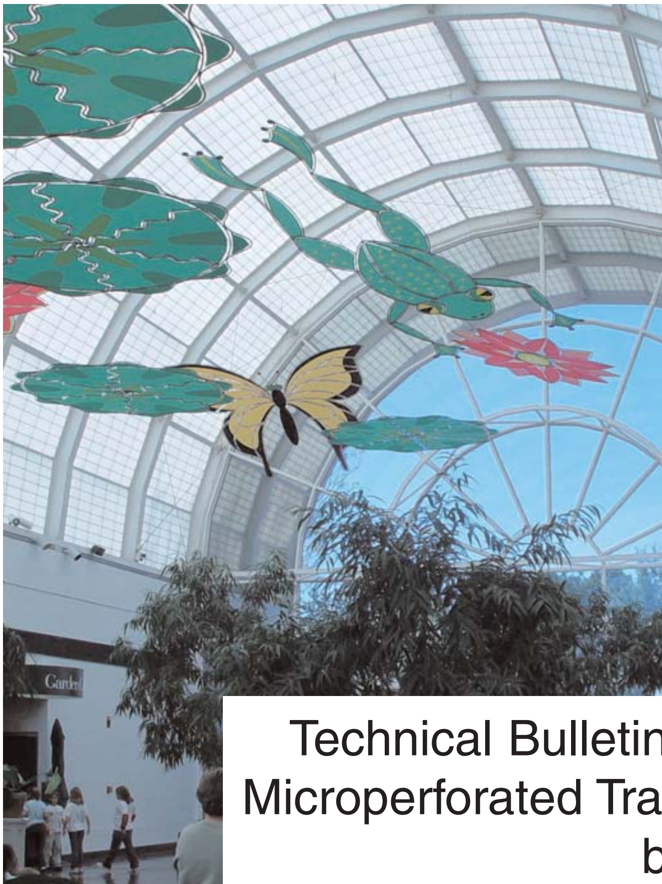
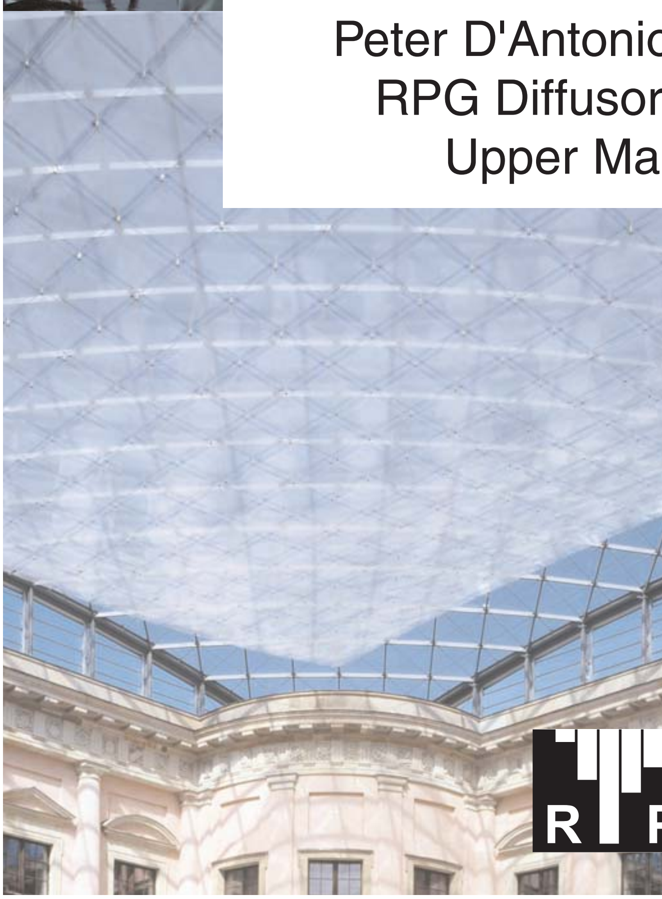
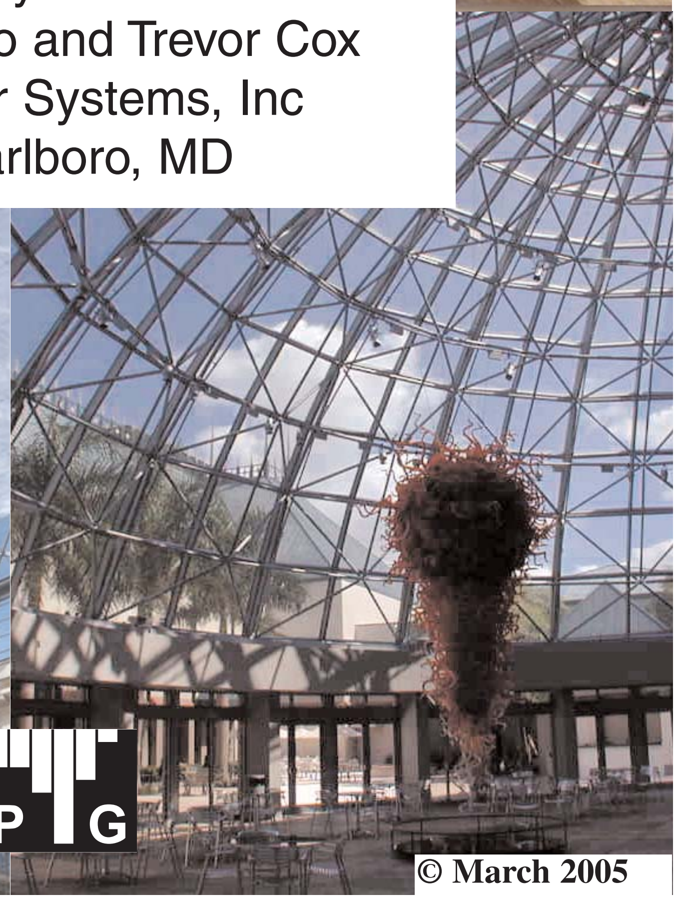


