Proceedings of the Institute of Acoustics

CHARACTERISATION OF ACOUSTIC DEVICES FOR APERTURES

R. Lyons (1) R.H. Brown (1)†, J.L. Horner (2), and B.A.T. Petersson (2)

(1) Dept of Civil & Building Eng, Loughborough University, Loughborough, LE11 3TU
(2) Dept of AAETS, Loughborough University, Loughborough, LE11 3TU

1. INTRODUCTION

This paper presents some preliminary results from research into the characterisation of acoustic devices for apertures, such as louvres. From the literature survey it was found that a variety of devices have been analysed, often with a different objective driving the work. In order to compare the performance of such devices in an acoustic sense, a generic approach was employed which eventually will include flow through the aperture. The work so far has provided normalised and condensed transmission data in the wave number domain, which enabled qualitative and partially quantitative comparison of devices.

2. PREVIOUS WORK

Current literature covers many disciplines all addressing, to a different degree, the problem associated with aerodynamic and acoustic properties of attenuating/reflecting devices. The work tends to fall into one of four categories; General theory on the diffraction of sound through apertures, waveguides, louvres/open screens and other devices, which include for example Thnadners, gratings, noise sluices and resonators.

Different theories exist for predicting possible attenuation, which depend as expected, upon the ratio of the wavelength of the incident sound to the radius of the aperture. Some simple theories are less mathematically rigorous, giving predictions [1] which prove accurate when $ka<1$, where 'a' is the radius of the aperture and k is wave number. As the aperture becomes smaller and deeper, viscous effects degrade sound energy into heat, so that viscosity needs to be taken into account when considering apertures of this form. Predominantly, most theories are concerned with a static environment and sound incident at normal angles, although some references provide expressions which account for convective flow [2-4].

† Now at R.I.C.E. Holywell Building, Holywell Way, Loughborough, LE11 3UZ.

The approximate solutions mentioned here are for the case of a plane wave which is incident normally on the aperture. For a plane wave at normal incidence, the presence of the plane wall will result in a reflected plane wave, and that of the aperture a 3-D reflected wave. The transmission coefficient of the aperture has been arrived at by two different methods, firstly by postulating rigid, massless, infinitely thin, plane pistons in each end of the aperture , whose motions simulate the movement of air particles at these positions under acoustic excitation [5, 6] , and secondly by finding a relationship between the velocity potential immediately before and behind an aperture in a wall of finite thickness [1].

Using both methods, transmission coefficients for circular and slit/rectangular shaped apertures have been found and Table 1 indicates the applicable regions of wavespace for these aperture shapes. k is the wavenumber of the incident wave, a is the radius of the aperture or in the case of Sauter & Soroka the radius of a circle having the same area as the rectangle, and b is the breadth of the slit. It is clear that the theories developed by Wilson & Soroka and Sauter & Soroka have much greater applicability than that of Gomperts. However, Gomperts' results for slit-shaped apertures need to be used in favour of Sauter & Soroka's when considering long, narrow slits due to the limited aspect ratio (ratio of long side to short side) for which the latter is applicable (up to a ratio of 8:1).

Table 1 Applicable regions of wavespace

	Wilson & Soroka [5]	Sauter & Soroka [6]	Gomperts [7]
Type of aperture	Circular	Rectangular	Circular & Slit shaped
Region of wavespace	$ka < 8\pi$	$0.05<ka<3.2$	$ka<1$ $kb<1$

A possible explanation for the restricted application of the theories lies with the assumption of plane wave propagation within the aperture. It is known that the waves in a cylindrical tube in which the air is caused to vibrate are plane waves below the cut-on frequency of the first mode. This is the case provided that $ka < 1.841$, for example, if the frequency of the incident sound is 2000Hz then the radius of the tube must be less than 5cm. Also, the open end of a cylindrical tube behaves approximately as a point-source and therefore emits spherical waves provided $ka < 0.5$. Since all the authors included these assumptions in their derivations, it is not unexpected that their results are restricted, indeed it seems surprising that the work of Wilson & Soroka can be applied to the extent that it is.

