes or slits.

The acoustic model of a perforated panel is based on the analysis of sound propagation in a tube, the exact solution to which was derived by Rayleigh[1]. Crandell[5] simplified the analysis by considering circular tubes that are short in comparison with wavelength, giving limiting values for the impedance at the tube end as a function of various ranges of tube radius. Appropriate end corrections are also included to account for the mass reactance.

By considering a perforated panel as a combination of short tubes in an otherwise rigid plane of finite thickness, it is a simple step to calculate the surface impedance as a function of perforation ratio and the dimensions of those perforations. The effect of reducing the diameter of the perforations and thus increasing the acoustic resistance, has been the subject of many papers on so called micro-perforated absorbers[6]. In such cases, there is no need for a porous material, as the necessary acoustic resistance is provided by the viscosity of the oscillating air within the small holes. The reactance of a perforated panel can therefore yield absorption at a lower frequency than the dimensions would suggest and has been well demonstrated in recent papers[7] .

2.3 Mass Layers

For the sake of completeness, brief mention is made here of the absorptive effects of so-called panel absorbers. Specifically-designed panel absorbers are often used in listening/recording spaces and dry-wall constructions absorb low frequencies via the same mechanism. The absorption of these panels is a function of the size and material properties of the panel itself, the edge condition (e.g. clamped) and the loading on it (e.g. the stiffness associated with a sealed air space). The interested reader is referred to Cremer and Muller's excellent theoretical discussion on the subject[8] and the work of Bradley[9] and others[10] for more experimentally biased research.

The primary reason for inclusion here is that mass layers are readily used in building constructions. The analysis used is a simple model of rigid layers as limp masses, thus local reaction is assumed and the existence of flexural waves is ignored. By modelling only in terms of a mass reactance, the analysis is simplified, though results are limited to structures and frequency ranges where this assumption is reasonably valid.

2.4 The Model and Multi-Layer Structures

The analysis of the acoustic properties of a combination of layers of different materials is described by Guy[11] and forms the basis of the computational model. In his paper, Guy shows how a system of many different layers can be modelled from knowledge of the individual layers' impedances and propagation constants and the continuity relationships between the layers.

The model starts from a known terminating impedance and works through the multi-layer system calculating the transmission of sound through each layer according to the characteristic impedance and propagation constant of that layer. Equations of continuity are used at the junctions between individual layers. An example of how this is represented in the computational model is given in

Figure 1. On the far right hand side is a simple limp mass, which is the terminating layer. Subsequent layers of the multi-layer structure consist of air, porous material, limp masses or perforated panels. A plane wave is assumed to be normally incident to the system. The porous material can either be foam or fibrous material, with foam being modelled using Qunli's method[4].

User inputs are the surface density of each mass, the perforation ratio, hole diameter and material thickness of each perforated panel and the flow resistance and thickness of the foam or fibrous materials and any air gaps.

Outputs of the model are:

- normal incidence absorption coefficient
- random incidence absorption coefficient[12]
- transmission loss
- phase of absorption co-efficient
- amplitude and phase of reflection coefficient
- magnitude and phase of the pressure at the incident face
- real and imaginary components of the resulting acoustic impedance