Technical Bulletin on the Design of Microperforated Transparent Absorbers

by
Peter D'Antonio and Trevor Cox
RPG Diffusor Systems, Inc
Upper Marlboro, MD





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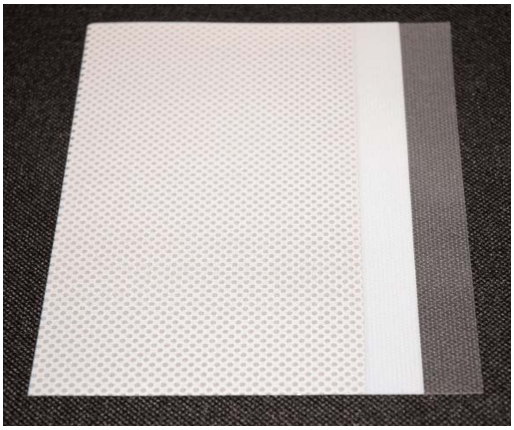
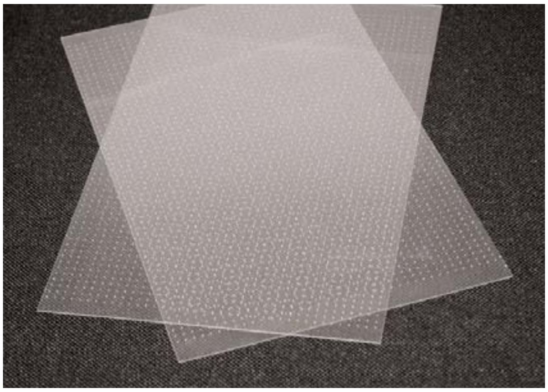
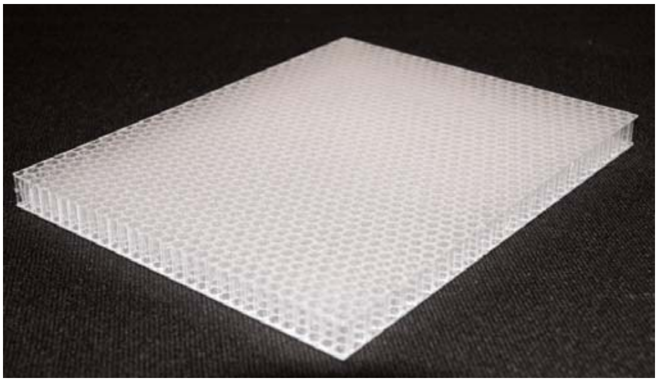