Oldham and Zhao [7] looked for theories against which they could test the accuracy of techniques for measuring the sound transmission loss of circular and slit shaped apertures. The theories considered to be the most appropriate were in agreement with the above, though for slit-shaped apertures later work of Gomperts and Kihlman [8] was used, which further simplified the formula given by Gomperts for the transmission loss. The range of wavespace for which the revised formula is applicable remains unaltered. The work of Oldham and Zhao served to further validate experimentally the above theories. More recent work of Jun [9] investigates acoustic scattering from a circular aperture in a thick hard screen. In this numerical computations illustrate the behaviour of scattering and transmission in terms of the aperture size, frequency, and incident angle.

The majority of existing work relates to small apertures of around 5cm in diameter, though in practice large openings in buildings require much larger areas to be investigated. The results for smaller apertures might be used for larger aperture problems by normalising data and presenting performance in terms of the Helmholtz number.

3. CHARACTERISATION OF DEVICES

It was considered important to contrast the different devices in terms of the wave number domain and attenuation in decibels. Examples of the attenuating devices investigated included slotted and prismatic waveguides, grating of compliant tubes, multiple resonator systems, bar lattice, noise sluice, open screens / louvres and thnadners. A matrix of such devices emerged giving the dominant mechanisms of control such as absorption and diffraction and the dominant parameters such as depth, spacing and flow resistivity. Additionally these were characterised in the wave number domain by areas where they provided greater than 6dB attenuation (this being considered as a useful level of attenuation).

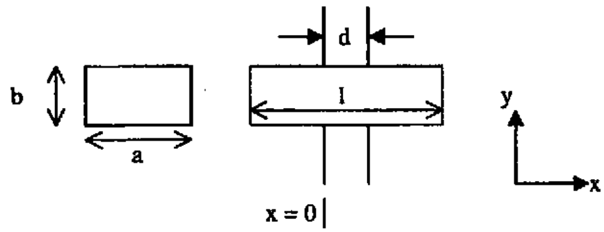
Much of the reported work lacked sufficient information to provide for a full comparison, for example physical dimensions of the device which allow the attenuation in wavespace or aperture effects to be assessed. However, it was still possible to characterise the devices by the main mechanisms and parameters that govern the way each device works.

The work presented here is concerned with the comparison of this data, which must be adjusted for size of the device, hence the use of Helmholtz number, but mainly with normalising the data to the aperture characteristic which will be superimposed upon the device when installed in the aperture. A simple hole can provide some attenuation at certain wavelengths associated with the modal behaviour of the aperture and to determine how much effect this has over the attenuating device it was decided to compare the attenuation provided with that of an aperture of the same overall dimensions.

Unfortunately, this approach has its limitations. There are few cases where the equivalent aperture effect is reported separately and available theories from the literature appear to be limited to small apertures in infinite walls or very large openings. It appeared simpler to try and derive an expression for the impedance of any aperture under consideration and to normalise the device impedance in order to be able to compare the data for different attenuating devices .

4: THEORY

Consider an opening of cross-section 'a x b' in a rigid wall as shown below:



The edge effects of the opening may be accounted for by considering the volume of fluid in the opening to be larger than the actual orifice. For an orifice of rectangular cross-section[3]:

$$L = d + 2\,l_o \qquad \text{Where:} \qquad l_o = \frac{16(ab)}{3\pi(2a+2b)}$$

If a plane through the opening is considered, the acoustic field may be represented by:

$$p(x,y,t) = \left(C_1 e^{-ik_x x} + C_2 e^{ik_x x}\right)\sum_{m=0}^{\infty}\cos\left(\frac{m\pi y}{b}\right)e^{i\omega t}$$

Where the amplitudes C_1 and C_2 are determined from the boundary conditions at $x = -l_o$, and $x = d + l_o$:

Also $\qquad k_x = \sqrt{k^2 - k_y^2} \qquad$ and $\qquad k_y = \frac{m\pi}{b}$

Assuming that pressure is zero at the ends of the virtual volume of air, then $C_1 = -C_2$ and:

$$p(x,y,t) = \left(-2iC_1 \sin k_x x\right)\sum_{m=0}^{\infty}\cos\left(\frac{m\pi y}{b}\right)e^{i\omega t}$$

If there is no flow through the orifice, the particle velocities U_x and U_y in the x and y directions respectively may be found from the continuity equations.

$$U_x = \frac{\partial p}{\partial x}\cdot\frac{1}{i\omega\rho} \qquad\qquad U_y = \frac{\partial p}{\partial y}\cdot\frac{1}{i\omega\rho}$$

Giving: $$U_x(x,y,t) = \frac{2C_1}{k_x\omega\rho}\cos k_x x \sum_{m=0}^{\infty}\cos\left(\frac{m\pi y}{b}\right)e^{i\omega t}$$

And: $$U_y(x,y,t) = \frac{2bC_1}{m\pi\omega\rho}\sin k_x x \sum_{m=0}^{\infty}\sin\left(\frac{m\pi y}{b}\right)e^{i\omega t}$$

Impedance, Z_a is then determined from: $$Z_a = \frac{p}{U_x} \qquad [1]$$

If x is set to d in the above expressions, Za will give the transfer impedance of the opening.

