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THE ACOUSTIC IMPEDANCE OF PERFORATED PLATES SUBJECTED TO GRAZING FLOW AND BACKED BY POROUS MEDIA

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1. INTRODUCTION

The use of perforated structures is common in applications such as exhaust silencers. In dissipative silencers, the perforate is commonly used in the form of a concentric tube which, in addition to altering the acoustic performance of the silencer, holds a porous material in a surrounding box, preventing loss of or damage to the material. In most cases the perforate is subjected to grazing flow by the exhaust gas from the engine. It has long been known that, even without a porous material present, the presence of mean flow (grazing or incident) increases the resistance and decreases the mass end correction of the perforate when compared to the no flow situation (see Ronneberger [1]). The physical reasons behind this change of behaviour are complex and therefore effort has concentrated on finding the acoustic impedance experimentally (see Goldman and Chung [2]). Kooi and Sarin [3] measured a number of different perforates and they showed that the resistance of the perforate could be written as a function of the inverse Strouhal number u_*/fd (where u_* is the friction velocity, f the frequency and d the orifice diameter) and the mass end correction as a function of u_*/ft (where t is the orifice depth). Cummings [4] later showed that both the resistance and the reactance could be written as a function of t/d and this allowed a general empirical expression to be derived which encompassed a number of perforates. The additional effect of a porous material backing a perforate subjected to grazing flow has yet to be examined and this is the subject of the present investigation.

2. EXPERIMENTAL METHOD

The acoustic impedance of three flat perforate plates was measured. The plates had t/d ratios of 0.286, 0.484 and 0.536 and a porosity (fractional open area) of 0.272, 0.201 and 0.205 respectively. The two-microphone experimental method of Cummings [4] was used to provide measurements both with and without a porous material backing the perforate. Measurements were performed first without a porous material, correlation of the data being performed in the same manner as that of Cummings. This involves normalising the acoustic impedance without a porous backing, $\zeta_{NP} = \theta + i\chi$, where θ is the resistance of the orifice and χ the reactance. The resistance of the orifice has two components, the resistance induced by the flow θ_f and the resistance attributable to the viscous acoustic boundary layer $\theta_{VISC.}$ (see Kooi and Sarin [3]). In order to examine the flow induced resistance alone, $\theta_{VISC.}$ is subtracted from the measured data. The reactance is also re-written by defining the total mass end correction δ, in which the orifice length is subtracted from the effective orifice length ℓ to give $\delta = \ell - t$, where $\ell = \chi / k_0$ (k_0 being the wavenumber). Both the resistance and the mass end correction were non-dimensionalised here in the same manner as that of Cummings [4]; an empirical formula was then found to encompass the three perforates. Once empirical formulae had been found for the perforates backed by air, three different porous materials (A glass, E glass and basalt wool) were packed in the cavity behind the perforate and the experiments were repeated. In this method, the properties of the porous material must replace those of air in the experimental formulae used by Cummings.

3. EXPERIMENTAL RESULTS

The acoustic impedance of the perforates without a porous material were measured for four different friction velocities, 0.476m/s, 0.986m/s, 1.626m/s and 2.192m/s. Correlation of the data for the three plates gave values for the resistance of

$$\theta_f c_0 / fd = \left[26.16(t/d)^{-0.169} - 20\right](u_* / fd) - 4.055, \qquad (1)$$

and for the end correction

$$\begin{aligned} &\delta/\delta_0 = 1, \quad u_*/ft \leq 0.18d/t; \\ &\delta/\delta_0 = (1 + 0.6t/d)\exp\left[-(u_*/ft - 0.18d/t)/(1.8 + t/d)\right] - 0.6t/d, \\ &u_*/ft > 0.18d/t, \end{aligned} \qquad (2)$$

where c_0 is the isentropic speed of sound and $\delta_0 = 0.849d$. When the experiment is repeated with a porous material in place it is no longer possible to correlate the data as a function of u_*. Obviously, in most applications, it is desirable to be able to represent the impedance as a function of flow speed, thus avoiding the need to re-measure the impedance every time a new flow speed is encountered. Therefore, instead of correlating the experimental data as a function of frequency for individual friction velocities, an attempt is made here to predict the impedance as a function of the friction velocity as well as frequency. This is to be done by combining theoretical predictions of the effect of the porous material with the empirical formulae found when a porous material was not present. This will form a semi-empirical model which can then be compared to experimental measurement. The effect of the absorbent can be accounted for by removing the mass end correction that is present without a porous material and adding the mass end correction due to the porous material onto the acoustic impedance. This redefines the normalised acoustic impedance to include the porous material (ζ_P) giving

