Applied Acoustics 93 (2015) 15–22

Contents lists available at ScienceDirect

Applied Acoustics

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

Impedance assessment of a dual-resonance acoustic liner

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ARTICLE INFO

Article history:
Received 18 June 2014
Received in revised form 16 December 2014
Accepted 13 January 2015
Available online 5 February 2015

Keywords:
Acoustic liners
Absorption
Noise control

ABSTRACT

Acoustic liners are commonly used to reduce noise from commercial aircraft engines. Engine liners are placed in the nacelle inlet and aft bypass duct to attenuate the noise radiated from the engine. Traditional engine liners are constructed of a perforated facesheet over a honeycomb structure to create a quarter-wave absorber. With this design, the low frequency performance of the liner is limited by the depth of the honeycomb. However, with advances in engine design, lower frequency sound absorption is becoming more critical while liner depth must be minimized. Acoustic metamaterials can exhibit unique acoustic behavior using periodically arranged sub-wavelength resonators. Researchers have shown that acoustic metamaterials can effectively block the propagation of low-frequency acoustic waves. Therefore, acoustic metamaterial-inspired concepts are being investigated to improve the low frequency performance of engine liners. A proposed dual-resonance liner is presented here that combines the idea of a Helmholtz resonator metamaterial with a traditional quarter-wave acoustic liner. The low frequency acoustic absorption of a traditional liner can be significantly increased by adding a second, low frequency resonance to the system. The normal incidence absorption coefficient of the proposed liner is more than 10 times larger than a conventional honeycomb liner at the designed Helmholtz resonance frequency while retaining similar performance at higher frequencies.

1. Introduction

In order to meet community noise standards, there is a need to reduce noise from turbofan aircraft engines. To combat the noise created by the engine, treatment is applied to the interior walls of the nacelle inlet and aft-fan ducts. Current treatments, or liners, attenuate the noise radiated from the engine with the greatest reduction occurring at the first harmonic of the blade pass frequency, which is commonly seen at around 1500 Hz. However, new engine and turbofan blade designs will require greater attenuation at lower frequencies than are achievable with the current liner design due to their depth restriction, while retaining comparable performance at higher frequencies. Therefore, new methods must be developed to achieve lower frequency noise reduction.

Historically, acoustic engine liners consist of a porous, metal or composite facesheet bonded on top of a honeycomb core that is fixed to a rigid backplate. Fig. 1 depicts a traditional perforate-over-honeycomb-core (POHC) acoustic liner. The honeycomb core forms a two dimensional array of cavities, which creates individual quarter-wave resonators. The parameter d defines the size of the honeycomb cells. While the cells are necessary for the liner to be locally reacting, the size of the cell has little impact on the performance of the liner when d less than a ¼ of a wavelength. The perforated facesheet placed on top of the cavities increases the losses in the device, which broadens the absorption peak in the frequency domain. The perforate panel also adds an inertial component, which reduces the resonant frequency of the device by a relatively small amount. The depth of the cavities is the primary variable controlling the resonant frequency. The low frequency performance of POHC liners is typically limited by the available cavity depth, D. The design of the POHC liners is similar to that of micro-perforated panel absorbers, which typically consist of a micro-perforate panel backed by an acoustic cavity [1]. However, the motion of the micro-perforate panel is usually utilized for increased absorption [2–4], while POHC liners utilize the honeycomb core to limit this motion and retain locally reacting impedance for grazing incidence sound.

The absorption of POHC liners at low frequencies is increased with a larger depth; however, an increase in liner depth requires a corresponding increase in the thickness of the engine nacelle, which significantly increases weight, drag, and fuel burn. Therefore, new designs for acoustic liners are needed to improve low frequency absorption and increase the bandwidth of performance

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http://dx.doi.org/10.1016/j.apacoust.2015.01.011
0003-682X/

Nomenclature

a	empirical constant	V	Helmholtz resonator volume
C_D	discharge coefficient	v_{rms}	root-mean-square velocity
c	speed of sound	W	Helmholtz resonator neck width
D	liner depth	α	absorption coefficient
d	perforate hole diameter	α_w	absorption coefficient for a wide duct
k	acoustic wavenumber	γ	ratio of heat capacities
L	Helmholtz resonator neck length	ε	end correction
L'	effective neck length	ζ	normalized acoustic impedance
m	mass	θ	normalized acoustic resistance
P_{ref}	reference pressure	μ	dynamic viscosity
Pr	Prandtl number	ρ	density of air
r	reflection coefficient	σ	perforate open area
S	Helmholtz resonator neck open area	χ	normalized acoustic reactance
SPL	sound pressure level	ω	angular frequency
t	facesheet thickness		

without changing the depth of the liner. Other absorbing designs have been shown to increase bandwidth and low frequency absorption through stacking Helmholtz resonators [5,6] or perforated panels [7–9], however these significantly increase the size of the system. One potential solution is to utilize a type of engineered heterogeneous material called an acoustic metamaterial.

