Applied Acoustics 117 (2017) 86–93

Contents lists available at ScienceDirect

Applied Acoustics

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

Numerical determination of transmission losses of a turbofan inlet duct lined with porous materials

C. Chan [a,b], E. Perrey-Debain [a,*], J-M. Ville [a], B. Poirier [b]

[a] Sorbonne universités, Université de technologie de Compiègne, Laboratoire Roberval UMR CNRS 7337, CS 60 319, 60 203 Compiègne cedex, France
[b] Safran/Snecma, Etablissement Villaroche Sud, Rond-point René Ravaud - Réau, 77550 Moissy-Cramayel, France

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form 15 September 2016
Accepted 20 September 2016
Available online 9 November 2016

Keywords:
Mode matching method
Porous materials
Duct acoustics with flow
Optimization

ABSTRACT

Acoustic performances of turbofan inlet duct lined with a metal foam are numerically investigated. The computational method, based on a mode matching technique, allows to tackle realistic turbofan inlet ducts specifications, which includes all cut-on modes. It permits to deliver very accurate results at high frequencies at a modest computational cost, and provide an adequate tool for optimization purposes. By choosing appropriate design variables, a methodology is proposed to determine the nearly-optimal liner consisting of a perforated plate backed by a porous material. Results are given for two different Mach numbers corresponding with sideline and cutback flight conditions. The optimized liner solution is compared to traditional double degree-of-freedom liners designed to provide the best acoustic attenuation. While similar acoustic performances are observed over most part of the spectrum, noticeable improvements can be found in the low frequency regime, i.e. below 500 Hz. These preliminary results demonstrate the interest for this new type of liners.

1. Introduction

Air traffic development and noise regulations near airports have led aero-engines constructors to develop new technologies able to reduce fan noise. At subsonic fan speeds, rotor-stator interaction noise is known to be the principal engine noise source. In practical applications, the turbofan inlet, which acts as an acoustic waveguide, is lined with locally reacting cavity liners. These acoustic treatments are efficient around a target frequency corresponding to the damped resonance of the cavity and are well suited for the reduction of engine tones. Recent changes in turbofan engine design led to a reduction of the tonal noise to the detriment of the broadband noise, this have contributed to the renewed interest in acoustic liners able to reduce over a range of frequencies such as extended-reacting liners involving the use of porous materials [1].

In this context, the use of metal foam liners is of particular interest because they have the potential to survive in harsh environments like aircraft engines contrary to non-metallic porous materials. Owing to their physical and mechanical properties, they are widely used in many industrial applications including light weight structures, filters, electrodes, heat exchangers but their usage for noise control is relatively recent and research is developing in order to better understand absorption mechanisms in the material and to develop new process able to improve their acoustic attenuation performance [2]. A metal foam located in the inlet fan duct and covered with a perforated sheet has been tested at NASA Glenn [3]. Results obtained for a specific metal foam liner showed equivalent acoustic attenuation to traditional liner designs and demonstrated their potential for reducing fan noise at low-speed. Contrary to classical liners, liners made of metallic foams can be mounted over the rotor as a rub strip and thus provide an additional treatment area [4].

Although, from a practical point of view, the utilization of these new materials are expected to raise a certain number of issues, such as the weight and the life-time of these metallic foams or the production cost, it is essential, in a preliminary stage, to conduct a series of experiments and/or numerical tests in order to assess their potential interest for noise control. In this respect, it is desirable to develop numerical models in order to simulate and tackle realistic configurations involving large diameter nacelles and the presence of a high-speed flow.

The prediction of the acoustic performance of a dissipative silencer is commonly performed using the Finite Element Method (FEM) [5]; Peat and Rathi [6] presented a general finite element formulation for the computation of sound propagation through an arbitrary flow duct surrounded by a volume filled with porous material. Other approaches based on the Boundary Element

* Corresponding author.
E-mail address: emmanuel.perrey-debain@utc.fr (E. Perrey-Debain).

http://dx.doi.org/10.1016/j.apacoust.2016.09.024
0003-682X/

Method (BEM) have been developed by Selamet et al. [7] and Wu [8] for the prediction of the acoustic attenuation in mufflers. These three-dimensional numerical models require a significant CPU expenditure and their utilizations are often restricted to the analysis of low to medium frequency problems. When the silencer geometry contains an axially uniform cross section, it is desirable to take advantage of the mode matching method (MMM) which is especially favoured for reducing the computational time. Mode matching techniques have been successfully applied in the automotive and aircraft industries for analyzing the sound transmission through exhaust systems [9] and for turbofan liner optimization [10]. The method is also used in the building sector for ventilation and air-conditioning systems [11]. It consists in predicting the sound transmission in a silencer by forcing the appropriate axial matching conditions over the wave-guide discontinuities. It relies mainly on the accurate knowledge of acoustic modes in the dissipative silencer as well as in the inlet and outlet duct so as to express the wave field as a modal decomposition in each segment of the waveguide.