Clearsorber™ Foil



Clearsorber™ Sheet

Clearsorber™ Panel



Clearsorber™ Honeycomb

0 INTRODUCTION

Acousticians have long sought a fully transparent, absorptive finish to control reverberation in a room, while maintaining the view through glazing. Glazing is a popular building material, and there are considerable advantages in combining lighting and acoustic function into one device to save on materials and cost. One solution to getting a clear absorber is to use microperforation. These are Helmholtz devices, but without the normal resistive material. The device is rather like a double glazing unit, with the first pane being microperforated 0.1 mm foil, 1 mm sheet, 2-15 mm panel or 19 mm honeycomb composite with sub-millimetre diameter holes spaced 2-5 mm apart. The holes are drilled mechanically. The device provides absorption through high viscous losses as air passes through the small holes, which are only a bit larger than the boundary layer. This inherent damping eliminates the need for fiberglass or other porous materials in the air cavity between the perforated sheet and the reflective surface behind it. Thus, it is possible to provide fiber-free, clear absorption. To augment the mid to low frequency absorption, the device can be curved, tilted or shaped to provide redirection or diffusion in the mid to high frequency region. The surface is transparent when looked at from straight on, but at oblique angles the holes become more apparent although the surface is still translucent. The requirement for small holes restricts the frequency range over which the resonant absorption can be achieved within manufacturing constraints. So these are useful devices for treating troublesome low to mid frequency noise and reverberance in spaces such as atria, lobbies, prefunction spaces, museums, botanical gardens, convention centers, etc.

We will begin by discussing the design equations of conventional Helmholtz absorbers and then the microperforated devices will be outlined and shown to be accurate. This class of new fiber-free transparent absorbers is called Clearsorber™.

1.0 DESIGN EQUATIONS: RESONANT FREQUENCY

Resonant absorbers involve a mass vibrating against a spring. The construction for a Helmholtz absorber is shown in Figure 1, where the mass is a plug of air in the opening, Φ, in the perforated sheet. The resonance is produced by the same mechanism which generates a note when you blow across a beer bottle. To make this into an absorber, losses are provided by some damping mechanism to remove acoustic energy, such as a layer of mineral wool forming the porous absorbent. The spring is provided by air enclosed in the cavity, d. By changing the vibrating mass and the stiffness of the air spring, the resonant frequency of the device can be tuned, and it is at the resonant frequency that absorption is a maximum.

To achieve losses, damping is required. This can be achieved by placing porous absorbent where the particle velocity is large - in the neck of the Helmholtz resonator. For Helmholtz devices with small openings, viscous losses within the neck can be used to gain absorption. This is a technique which allows devices without porous absorbent, such as microperforated absorbers, to be produced, which is the main topic of this technical bulletin.

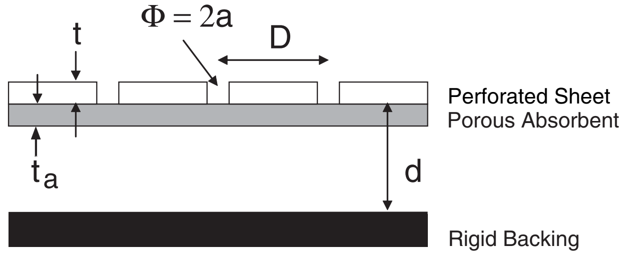


Figure 1. Construction of a Helmholtz absorber

Consider a simple absorber formed by a cavity with a covering sheet. The sheet is perforated forming a Helmholtz design. The impedance is given by a mass (j m) and resistance (rm) terms. These are the acoustic mass and resistance respectively, arising due to the perforated sheet. The surface impedance of the resonant system is:

$$z_1 = r_m + j\left[\omega m - \rho c \cot(kd)\right] \tag{1}$$

Where k=2π/l is the wavenumber in air; d the cavity depth; m the acoustic mass per unit area of the panel; ω the angular frequency; ρ the density of air, and c the speed of sound in air.

For now, the presence of porous absorbent within the cavity is ignored for simplicity. Systems resonate when the imaginary part of the impedance is zero. So to find the resonant frequencies the imaginary terms in Equation 1 are set equal to zero. Consider a case where the cavity size is much smaller than the acoustic wavelength, i.e. kd<<1, so that cot(kd) approaches 1/kd, then the resonant frequency f is the familiar expression:

$$f = \frac{c}{2\pi}\sqrt{\frac{\rho}{md}} \tag{2}$$

This is a general formulation, now the specific instance of the Helmholtz resonator will be considered, followed by the case of the membrane absorber.