Within the literature, a metamaterial is considered to be any engineered material built of individual elements of small conventional materials, usually periodic, that exhibits properties not found in nature. Acoustic metamaterials were first classified as such by Li and Chan [10], however acoustic analysis of periodic media and sonic crystals had been studied earlier [11–14]. Metamaterials can exhibit unique properties such as increased transmission loss due to stop-bands, negative effective density and/or stiffness, and negative refractive index. These novel properties are due to the periodic impedance mismatch of elements. By introducing mechanically-resonant inclusions within an elastic medium, stop-bands can be formed at low frequencies where the elastic wavelengths are much larger than the inclusion size [15]. Using the same methodology but with greater coupling to air, Hu et al. [16] developed an acoustically resonating sonic crystal using an array of split cylinder Helmholtz resonators. This implementation placed the resonant devices within the fluid medium. In contrast, Fang et al. [17] developed an ultrasonic metamaterial with Helmholtz resonators placed on the side of a waveguide. Further studies were performed by Cheng et al. [18,19] to investigate transmission versus the number of cells, periodic constants, and configuration of these one-dimensional metamaterials. Their studies showed significant transmission loss at the resonant frequency of the Helmholtz resonators. Similarly, García-Chocano et al. [20] demonstrated a large reduction in the transmitted waves in a duct using a quarter-wave resonator metamaterial, which was similar

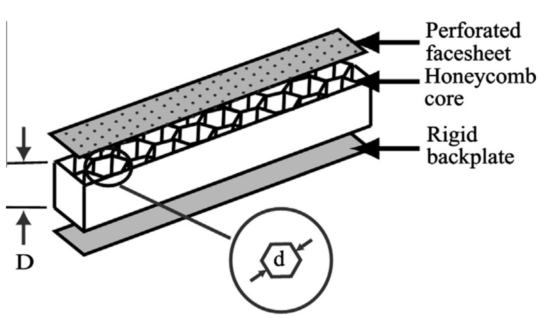

Fig. 1. Schematic of a perforate-over-honeycomb-core acoustic liner sample.

to a traditional POHC liner. Therefore, it should be possible to incorporate these metamaterial structures into an acoustic liner to increase the low frequency performance.

The goal of the present work is to increase the low frequency noise reduction of an acoustic engine liner by utilizing acoustic metamaterials. Specifically, a new metamaterial-inspired liner is presented, which combines a traditional perforated panel over honeycomb liner with an array of Helmholtz resonators. To assess the noise reduction potential of an engine liner, the normal incidence impedance of the liner is determined before considering the grazing incidence aeroacoustic environment. Therefore, analytical normal incidence impedance models of a POHC liner, a Helmholtz resonator, and the proposed dual-resonance liner are presented. This is followed by a description of a finite element model of the liners. The experimental setup and procedure used to validate the models are then presented. Then, the results and analysis are given. Finally the conclusions are presented along with ideas for future work.

2. Analytical modeling

To predict the acoustic characteristics of candidate engine liners, the normal incidence, normalized specific acoustic impedance of a liner is estimated using a lumped-element analytical model. A model for a POHC liner is presented first followed by the analytical model of a single Helmholtz resonator. The final section describes the dual-resonance metamaterial-inspired acoustic liner and a lumped-element model for its normalized acoustic impedance.

2.1. Traditional POHC liner

Many researchers have proposed impedance models for a POHC liner. The model utilized in this work was described by Parrott and Jones [21]. The normalized specific acoustic impedance of the POHC liner can be described with four terms

$$\zeta_t = \theta + i\chi = \theta_{\text{lin}} + \theta_{\text{nonlin}} + i\{\chi_{fs} - \cot(kD)\} \quad (1)$$

where θ_{lin} and θ_{nonlin} are the linear and nonlinear resistance terms of the perforated facesheet, χ_{fs} is the reactance term of the facesheet, and the final term is the total impedance of the honeycomb core cavities. The impedance is normalized by the characteristic impedance of air, ρc. The impedance of the honeycomb core is purely reactive and is determined by the acoustic wavenumber k and the cavity depth D. The resistance of the perforated facesheet has both linear and nonlinear terms. These two terms can be described by a semi-empirical formulation of the flow resistance,