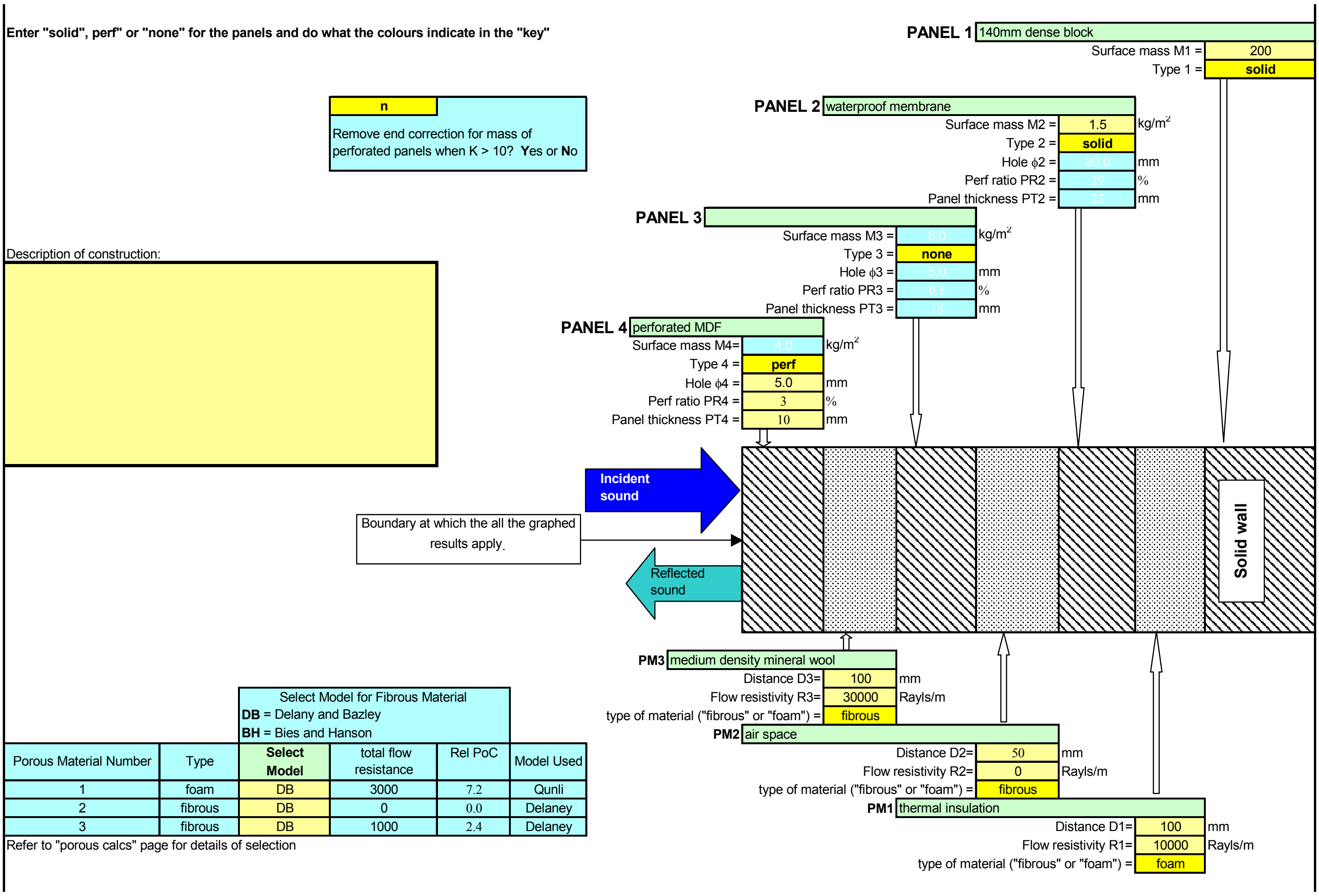

Figure 1 – Illustration of multi-layer system used in the computational model

3 VERIFICATION OF MODEL

Clearly, it is vitally important to verify that a computer model is able to produce reliable results. In this section, comparison will be given between different multi-layer systems in terms of absorption coefficient. Results for transmission loss will be given later.

3.1 Absorption Coefficient of Perforated Panel Systems

The experimental study carried out by Davern[13] on multi-layer absorbers is used here as a comparison for the model. In his paper, measurements of diffuse field absorption coefficient are made for different combinations of perforated panel - glass wool - air space absorbers.

Figure 2 shows the theoretical-experimental comparison for one of these multi-layer absorbers (illustrated in the figure).

The agreement between the two traces can be seen to be very good – indeed this is the case for the other designs of absorbers tested by Davern. Changes to the perforation ratio, depth of air space or mineral wool layer and thickness of perforated layer are all well modelled using the analysis described in the previous section.