1.1 Helmholz Resonator

The perforated surface is divided into individual cells, which are assumed to behave independently with a repeat distance D. D is defined in Figure 1, which shows a cross-section through the absorber. The absorber is assumed to be perforated in two directions, with the repeat length being the same in both directions. The individual cells will not be entirely independent at low frequency, and consequently physical subdividing of the volume may be required as the wavelength becomes large. This is especially true if good oblique incidence absorption is required, as would be needed for good random incidence absorption, and lateral propagation within the cavity must be suppressed to maximize absorption. When a porous absorbent is placed in the cavity, sound propagation is generally normal to the surface and so the need for subdividing is less critical, except at very low frequencies. The hole spacing should be large compared to the hole diameter. The acoustic mass per unit area is then m= $\rho D^2 t' / \pi a^2$ where t' is the thickness of the perforated sheet with the end corrections (end corrections allow for the radiation impedance of the orifices and are discussed later) and other variables are as defined in Figure 1. The sheet thickness, t, and hole radius a are assumed to be much smaller than wavelength of sound in air. Under these assumptions, the resonant frequency is:

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{t'V}} \quad (3)$$

Where S= πa^2 is the area of the holes, and V the volume=$D^2 d$ of each unit cell.

An alternative, but entirely equivalent formulation for the Helmholtz resonator uses the porosity, or fraction of open area, . This is often more convenient to work with when using perforated sheets and can be derived by considering the geometry in Figure 1 to revise Equation 3:

$$f = \frac{c}{2\pi}\sqrt{\frac{\varepsilon}{t'd}} \quad (4)$$

$$\varepsilon = \frac{\pi a^2}{D^2} \quad (5)$$

The vibrating plug of air within the perforations provides the mass of the device. The length of the plug of air is not just the perforated plate thickness. The effect of radiation impedance must be considered, including the mutual interaction between neighbouring vibrating air plugs. Consequently, the vibrating plug of air has a length given by the thickness of the panel plus end corrections to allow for the radiation impedance of the orifice. A full expression for the mass in Equation 2 is therefore :

$$m = \frac{\rho}{\varepsilon}\left[t + 2\delta a + \sqrt{\frac{8\nu}{\omega}\left(1 + \frac{t}{2a}\right)}\right] \quad (6)$$

The last term in the equation is due to the boundary layer effect, and ν =15x10-6 m^2s^{-1} is the kinemetric viscosity of air. This last term is often not significant unless the hole size is small, say sub-millimetre in diameter. δ is the end correction factor which to a first approximation is usually taken as 0.85 and derived by considering the radiation impedance of a baffled piston. A value of 0.85 does not, however, allow for mutual interactions between neighbouring orifices because it is based on a calculation for a single piston. Consequently, other more accurate formulations exist. For a porosity of $\varepsilon < 0.16$, Ingard gives the correction factor as :

$$\delta = 0.8(1 - 1.4\varepsilon^{1/2}) \quad (7)$$

In the limit of only one hole in an infinite plane, this is roughly 0.85 as given earlier. An alternative formulation which works for more open structures was developed by Rschevkin and reported by Cremer and Mòller. This reportedly includes the limiting case of ε =1:

$$\delta = 0.8(1 - 1.47\varepsilon^{1/2} + 0.47\varepsilon^{3/2}) \quad (8)$$

For a square aperture, the formulation for $\varepsilon < 0.16$, Equation 6.7, changes slightly to:

$$\delta = 0.85(1 - 1.25\varepsilon^{1/2}) \quad (9)$$

As the open area decreases, additional low frequency absorption is generated due mainly to the increased stiffness of the spring in the unit cell as the volume reduces. The high frequency absorption decreases because the proportion of solid parts of the perforated sheet increases, and these parts reflect high frequency sound. The maximum absorption decreases somewhat as the resonant frequency decreases. If these absorbers were tuned to a lower frequency, this decrease would be more marked. The reason for this is that the impedance of the porous material moves further from the characteristic impedance of air at low frequencies, making the absorption less efficient.