Automotive exhaust silencers generally consist of an expansion chamber filled with a porous or fibrous material. The numerical prediction of their acoustic performance generally includes the presence of a perforate sheet between the airway and the absorbent material [12,13]; the effect of uniform flow in the central channel is also investigated in [14]. For arbitrary shaped cross-section, acoustic modes are found using classical finite element discretization techniques. The model of Kirby [15] leads to a quadratic eigenvalue problem while the order is 4 without the perforate plate [16]. When the cross-section is circular, the acoustic pressure in the silencer can be written in terms of Bessel functions of integer order and acoustic modes are found by solving a transcendental eigenvalue equation for the axial wave number. Cummings and Chang [17], who have voluntary omitted the perforate plate in their model, use the secant method to solve the governing eigenequation. Kirby and Denia [18] apply the Newton-Raphson method to locate the roots but the method requires the derivative of the governing eigenequation. A more accurate method, called homotopy, is proposed by Sun et al. [19] for solving the eigenvalues for locally or non-locally reacting acoustic liners in flow ducts. Another numerical approach to solve these eigenvalues for locally reacting linings is proposed by Alonso and Burdisso [20] and is based on the minimization of the absolute value of the eigenequation by the Nelder-Mead method, the main advantage is that it does necessitate numerical differentiations. The common problem to all of these methods is the possibility of missing roots because they highly depend on initial guesses [18].

Modelling sound propagation in aero-engine ducts has been studied for many years to predict the performance of turbofan inlet ducts treated with locally reacting cavity linings. Gabard and Astley [21] proposed a numerical procedure based of finite element discretization for calculating the eigenmodes in ducts with peripherally varying impedances and found that complete set of modes can be obtained for frequency and flow conditions which are specific of turbofan duct. Recently, there has been interest in studying the effect of liner splices which causes sound scattering into modes that are poorly absorbed by the liner. Analysis is performed for a single incident mode and aimed at examining the sound attenuation at a specific Blade Passing Frequency (BPF), using both mode matching and 3D finite element method [22,23]. McAlpine shows that fan tones can be well-absorbed by the liner with thinner splices at low supersonic fan speed, however, the authors consider an axially segmented liner in order to increase the attenuation at the BPF for high supersonic fan speed [24]. An approximate mode-matching technique with only two radial modes is used by neglecting cut-off modes and left-running lined duct modes. For a multimode incident sound, Bi et al. [25] show that the interferences between incident modes is relevant in the penalty mode scattering and that effect of splices is negligible for incident modes with random phases.

In this paper, a numerical model based on the modal decomposition for the acoustic pressure is developed in order to predict sound power transmission loss in large diameter ducts which are representative of real turbofan inlets. Convective effects of mean flow and dissipative effects due to the presence of a porous layer at the duct wall must also be taken into account by the model. In order to cover the whole frequency range of interest, the approach requires the computation of a very large amount of modes (say up to several hundred modes) with sufficient accuracy. To this end, a numerical root-finding technique based on Chebyshev spectral methods is presented and applied for both locally and non-locally reacting liners. In the line of previous work [15,9], a mode matching method based on the weighted residuals method is developed and presented in Section 3. By choosing appropriate design variables, a methodology is proposed to determine the nearly-optimal liner consisting of a perforated plate backed by a porous material made of metal foam. Acoustic performances are given for two different Mach numbers corresponding with two typical flight conditions and are compared with traditional double degree-of-freedom liners.

2. Acoustic modes in lined ducts with uniform flow

The duct geometry consists of a circular-section dissipative expansion chamber of length L, filled with isotropic porous material and separated from the central channel of radius r_1 with a perforated sheet (Fig. 1). The central channel contains a mean axial flow of Mach number M. The diameter of the inlet and outlet pipes (regions I and III respectively) are set equal to that of the airway in the dissipative silencer (regions II). All outer surfaces are assumed acoustically hard.

Assuming a time dependence of $e^{-i\omega t}$ and using the cylindrical polar co-ordinates (r, θ, z), the expression of the acoustic pressure can be written as $p(r, \theta, z, t) = p_{1,2}(r)e^{i(m\theta+\beta z-\omega t)}$ where subscripts 1 and 2 denote respectively the air and porous domains, m is the azimuthal order, and β the axial wave number. Using the separability of variables:

$$\frac{d^2p_1}{dr^2} + \frac{1}{r}\frac{dp_1}{dr} + \left(\alpha_1^2 - \frac{m^2}{r^2}\right)p_1 = 0, \quad (1)$$

$$\frac{d^2p_2}{dr^2} + \frac{1}{r}\frac{dp_2}{dr} + \left(\alpha_2^2 - \frac{m^2}{r^2}\right)p_2 = 0 \quad (2)$$

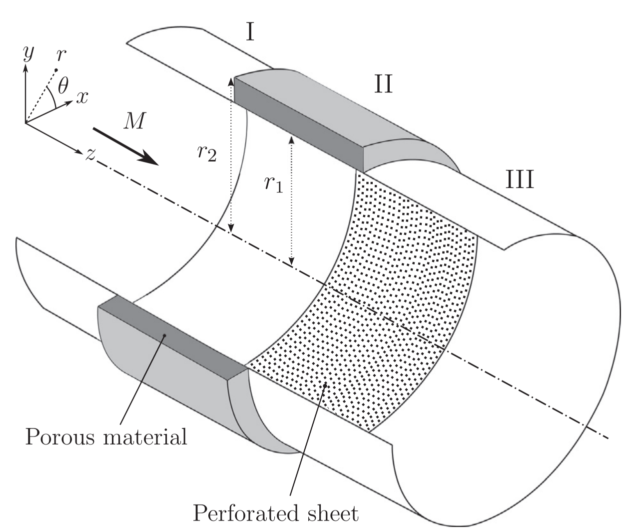

Fig. 1. Geometry of the silencer.