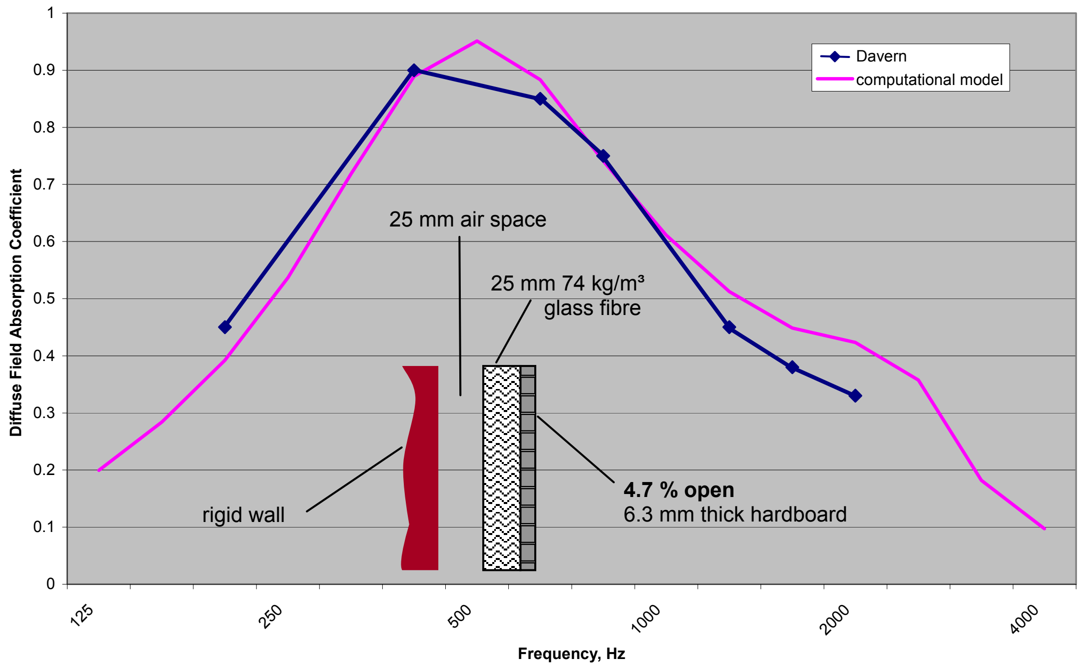

Figure 2 – Experimental and theoretical absorption for a multi-layer absorber

4 PRACTICAL APPLICATIONS

In this section, examples are given of the practical use the model, both from design and project perspectives. Description of the projects is given where relevant and results for predicted absorption and transmission loss presented.

4.1 York University Music Research Centre

The design brief for the above project was to provide a building which exhibits an excellent acoustic environment in keeping with a department at the forefront of psycho-acoustic research. As such, the acoustic specification was based on EBU recommendations for monitoring environments[14], though this was refined through considerable dialogue with the University.

The restricted budget meant that most proprietary products were too expensive and as such it was decided, in light of the author's research into mechanisms of passive absorption[15], that a bespoke design of absorber should be adopted. The aim was to develop an absorption strategy which could be built by a non-specialist contractor, using inexpensive materials, whilst exhibiting all the required acoustic characteristics. In order to achieve the required wideband absorption, two elements were used: one to absorb frequencies above 250 Hz and the other, below 250 Hz. The distribution of the two elements is pseudo-random, with 60% high frequency and 40% low frequency absorption. A section through the absorber design, comprising the high and low frequency elements, is shown in Figure 3.

