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ATTENUATION OF HIGH AMPLITUDE ACOUSTIC WAVES IN PERFORATED STRUCTURES

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Introduction

There has recently been considerable interest in the attenuation of acoustic waves in jet flow shear layers (1, 2), especially in terms of the net sound power loss incurred as a wave propagates through the shear layer. The acoustic wave, interacting with the shear layer, produces additional vorticity and this vortical energy dissipates without significantly radiating sound (exceptions to this are unusual). It has been know for some time that high amplitude acoustic waves can cause flow separation upon interaction with perforated structures, even in the absence of mean flow, though the associated acoustic power losses have been hitherto ignored in preference to the nonlinear acoustic resistance. This latter type of power dissipation mechanism, where it occurs, can be equally as important as that in mean gas flows, and the purpose of this paper is to indicate means of predicting the attenuation, and to comment briefly on the application of perforated materials in Noise Control.

Theory

Consider the situation shown in Figure 1(a). Plane acoustic waves (pressure p_i) are incident upon an orifice plate in a pipe (containing no mean fluid flow). Reflected and transmitted waves are also shown. When the peak velocity in the orifice is high, the flow through the orifice separates (Figures 1(b)), and vorticity present in the boundary layer is convected through the orifice to form a ring vortex, the total circulation and kinetic energy of which are dependent upon the convected vorticity. Vortices are shed from both sides of the orifice (Figure 1(c)), because of the alternating flow, and since these radiate virtually no sound and eventually dissipate their energy, there is a net acoustic power loss at the orifice. Ingard and Labate (3) report a study of these effects. At present there is no satisfactory theory for calculating the vortex energy directly from the orifice velocity. An alternative approach is taken here. If one assumes that there is no "pressure recovery" in the flow after it has passed through the orifice (this seems reasonable on the basis of Bernoulli's equation since the flow does not expand significantly, although of course this argument is based on the idea of irrotational flow; it is also observed that the pressure in the vena contracta of a steady orifice flow is equal to that in the surrounding fluid), then the net orifice pressure loss may be equated to that incurred by the acceleration of the fluid into the orifice. Hence one finds that

$$\Delta p = \rho_o v^2 (1 - C_c^2 \sigma^2)/2C_c^2, \tag{1}$$

where Δp is the pressure drop, v is the orifice velocity, C_c is a "contraction coefficient," which for steady flow is equal to 0.61 - 0.65 for sharp-edged orifices, σ is orifice area/pipe area, and ρ_o is the fluid density. This sort of formula actually gives tolerably good prediction of observed behaviour (4, 5). If $\Delta p = P \cos \omega t$, where ω is the radian frequency, then (1) shows that

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$v = \pm V_{max} |\cos \omega t|^{\frac{1}{2}}$. Ingard (5) has given a Fourier series for $\pm|\cos \omega t|^{\frac{1}{2}}$, in which the Fourier coefficient of the fundamental component is 1.11 V_{max}. Equ. (1) may now be written

$$\Delta p/v(1) = (1 - C_c^2\ \sigma^2)\rho_o\ V(1)/2.464C_c^2, \quad (2)$$

where v(1) is the fundamental component of the orifice velocity and V(1) is the amplitude of this component. Equ. (2) defines a nonlinear orifice resistance which may be incorporated into an otherwise linear acoustic theory, describing acoustic transmission through the orifice. This will be valid provided nonlinear processes in other parts of the system are fairly small. The orifice reactance has not been included in the above calculation, and may be incorporated as a single "mass end correction" on the orifice; the jet formation on one side of the orifice effectively removes the end correction on that side by convecting away kinetic energy. The (small) viscous boundary layer resistance at the orifice may also be included. The complete expression for the orifice impedance - with linear and nonlinear terms - may be denoted z(1). If the radiation impedance seen by the orifice to the right hand side, in Figure 1 (a), $z_r = r_r + ix_r$ (defined as the ratio between the fundamental components of pressure and velocity) is specified, then the net acoustic power - in the fundamental component - on either side of the orifice may be calculated. The acoustic radiation on the "receiver" side of the orifice is monopole in nature, and the expressions for W_1 and W_2, the acoustic powers on the "source" and "receiver" sides of the orifice are:

$$W_1 = A|P_i|^2(1 - |\zeta - 1|^2/|\zeta + 1|^2)/2\rho_o c_o \quad \text{a)}$$

$$W_2 = A_o\ r_r\ V^2(1)/2, \quad \text{b)} \quad (3)$$

where $\zeta = [z(1) + z_r]/\rho_o c_o \sigma$ and P_i is the (complex) pressure amplitude in the incident wave; V(1) is taken to be real. The power, W_i, in the incident wave is given by $W_i = A|P_i|^2/2\rho_o c_o$. One might reasonably expect $|P_i|$ to be specified, but V(1) needs to be calculated. It may show that

$$\sigma\rho_o c_o\ V(1)\ |1 + \zeta| = 2|P_i| \quad (4)$$

and then this equation may be solved numerically (this was done here using the Newton-Raphson method) for V(1). If one considers the power transmission coefficient of the orifice, W_2/W_1, it may be seen that z_r is a factor which determines ζ (and hence W_1), r_r and V(1) (and hence W_2), for any given geometry and value of $|P_i|$. It is therefore of interest to see how altering z_r alters W_2/W_1, and also other quantities like W_2/W_i.

