Applied Acoustics 106 (2016) 144–154

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Review

The acoustic impedance of perforated plates under various flow conditions relating to combustion chamber liners

Chris Lawn *

School of Engineering and Materials Science, Queen Mary, University of London, Mile End Rd, London E1 4NS, UK

A R T I C L E   I N F O

Article history:
Received 29 March 2015
Received in revised form 21 December 2015
Accepted 4 January 2016
Available online 4 February 2016

Keywords:
Acoustic absorption
Orifice impedance
Bias flow
Grazing flow
Perforated liners

A B S T R A C T

The absorption of sound by cavities lined with perforated sheets depends crucially on the impedance of the orifices in the sheets. Although the theory for that absorption in the absence of a mean flow was well-developed in 1926, the presence of either a 'bias' flow through the orifices, or of a flow 'grazing' the sheet and deflecting the acoustic jets, radically alters the absorption. There are many theoretical and experimental treatments of the various cases, some of which are reviewed here. However, there has been little attempt to show how these data relate to one another, and this is also undertaken. The frequency dependence of the impedance is here expressed in terms of a Helmholtz number and used as the prime parameter for comparison. Theories for the cases where the mean flow is negligible are naturally based on the viscous penetration depth, whereas those for bias flow have a Strouhal number as the main parameter and are independent of viscosity. It is found that there are major uncertainties in the impedance for higher Strouhal numbers, when the bias flow is small. A criterion for transition to the no-bias flow theory is proposed. Theories and correlations for grazing flow rationally feature a Strouhal number based on the friction velocity in the duct, since this determines the boundary layer characteristics, but there should be a smooth transition to the case where the grazing flow can be considered negligible. Criteria for this are also proposed, based on the available experimental data. When both types of flow are present, particularly when the grazing velocity is larger than the bias velocity, the available data are very limited.

Contents

1. Introduction

A common method for the suppression of noise in ducts is to line them with perforated sheets. This has found application on automobile engines as a means of absorbing noise in the exhaust pipe, on the intakes of large turbo-fan engines, and more recently on the combustion chambers of gas turbines. Acoustic waves through the penetrations in these liners can damp waves propagating along the ducts.

For 'perforated tube mufflers' on automobile engines, in which the frequencies of interest range up to 5 kHz with sound pressure

* Tel.: +44 20 7882 5279.
E-mail address: c.j.lawn@qmul.ac.uk

http://dx.doi.org/10.1016/j.apacoust.2016.01.005

Nomenclature

Symbol in Main Text	Meaning
a	radius of holes in liner
C_d	discharge coefficient of orifice
c	speed of sound
f	frequency, or Darcy friction factor for the main duct
g	function describing influence of bias flow on non-linear response
H_n	Helmholtz number, ka
K	loss coefficient referred to upstream kinetic energy
K'	loss coefficient referred to kinetic energy in plane of orifice
k	wave number, ω/c
l_0	equivalent length of gas in orifice in computing the reactance
M_b	bias flow Mach number through the orifices, $\overline{V}/c$
M_g	grazing flow Mach number, U_g/c
n	order of Bessel function
$P/\overline{P}$	pressure/mean pressure
Pr	Prandtl number of the fluid
p	acoustic pressure
Re	Reynolds number of the orifice based on radius, $\rho a\overline{V}/\mu$
Str	Strouhal number of orifice based on radius, $a\omega/\overline{V}$
Str_t	Strouhal number of orifice based on thickness, $t\omega/\overline{V}$
t	thickness of the liner, or time
U_g	mean velocity of grazing flow in the duct
u_τ	friction velocity of grazing flow, $\sqrt{\tau/\rho}$, where τ = shear stress
u	velocity variable in the momentum equation
$V/\overline{V}$	velocity/superficial mean velocity through the orifice
v	superficial acoustic velocity through the orifice
x	axial distance
Z	specific acoustic impedance
Z_μ	viscous component of specific acoustic impedance
α	coefficient of viscous term in loss equation
β	coefficient of inertial (non-linear) term in loss equation
γ	ratio of specific heat capacities, or parameter in Howe's theory
δ	parameter in Howe's theory, or grazing boundary layer thickness
δ_v	viscous penetration depth
Δp	acoustic pressure loss
ς	coefficient in non-linear acoustic resistance in Bellucci et al. [10]
κ	$(1-i)/\delta_v$
μ'/μ	ratio of effective gas viscosities for a conducting wall relative to a non-conducting one in the theory of Melling [16]
μ	dynamic viscosity
$\phi(\kappa a)/\phi'(\kappa a)$	function in the solution of Crandall/the function with conducting wall viscosity μ'
ρ	density
σ	porosity
ω	circular frequency