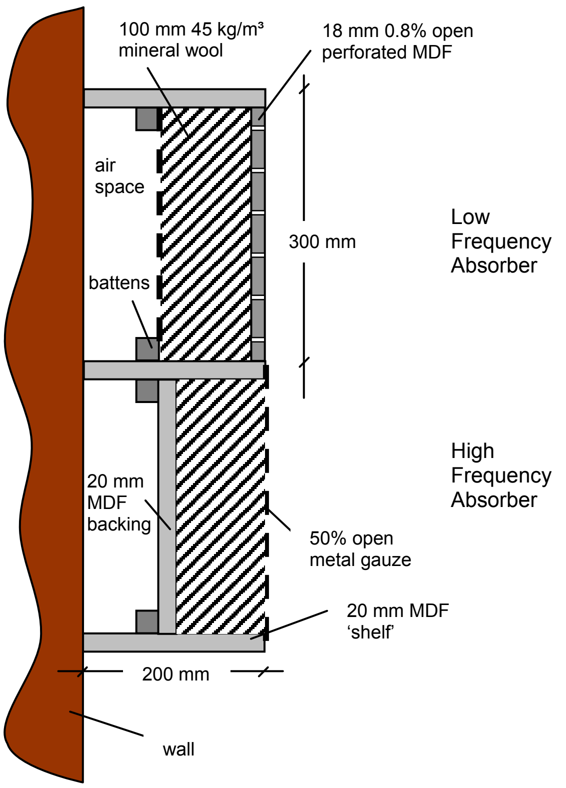

Figure 3 – Section through absorbers

The high frequency absorber is simply a 100 mm thickness of 45 kg/m³ fabric faced mineral wool; the low frequency unit though is a little more complicated.

There are many different ways in which sound energy at frequencies below 500 Hz can be dissipated. The decision of which to employ was based on three factors : an adaptable design utilising inexpensive materials, that exhibits a low Q absorption characteristic in the frequency range of interest. Based on these criteria, an absorber comprising a perforated timber facing, mineral wool layer and air gap was designed.

The final design was almost entirely dictated by the predicted results from the computational model. Once the means of high frequency absorption had been established, the low frequency unit was designed to give the aforementioned absorption characteristic within the minimum practicable depth. Given the likely distribution of absorbers, the design was finalised to 'cross-over' at the appropriate frequency and magnitude of absorption, in order to give the required decay characteristic within the room.

The resultant diffuse field absorption coefficients for the high frequency and low frequency absorbers are shown in Figure 4.