$$\zeta_P = \theta_f + \theta_{VISC.} + ik_0(\delta + t) + 0.4245dk_0[z_a\Gamma/\rho_0 c_0 k_0 - i], \qquad (3)$$

where z_a is the characteristic impedance of the porous material, Γ is the propagation coefficient, ρ_0 the mean fluid density and θ_f and δ are the empirical values found previously when no porous material was present. Figure 1 shows an example of the measured resistance and reactance compared to the predictions made using equation (3) (solid line).

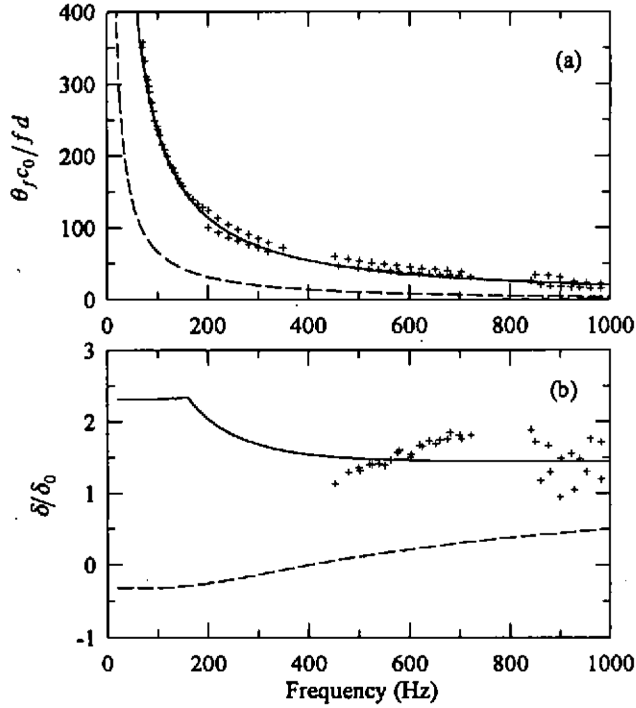

Figure 1. Acoustic impedance of perforate backed by E glass (120 kg/m^3), (a) Resistance, (b) Mass end correction. + , Experiment; —— , Semi-empirical predictions; – – – , Formulae without absorbent.

For the perforate in Figure 1 the t/d ratio was 0.536, the porosity 0.205, the friction velocity 2.192m/s and the porous material was E glass. The empirical predictions for the perforate without a porous material present are given by the dashed line in Figure 1.

4. CONCLUSIONS

The measurements without a porous material were successfully correlated using the method of Cummings [4], although it is noticeable from equations (1) and (2) that different values for the resistance and mass end correction have been obtained. This is probably due to a wider range of u_*/fd and u_*/ft values being measured in the present study, which can be shown to have a large effect on the final empirical formulae, particularly for large t/d ratios. It is expected that the values obtained in equations (1) and (2) are valid for the range of t/d values covered but caution should be exercised when using extreme values of t/d.

The addition of a porous material behind a perforate can be seen to cause a large increase in the impedance of the perforate in Figure 1. A systematic increase in both the real and imaginary parts has been measured, compared to the predictions found without a porous backing. The size of the increase was found to depend upon the porous material backing the perforate; materials with a high flow resistance caused the largest increase in impedance. It is evident from Figure 1 that the semi-empirical predictions of equation (3) are in good agreement with the measured data, especially for the resistance. Some problems were experienced in predicting the reactance accurately, but this was probably caused by experimental error. Indeed the experimental errors were such that it was found impossible to obtain data for the mass end correction below 500Hz. In general, good agreement was found by using equation (3) and this allows the acoustic impedance of a perforate to written for any friction velocity. It also removes the need to perform experiments on perforates backed by porous materials, since experimental data for perforates without absorbent are all that is required. The large increase in the acoustic impedance of the perforates when a porous material is present means that, even for plates with a large percentage open area, the perforates must be accounted for when modelling silencers. It appears possible that, especially for materials with a high flow resistance, the influence of the perforate upon the acoustic performance of a dissipative silencer could well be large.

References

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