Subscripts

u	'upstream'
d	'downstream'

levels up to 170 dB, a small number of comparatively large (typically 2–5 mm diameter) perforations are chosen. The seminal work on this is typified by the papers of Sullivan [1] in which he shows that the transmission losses for both a straight-through resonator (a perforated pipe surrounded by a cylindrical cavity) and a cross-flow configuration (the same, but with a plug in the middle of the pipe) can be very satisfactorily modelled by writing a transfer matrix for each 'segment' of the muffler. Later, Jayaraman and Yam [2] and Thawani and Jayaraman [3] decoupled the equations describing the inner and outer flows under restricted conditions, and this approach was generalized by Munjal [4].

The intakes of turbo-fan engines are usually perforated by numerous small holes in the outer liner, backed by an impermeable plate, but separated from it by honeycomb cells. The Mach numbers of the flow past these liners are usually high (>0.4) and the perforations are small (about 1 mm). Astley et al. [5] survey many of the computational approaches to this problem. One approach, not included in [5], is that of Sbardella et al. [6], who solved the governing Euler equations for a duct lined with a porous sheet with a 2-D finite difference formulation, treating the cells behind the liner with a 1-D discretization. An example of a method for tackling the inverse problem, that of deducing the absorption of the liner from measurements on an opposite duct wall is that of Jing et al. [7], who used a finite element solution procedure. In examining the possibility that the absorption can be effectively controlled through varying the flow through the liner, Dean and Tester [8] had earlier computed the absorption of a multi-layered liner. They showed good correspondence of their theory for impedance with their experimental results for waves with a range of frequencies at normal incidence.

Combustion chamber liners in gas turbine engines are designed particularly to cool these walls to well below the flame temperature with air taken directly from the compressor exit. However, they are also being employed to suppress sound generated by thermo-acoustic instabilities, and the frequencies of interest are generally below 1 kHz. Not only is there a significant 'grazing' flow but usually there is a 'bias' flow through the orifices, which are typically also about 1 mm in diameter. In this context, Hughes and Dowling [9] and Bellucci et al. [10] investigated the absorption of sound at normal incidence by a liner with a bias flow. Eldridge and Dowling [11] later computed the absorption by such a liner in a duct. They tackled the additional complication of an outer or 'metering' liner coaxial with the inner chamber liner. This forms an annular cavity and axial acoustic waves in this cavity interact with those in the chamber duct to modify the driving acoustic pressures across the orifices. With no bias flow, Jayatunga et al. [12] compared with measurements the results of absorption calculations for frequencies up to 400 Hz, for which their cavities could be regarded as compact compared with the wavelength, and obtained excellent agreement. Macquisten et al. [13] successfully compared the absorption predicted using the approach of [11] with measurements on a real gas turbine as a function of the cooling flow rate, and more recently, Lahiri et al. [14] established a data-base of absorption for a wide variety of geometries and cooling flow rates.

The absorption in all these calculations depends crucially on the acoustic impedance of the orifices in the liners, which in turn depends on the mean flow through the orifices (the 'bias' flow), and the flow in the duct along the surface of the sheets (the 'grazing' flow). There have been many theories and experimental investigations of the impedance of orifices under various flow conditions, and it is beyond the scope of this paper to review them all or to discuss mechanisms in great depth. However, there is a need to explore how the various approaches relate to one another, because in many cases they have been developed for restricted conditions. With considerable judgement about which papers have effectively built upon previous work, and which are still the