1.2 Losses

So far, the above formulations have only allowed a calculation of the resonant frequency. A proper design method must also allow the absorption coefficient and surface impedance to be determined for all frequencies. To do this, the losses within the device must be modeled. Losses are determined by the resistance term rm in Equation 1. For a Helmholtz device with no additional porous absorbent this can be calculated using:

$$r_m = \frac{\rho}{\varepsilon}\sqrt{8\nu\omega}\left(1 + \frac{t}{2a}\right) \quad (10)$$

This formulation assumes that the hole radius is not sub-millimetre in size, to ensure it is larger than the boundary layer thickness. An alternative formulation for this resistive term derived by Ingard is often used:

$$r_m = \frac{\sqrt{2\rho\eta\omega}}{2\varepsilon} \quad (11)$$

Where η is the viscosity of the air, with a value of 1.84 10-5 poiseuille. These theoretical equations do not allow for increased resistance that happens if burrs are present. Indeed, Ingard carried out empirical work to show that Equation 11 was approximately correct, but taking a value twice as large matches experimental results better. Equation 11 is more commonly quoted than Equation 10, but for most practical absorbers both are negligible, as is the difference between them! The exception is with devices such as microperforated absorbers where the size of the resistance is critical. For most designs, the losses contributed by Equation 10 are very small, and in order to get good absorption it is necessary to add porous material.

Microperforation is rather specialized, so first attention will be focused on devices with additional porous material and more normal sized holes. The effect of the porous absorbent depends on where it is placed. Ideally, it should be placed where the particle velocity is a maximum. Porous absorption works primarily by viscous losses as sound penetrates the small pores. For this to be maximized, the air motion must be at its greatest, and this is achieved where the particle velocity is largest. For a Helmholtz resonator this means the absorbent being as close to the openings as possible, or even in the openings. A balance must be struck, however, as too much absorption in the neck might prevent resonance. The effect of placing an air gap between the perforated sheet and the porous absorbent is to reduce the resistance, and in most cases this will result in a decrease in absorption.

For a Helmholtz device, the design equations for the case with porous absorbent depend on where the porous layer is located. The simple formulation will be presented here. A more complex and accurate treatment using transfer matrixes can be found in Cox and D'Antonio, Acoustic Absorbers and Diffusers: Theory, Design and Application by T.J. Cox and P. D'Antonio, Spon Press (2004). When the porous layer is right in front or behind the perforated plate, then the resistance behaves as though it is actually in the openings. This comes from a consideration of the flow through the device. As sound is squeezed through the holes, the particle velocity is increased. On the other side of the perforated sheet, the flux lines return to a free field case somewhat gradually; this is shown schematically in Figure 2. If the porous

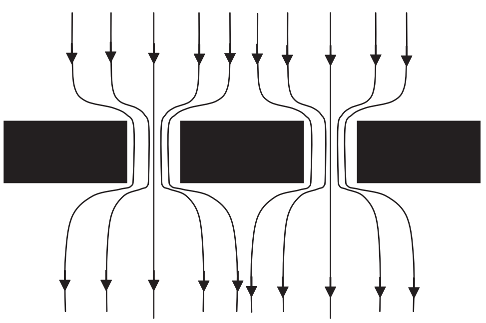


Figure 2. Flow through a perforated sheet.

layer is within a hole diameter of the perforated sheet, it is assumed that the flux has not yet had time to return to a free field like state. Consequently, the resistance added by the porous material, r_m, is altered by fractional open area of the perforated plate (porosity), ε . The resistance is:

$$r_m = \frac{\sigma t_a}{\varepsilon} \tag{12}$$

Where t_a is the thickness and σ the flow resistivity of the resistive layer. This form is assumed because the volume velocity is reduced by the open area (or porosity) ε , and has not yet had time to recover to a free space value. The key in absorber design is to make this resistance in Equation 12 as close to the characteristic impedance of air as possible, as this maximizes absorption. If characteristic impedance is achieved at resonance, absorption will be complete. Consequently, a balance between the open area, flow resistivity and absorbent thickness must be struck, while remembering that the resonant frequency of the device is also dependent on the open area of the perforated sheet.

2.0 MICROPERFORATION

If the perforations of a Helmholtz resonator are made small enough, then loses will occur due to viscous boundary layer effects in the perforations. To achieve this the perforations must be sub-millimetre in diameter so they are comparable to the boundary layer thickness. Then it is possible to achieve absorption without using a porous material. This becomes a useful technique because the perforated sheet and the back of the cavity can be made from transparent acrylic or glass and so forming a clear absorber. From an academic viewpoint, this is an interesting device, because the physics of the system is very simple and so accurate predictions are readily achieved. A microperforated device was reported by Cremer and Mòller, where a multi-layer system originally devised by Rschevkin is briefly outlined. It was Maa, however, who appears to have carried out the significant recent development of the concept.