Also the transmission loss of an opening may be defined as:

$$TL(dB) = 10\log_{10}\left|1+\frac{Z_m\cos\theta}{2\rho c}\right|^2 \qquad [2]$$

Where Z_m is the impedance on the outlet side of the opening. Figures 1-4 show Helmholtz number (kb) versus the ratio Z_m/Z_a for different devices where b is the breadth of the device.

5. DISCUSSION

Equation 1 has been used to determine the theoretical impedance of any of the apertures associated with the devices investigated. This is essentially a transfer impedance for the aperture and is used to assess the effectiveness of the device. It should be noted that only normal incidence has been reported in this paper and that there are no losses included in the theory, such that high impedance will be seen at the aperture modes.

Meyer shows the impedance referenced to the characteristic acoustic impedance for his bar lattice against Helmholtz number [10]. By way of corroboration the predicted transfer impedance of the bar lattice aperture has been compared to Meyer's data. Meyer indicates a value of $Z_a/\rho c$ of 0.4 at the first resonance and the same order of magnitude is seen in Figure 1, a value of about 0.5.

Figures 2, 3 and 4 represent the ratio Z_m/Z_a versus Helmholtz number (using the characteristic dimension of breadth) for three cases, a slotted waveguide [11], a picket screen [12] and a cricket screen [12]. The actual attenuation and predicted impedances could not be included here for comparison. The figures indicate the effective performance of the device in its aperture so that for:

$Z_m/Z_a = 1$: The effect is more likely to be wholly due to the aperture.
$Z_m/Z_a < 1$: The device is having a negative effect.
$Z_m/Z_a > 1$: The device contributes positively to the atttenuation.

As can be seen from figures 2-4, the effect of the devices varies across the wave number domain. For the slotted waveguide (Figure 2) the device only contributes to the attenuation at high Helmholtz numbers. The opposite effect is seen with the other two devices where the device effect falls off with increasing Helmholtz number. Physically the slotted waveguide is designed as a tuned interface device, primarily at frequencies related to the slot sizes. Where as the screen devices shown in Figures 3-4 would be expected to produce attenuation at much larger frequencies, due to the mass layer effects. In Figure 4, the double picket fence effect is noticeable by the peaks in the Helmholtz region of 15-25.

6. CONCLUSIONS

The objective of the investigations has been to characterise acoustic devices for apertures, keeping the approach as generic as possible. The initial literature review proved that whilst many different device's attenuating properties have been investigated as individual pieces of research, no work has been done to bring these together to form a broad and common characterisation of all existing devices.

As an initial investigation of the effect of aperture dimensions on device performance, calculations where undertaken of the impedance of an orifice without flow. Measured impedance data was then normalised by this predicted impedance to allow device comparisons. These highlighted the regions of device effectiveness. This model will be extended to include random incidence impingement and flow.

REFERENCES

[1] M.Gomperts, 'The "sound insulation" of circular and slit-shaped apertures' - Austica 14 (1) 1964

[2] P.M. Morse and K.U. Ingard, 'Theoretical Acoustics', Princeton.

[3] D.A. Bies and C.H. Hanson, 'Engineering Noise Control', Unwin Hyman.

[4] A.P.Dowling, I.J.Hughes, 'Sound absorption by a screen with slits', J.S.V. 156 (3), 1992

[5] G.Wilson, W.Soroka, 'Approximation to the diffraction of sound by a circular aperture in a rigid wall of finite thickness' JASA 37 (2) 1965

[6] A.Sauter, W.Soroka, 'Sound transmission through rectangular slots of finite depth between reverberant rooms', JASA 41 (1) 1970

[7] D.Oldham, X.Zhao, 'Measurement of the sound transmission loss of circular and slit-shaped apertures in rigid walls of finite thickness by intensimetry', J.S.V. 161 (1) 1993

[8] M.Gomperts, T.Kihlman, 'The sound transmission loss of circular and slit-shaped apertures in walls', Acustica 18 1967

[9] K.Jun, H.Eom, 'Acoustic scattering from a circulaer aperture in a thick hard screen', JASA U (4) 1995

[10] E.Meyer, H.Kuttruff, H.Matthaei, 'Acustica' 15 1965

[11] L.Mongeau, M.Amram, J.Rousselet, 'Scattering of sound waves by a periodic array of slotted waveguides' JASA 80 (2) 1986

[12] R.Lyons, 'Acoustic protection of open screens', Proc.I.O.A. 14 Part 4 1992.