The above theory is also valid for plates with multiple perforations, if one uses appropriate impedances.

Measurements and Comparison with Theory

Tests were carried out, using tonebursts of 2 or 4 cycles duration, on the power transmission characteristics of singly perforated orifice plates of various diameters, and with two types of terminating impedance: a "ρc" termination consisting of a straight pipe, and an "infinite flange" termination. Incident sound pressure levels (Lp^i) ranged from 120 dB to 150 dB. In the case of the flanged termination, considerable harmonic distortion of the transmitted pressure signal occurred, since the radiated pressure here is proportional to $\partial v/\partial t$, and the distortion present in v is magnified. This caused a problem in assessing the measured value of W_t since, at the time of carrying out the tests, an FFT analyzer was not available, and the peak-to-peak value of the transmitted signal was used as a measure of the pressure amplitude in the fundamental. Results for $Lp^i > 120$ dB for the flanged termination were unreliable, though the problems were much less severe with the ρc termination. Figures 2 and 3 show some representative data on W_2/W_1, for an orifice of 1.6 mm diameter. Quite good agreement is evident between experiment and theory for the ρc termination at all values of Lp^i, and higher levels increase the transmission loss (TL) of the orifice. Agreement in the case of the flanged termination is acceptable for $Lp^i = 120$ dB. The 135 dB and 150 dB measurements are not shown, except for one point derived from an FFT performed by computer on tabulated pressure/time data. This point is tolerably close to the 150 dB theoretical curve.

Discussion

Figures 2 and 3 show that z_r is indeed a determining factor in the orifice TL. The flanged termination, with $r_r \propto \omega^2$, shows the TL increasing as ω decreases, whereas with the ρc termination, the TL is much less sensitive to ω, though a slight tendency for the TL to increase as ω rises is evident. Curves of W_2/W_1 show a strong trend of increasing net energy loss with decreasing ω for the flanged termination, but little dependence on ω in the case of the ρc termination. In Noise Control applications, the impedances of the acoustical elements surrounding perforated materials clearly determine the energy losses attainable, as witnessed by the example above. One may very profitably utilize perforated structures in the absorption of high intensity noise, but the acoustics of the entire system need to be considered in the design, as well as the incident sound pressure levels. An extension of the above scheme would seem appropriate for the design of systems with zero mean gas flow.

References

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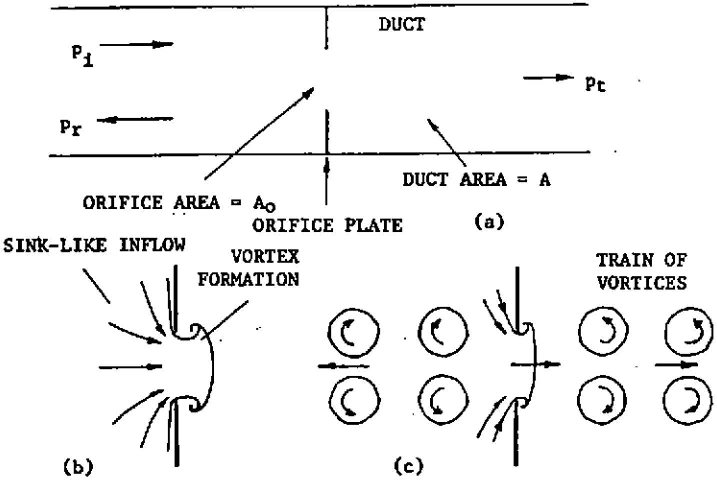

FIGURE 1. HIGH AMPLITUDE ACOUSTIC TRANSMISSION THROUGH AN ORIFICE PLATE

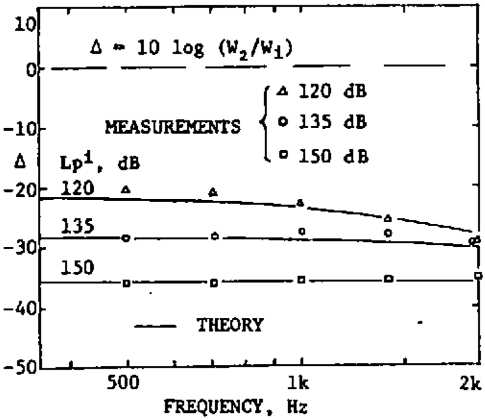

FIGURE 2. TRANSMISSION LOSS OF ORIFICE WITH ρc TERMINATION

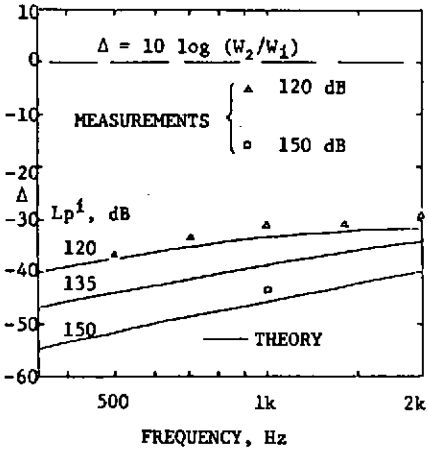

FIGURE 3. TRANSMISSION LOSS OF ORIFICE WITH FLANGED TERMINATION