The theoretical formulations begin by considering the sound propagation within a cylindrical hole. This problem is well established, and is the theoretical foundation of much work on microscopic propagation in porous absorbents. In fact, the earliest work was probably done by Lord Rayleigh. For a tube which is short compared to wavelength, it can be shown that the specific acoustic impedance of the tube is given by :

$$z_1 = j\omega\rho t\left(1 - \frac{2J_1\left(k'\sqrt{-j}\right)}{k'\sqrt{-j}\,J_0\left(k\sqrt{-j}\right)}\right)^{-1} \tag{13}$$

$$k' = a\sqrt{\frac{\rho\omega}{\eta}} \tag{14}$$

Where:

J_0 and J_1 are the Bessel functions of the first kind, of zero and first order respectively; t is the tube length, and a is the tube diameter.

To get the specific acoustic impedance of the perforated sheet, Equation 13 must be divided by the plate open area ε. Maa details approximate solutions to the above equation, but with the advent of modern numerical tools on computers, it is as easy to deal with Equation 13 directly as opposed to using an asymptotic solution. To deal with the Helmholtz resonator configuration, a transfer matrix must be used to get the surface impedance, z_h:

$$z_h = \frac{z_1}{\varepsilon} - j\rho c \cot(kd) + \frac{\sqrt{2\omega\rho\eta}}{2\varepsilon} + \frac{j1.7\omega\rho a}{\varepsilon} \quad (15)$$

The second term is the impedance of the cavity, which is assumed to be d deep and to be filled with air. The final term is the end correction to allow for the radiation reactance of the tube. The penultimate term is the radiation resistance for an orifice. Maa uses the formulation from Ingard for the radiation impedance. Once the impedance is known, the normal incidence absorption coefficient can be readily obtained. These equations are most applicable for common sound intensities, for large intensities, the impedance will change due to non-linear effects. Figure 3 compares the prediction according to Equation 15 to measurements presented by Maa. The hole separation is 2.5mm,

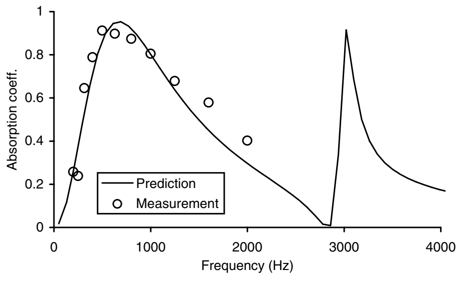


Figure 3. Predicted and measured absorption coefficient for a microperforated Helmholtz absorber (Measurement data from Maa).

the hole radius 0.1mm, the plate thickness 0.2mm and the cavity depth 6 cm. Reasonable agreement between measurement and prediction is achieved. The predictions show sharp peaks due to second order resonances. These resonances are relatively narrow in frequency, and so if the results are summed in one third octave bands, the second order peaks appear less significant.

One shortcoming of these systems is getting broadband absorption. As it relies on resonance, the absorption will be limited to low to mid frequencies, whereas an ideal clear absorber would probably be one that covered the entire speech frequency range. While in theory the speech frequencies could be covered, in reality the size of holes required are so small as to make the production difficult. To extend the bandwidth, Maa and others have shown that multiple layers can be used. Each layer is then tuned to a different frequency range. This can then be solved by a transfer matrix solution taking each layer in turn. The problem with double layer devices is they increase the depth and cost of the device, both of which are usually under strict restrictions by non-acousticians.

For oblique incidence, the sound in the cavity travels at an angle to the normal, in fact the same angle as the angle of incidence. Consequently, Equation 15 should be altered to:

$$z_h = \left[\frac{z_1}{\varepsilon} - j\rho c \cot(kd) + \frac{\sqrt{2\omega\rho\eta}}{2\varepsilon} + \frac{j1.7\omega\rho a}{\varepsilon}\right]\cos(\psi) \quad (16)$$

Where ψ is the angle of incidence. The effect of this is to increase the resonant frequency, and so raise the frequency at which absorption is significant. For large angles of incidence, however, the lateral coupling between adjacent holes within the cavity will become significant. This might be expected to lower the absorption for most if not all frequencies. Consequently, in a diffuse field the absorption would be expected to be broader, but the maximum absorption would be lowered.

3.0 CLOSING

We have outlined the basic design principles of resonant absorbers, with a specific description of the mechanism and design of microperforated absorbers. These new Clearsorbers™ offer the hope of providing architects with absorptive material choices that do not compromise the aesthetics and allow for visibility, natural and artificial lighting.