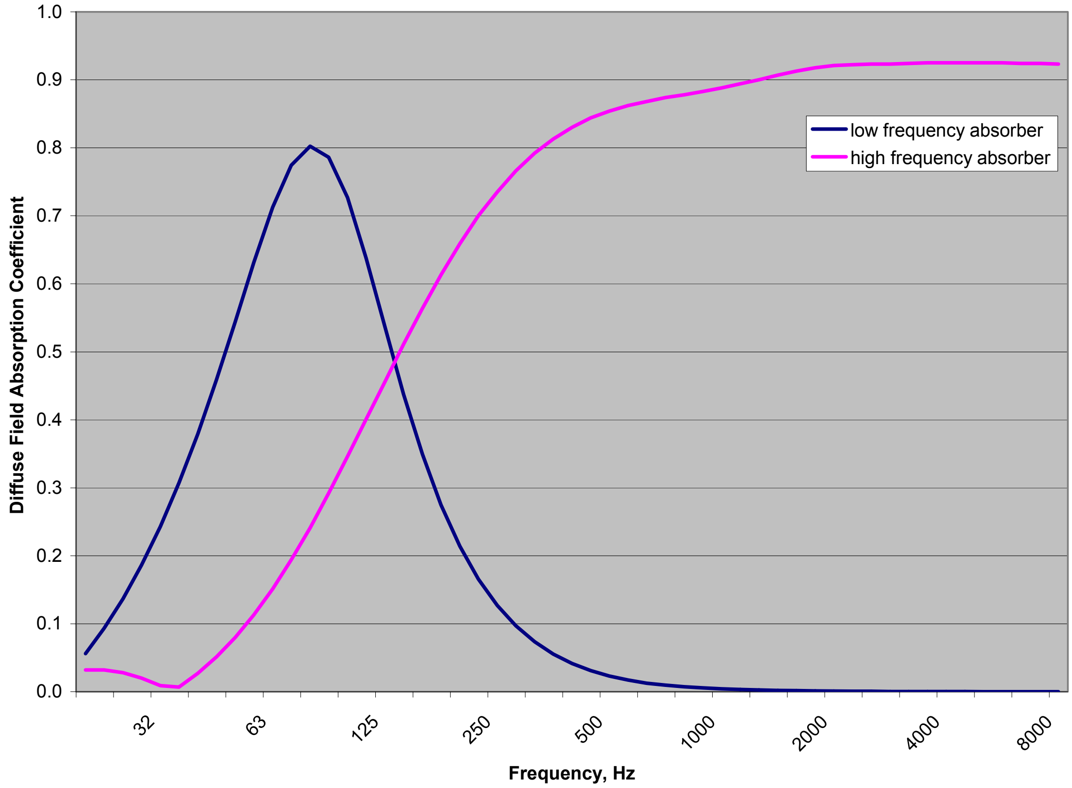

Figure 4 – Predicted absorption coefficients for the absorbers

4.2 Effect of Porous Material in a Panel Absorber

The changes in performance of a panel absorber by varying the location, thickness and flow resistance of porous material can be readily evaluated. A 6 mm panel of surface density 8 kg/m^2 is located 150 mm away from heavy masonry wall – the cavity is sealed. The 75 mm thick layer of rockwool used exhibits a flow resistance of 3 x 10^5 rayls/m (mks).

Figure 5 shows the three absorption coefficient responses for three different locations of the porous material. Response A is with the rockwool on the sound-incident side of the panel, Response B is with the material adjacent to the panel inside the cavity and Response C is with the material against the heavy wall. Considerable differences are evident in the low frequency absorption properties of the three arrangements.

4.3 Transmission Loss of Multi-Leaf Glazing System

Arup Acoustics was asked to investigate the poor isolation at low frequencies of a recording studio control room at Sydney Opera House. A contractor had designed and built the room. The triple-glazed system used for the window between the studio and control room consisted of three panes of 12 mm glass with two air gaps each of 120 mm, giving a total surface mass of 90 kg/m^2.

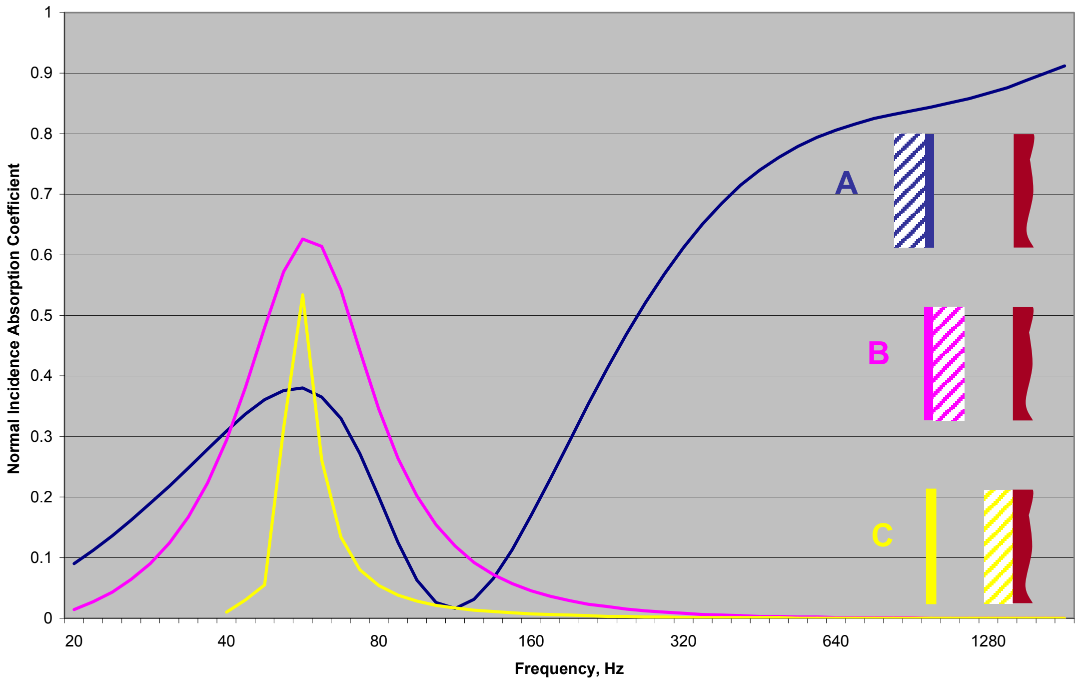

Figure 5 – Predicted absorption coefficients for different panel absorber systems (see text for details)

Figure 6 shows the predicted random incidence transmission loss of this system. The poor transmission loss of the window is due to the mass-air-mass resonances at 30 Hz and 53 Hz. Measurements of the sound transmission of the room near the glazing (using MLSSA) showed a similar response to that predicted.

