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Optimisation of micro-perforated cylindrical silencers in linear and nonlinear regimes

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ABSTRACT

This paper describes analytical and experimental studies conducted to understand the potential of lightweight non-fibrous alternatives to dissipative mufflers for in-duct noise control problems, especially under high sound pressure levels (SPLs) and in the low frequency domain. The cost-efficient multi-modal propagation method has been extended to predict nonlinear effects in the dissipation and the transmission loss (TL) of micro-perforated cylindrical liners with sub-millimetric holes diameter. A validation experiment was performed in a standing wave tube to measure the power dissipated and transmitted by a nonlocally reacting liner under moderate and high SPLs. Although nonlinear effects significantly reduce the dissipation and TL around the liner maximum damping frequency, these power quantities may be enhanced below the half-bandwidth resonance. An optimal value of the in-hole peak particle velocity has been found that maximizes the TL of locally reacting liners at low frequencies. Optimisation studies based on dissipation or TL maximization showed the sensitivity of the liner constituting parameters to variations in the design target range such as the center frequency, the levels of acoustic excitation and the nature of the surface impedance (locally or nonlocally reacting). An analysis is proposed of the deviation observed at low frequencies between the optimum impedance of the locally reacting liner under moderate SPLs and Cremer's optimum impedances.

1. Introduction

The control of the acoustic pressure field due to ducted sources within the aeronautic, automotive and building industries is a challenging problem as low frequency tonal and broadband components are present. For instance, the design of quieter turbofan engines to reduce the overall noise radiated by airplanes during take-off and approach conditions constitutes one example where noise control will become more difficult since future engines might have a lower number of blades and a shorter intake [1]. This will increase the contribution of low-frequency fan noise sources with a reduced surface available in the nacelle for the acoustic liners.

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Other active research areas within the same problematic deal with the passive insulation of the low-frequency noise content induced by turbulent flow in heating, ventilation and air conditioning systems [2]. They also concern the efficient design of intake or exhaust automotive mufflers able to reduce over a broad bandwidth the firing frequency of variable speed engines [3]. Perforated cylindrical expansion chambers, with hole diameters typically larger than 1 mm, have been used extensively for designing these silencers. They may include several tube sections within the car exhaust system, interconnected through perforated bridges or cross baffles, for attenuation performance in the medium and high frequency range [3]. In order to deal with low-frequency noise, a large volume is usually needed that increases the back pressure. Several works then focused on enhancing the TL performance of compact perforated silencers. Simulation studies on concentric perforated resonators by Sullivan and Crocker [4] showed the existence of an optimum value of the perforation ratio that maximized the overall TL for both short and long resonators. Moreover, inserting fibrous material into the chamber of a perforated silencer dramatically improves the TL from a multi-dome behaviour to a single resonance type, except at low frequencies [5,6].

Even though fibrous absorptive materials are widely used, they present disadvantages due to the transport of airborne particles in the working environment and life-cycle limitations. Such systems can be clogged by dust or oily substances which prevent their use in hospitals, food and pharmaceutical industries due to the risks of bacterial contamination. They can also be easily damaged by high flow velocity and temperature conditions, sources of fire hazards, so that they are difficult to use as such to attenuate the intake and exhaust noise of engines and blowers. To handle this, fibrous materials have to be shielded by perforated interfaces, but then at the expense of a reduced acoustical attenuation. Thus, there is a need for alternative techniques able to provide optimal noise control performance in ducts whilst reducing or even suppressing the use of porous materials. In aeronautics, one should also make sure that such techniques do not incur any weight penalty and are robust to impairment of their acoustical efficiency, for instance due to fluid drainage slots within the honeycomb core of the turbofan liners [7].

One approach that has attracted attention since several decades in room acoustics is the design of Micro-Perforated Panels (MPPs) and the study of their acoustical properties under normal, oblique or random incidence [8–9]. MPP absorbers consist of panels perforated with holes of sub-millimeter diameter and backed by a rigid or flexible wall. The goal is to increase the viscous losses through the apertures that dissipate the acoustic energy around the Helmholtz resonance. They can be made of fiber-free and lightweight materials such as metal or polymer, and optimized to achieve high absorption and insulation performance over several frequency bands using relatively compact devices. In duct acoustics, the use of micro-perforations for reactive and dissipative silencers has also been investigated, in particular the effect of grazing flow and high sound pressure levels on the acoustic impedance of such absorbers. It has been found that they can constitute efficient sound-absorbing devices under grazing plane waves at low frequencies and non planar wave modes at higher frequencies, even without the introduction of porous material [10–14].

Wu [10] considered a simplified model for predicting the sound attenuation of a plane wave by locally reacting micro-perforated duct silencers. The main factor for improving the insertion loss without significant pressure drop was found to be the perforation ratio, that needed to be carefully optimised. She provided significant guidelines but concluded that the model was not accurate enough to generate catalogue data. Wang *et al.* [11] have studied rectangular reactive plate silencers consisting of an expansion chamber with two side-branch cavities covered by flexible plates that reflect the sound to the upstream side. In order to broaden the reflection bandwidth, they proposed what they called a hybrid duct silencer, both reactive and dissipative, with two light and moderately stiff MPPs covering the rectangular cavities. A two-dimensional model for the nonlocally reacting silencer was developed, assuming plane wave excitation and considering vibroacoustic coupling between the MPP and the sound fields in the inner and outer duct cavities. The effect of the micro-perforations in broadening the TL stop bands and smoothing out the sharp TL peaks of the original silencers was confirmed experimentally using the four-microphone, two-load method. An optimal value of the plate bending stiffness was found that provides a threshold for the perforations diameter above which the TL bandwidth is significantly increased.

An experimental investigation about the TL performance of nonlocally reacting micro-perforated silencers with either circular or slit-shaped holes was carried out by Allam and Åbom [12] in the flow case using a two-port method and assuming plane wave excitation. The educed impedance enabled to generalize Maa's nonlinear model [13] by accounting for the effect of a one-sided grazing flow [14]. This impedance was used in a 3D FEM model to predict the TL and compare it against the measured one for several flow Mach numbers. It was found that there is an important drawback associated to TL minima due to axial resonances in the outer chambers of the silencer. Inserting a micro-perforated annular screen in the outer cavity increases the TL over a broad bandwidth, but it does not suppress the TL dips [15]. To minimise the effects of these resonances, Åbom and Allam [16] proposed to subdivide the chamber lengths down to half the wavelength at the first duct cut-on frequency in order to reach the "locally reacting limit". Partitioned MPP silencers can thus be optimized for their wall impedance to match the Cremer optimum impedance [17]. This target impedance has been derived for cylindrical locally reacting liners, without [18] or with flow [19], but well beyond the plane wave range, e.g. at high Helmholtz numbers kR_i, with k the acoustic wavenumber and R_i the inner duct radius. It has also been extended in the flow case at low Helmholtz numbers [20] in order to deal with IC-engine applications that occur below or around the first duct cut-on frequency.

Recently, Yu *et al.* [21] also showed that partitioning the outer cavity of rectangular MPP silencers in the no flow case dramatically enhances the TL over stop bands at low frequencies due to a more effective energy dissipation through the holes. The MPP holes diameter and perforation ratio were then optimized in order to maximize the overall TL over a