Figure 1: Z_a Characteristic impedance for Bar Lattice aperture - comparison to Meyer et at [10]

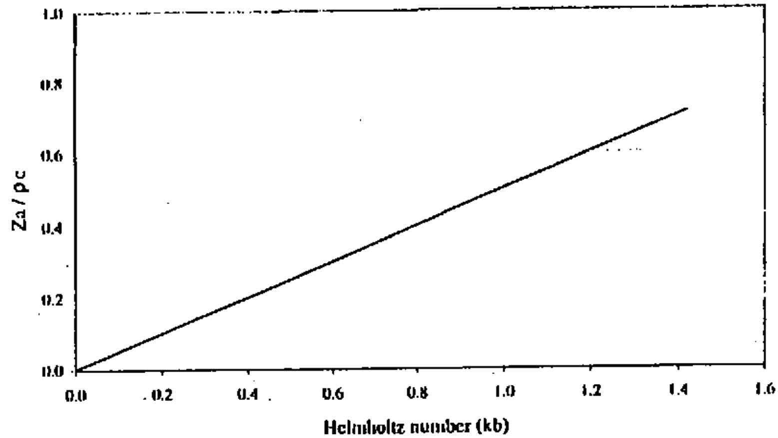


Figure 2: Z_m/Z_a versus kb for the Slotted Waveguide

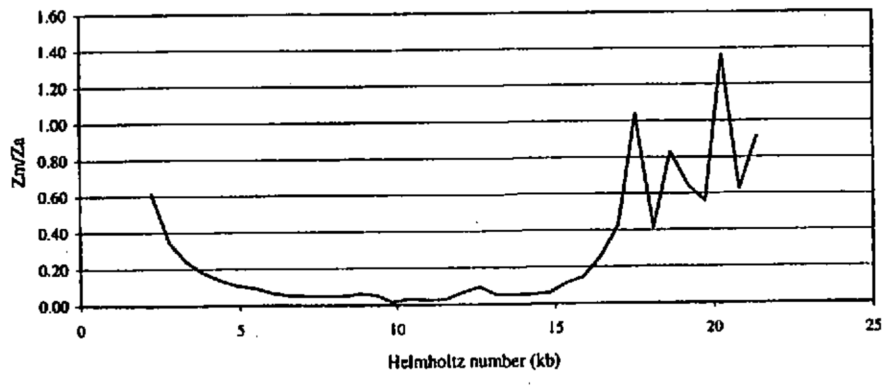


Figure 3: Z_a/Z_a versus kb for the Picket Screen

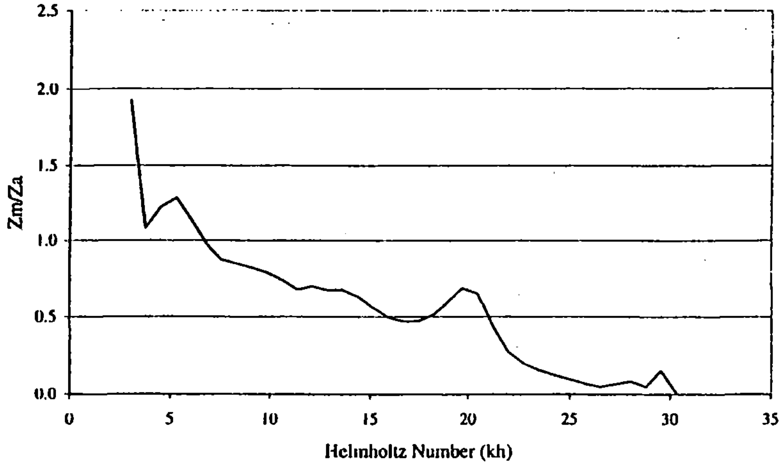


Figure 4: Z_a/Z_a versus kb for the Cricket Screen