A better approach is to use two glass layers of different surface mass and one air space of 240 mm. The single mass-air-mass resonance is now at 25 Hz and the resulting low frequency transmission loss is much higher. In this instance, the trade-off is between the higher transmission loss at high frequencies offered by the three-layer structure and the better low frequency transmission loss of the two-layer structure.

It should be borne in mind that the computational model assumes limp masses and fully decoupled layers, neither of which occur in practice. Given this approximation, the high transmission loss figures predicted by the model should be tempered with real world experience. The prime benefit of using the model to predict transmission loss is in gaining understanding, at low frequencies, of the mass and air-compliance resonances. This allows for them to be positioned out of the bandwidth of interest so that the mass law and the decoupling provided by air gaps, can be fully utilised.

Another use for the model has been the design of a multi-layer roofing system for a nightclub. The low frequency transmission loss was particularly important in ensuring that nearby residential dwellings were not disturbed by noise levels in excess of 120 dB in the 80 Hz octave band.

5 CONCLUSIONS

There is an ever increasing need for design tools that enable the acoustician to deliver solutions in designs that do not allow for standard products to be used. The challenges may arise because of architectural design, acoustic specification, or financial constraint. The analysis described in this paper shows how materials can be modelled both individually and as part of a multi-layer structure.

The results presented have shown to be reliable within the limits of the input data – the use of an impedance tube can help in this respect.

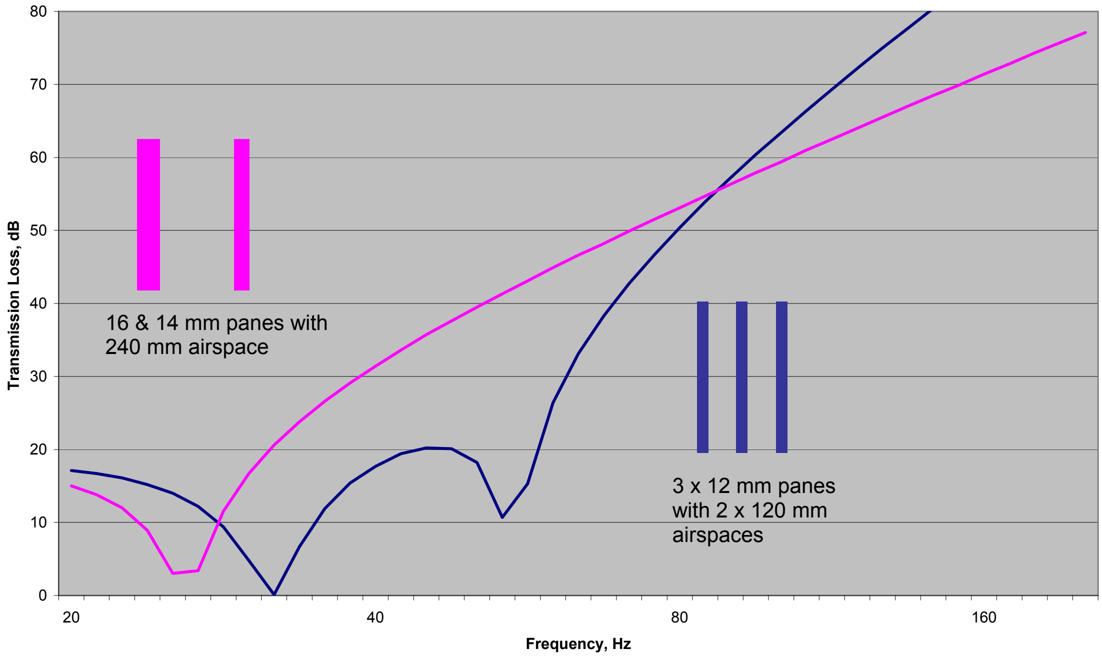

Figure 6 – Predicted transmission loss for different multi-layer window systems

In terms of acoustic design, the computational model has enabled bespoke absorption strategies to be developed and implemented in projects where there are financial constraints and stringent acoustic specifications. It has also been shown to be useful as a preliminary check of designs – this was illustrated in terms of transmission loss of a multi-layer window and roof construction where high levels of sound insulation were required.

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